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Surface ozone in the Lake Tahoe Basin

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HIGHLIGHTS

- The Lake Tahoe Basin experiences elevated concentrations of surface O_3.
- Diurnal maxima of ~50–55 ppb occur throughout the Basin for 10:00–17:00 PST.
- At night, there is large site-to-site variability in the observed O_3 concentrations.
- Nocturnal O_3 concentrations depend on elevation, topography, and surface cover.

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ABSTRACT

Surface ozone (O_3) concentrations were measured in and around the Lake Tahoe Basin using both active monitors (2010) and passive samplers (2002, 2010). The 2010 data from active monitors indicate average summertime diurnal maxima of approximately 50–55 ppb. Some site-to-site variability is observed within the Basin during the well-mixed hours of 10:00 to 17:00 PST, but large differences between different sites are observed in the late evening and pre-dawn hours. The observed trends correlate most strongly with elevation, topography, and surface vegetation. High elevation sites with steeply sloped topography and drier ground cover experience elevated O_3 concentrations throughout the night because they maintain good access to downward mixing of O_3-rich air from aloft with smaller losses due to dry deposition. Low elevation sites with flat topography and more dense surface vegetation experience low O_3 concentrations in the pre-dawn hours because of greatly reduced downward mixing coupled with enhanced O_3 removal via efficient dry deposition. Additionally, very high average O_3 concentrations were measured with passive samplers in the middle of the Lake in 2010. This latter result likely reflects diminished dry deposition to the surface of the Lake. High elevation Tahoe Basin sites with exposure to nocturnal O_3-rich air from aloft experience daily maxima of 8-h average O_3 concentrations that are frequently higher than concurrent maxima from the polluted upwind comparison sites of Sacramento, Folsom, and Placerville. Wind rose analyses of archived NAM 12 km meteorological data for the summer of 2010 suggest that some of the sampling sites situated near the shoreline may have experienced on-shore "lake breezes" during daytime hours and/or off-shore "land breezes" during the night. Back-trajectory analysis with the HYSPLIT model suggests that much of the ozone measured at Lake Tahoe results from the transport of "polluted background" air into the Basin from upwind pollution source regions. Calculation of ozone exposure indices indicates that the two most polluted sites sampled by active monitors in 2010 – the highest Genoa Peak site, located on the eastern side of the Lake at an elevation of 2734 m above sea level, and Angora Lookout, located to the south–southwest (SSW) of the Lake at an elevation of 2218 m above sea level – likely experienced some phytotoxic impacts, while the other Tahoe Basin locations received lower ozone exposures.

1. Introduction

Lake Tahoe (elevation 1897 m above sea level) is a large alpine lake that straddles the border between California and Nevada. With

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a maximum depth of 501 m, it is the fourth deepest lake in North America, and it is renowned for the clarity of its water (United States Geological Survey, 2014). Because of its importance as both a unique natural resource and a year-round vacation destination, Lake Tahoe has been extensively studied in terms of issues relating to hydrology and water clarity (Tahoe Environmental Research Center, 2014). The air quality within the Lake Tahoe Basin – especially the deposition of atmospheric pollutants into the lake – has also been investigated (Gertler et al., 2006; Dolislager et al., 2012a; VanCuren et al., 2012). Less attention, however, has been focused upon Lake Tahoe in terms of surface ozone and other air quality issues that are not directly linked to water clarity (Dolislager et al., 2012b).

Historically, the Tahoe Basin had been in compliance with ambient air quality standards for ozone until 2005, when the Air Resources Board of the State of California (CARB) adopted a more stringent 8-h ozone standard (not to exceed 70 ppb). Now some areas within the Basin violate this standard a few times each summer. Given that typically observed in-Basin ozone concentrations have remained low enough so that human health impacts are not a pressing concern (at least in comparison to heavily polluted regions like the western slope of the southern Sierra Nevada), many prior Tahoe Basin ozone studies have instead focused upon the impact of ozone on the health of the extensive pine forests that surround the Lake (Dolislager et al., 2012a; 2012b). Ambient ozone has pronounced adverse effects on forest health in California's mountain regions (Arbaugh et al., 1998). According to large-scale distribution maps of the Sierra Nevada bioregion, the Lake Tahoe Basin's summer-season, 24-h ozone levels are approximately 50–60 ppb (Fraczek et al., 2003). Such ozone levels may be toxic to vegetation (Krupa et al., 1998) and can adversely affect tree health (Arbaugh et al., 1998). Ozone has been observed to cause foliar injury to ponderosa (*Pinus ponderosa*) and Jeffrey (*Pinus jeffreyi*) pines in the central Sierra Nevada (Miller et al., 1996), including the Lake Tahoe Basin (Pedersen et al., 1989).

In addition to potential impacts on surrounding forests, prior Tahoe Basin ozone investigations have also examined the transport of ozone and ozone precursors from upwind source regions. Carroll and Dixon (2002) performed aircraft measurements of a Sacramento pollution plume and found that maximum ozone concentrations were frequently observed in the afternoon, 40–80 km downwind of the city, but subsequently decreased by about 50% at distances 120 km downwind. Zhang et al. (2002) used aircraft measurements to study nitrogen and phosphorus in and around the Lake Tahoe Basin. Bytnerowicz et al. (2004) studied spatial and temporal ozone distributions as two-week integrated averages measured by passive samplers during the 2002 summer season for the entire Lake Tahoe Basin and for upwind areas on the western slopes of the Sierra Nevada. They concluded that the Sierra Nevada crest west of the Lake Tahoe Basin acts as a barrier that restricts polluted air masses and high ozone concentrations from the Sacramento Valley and Sierra Nevada foothills from entering the Basin. Dolislager et al. (2012b) assessed the relative impacts of transport versus local photochemical production by making continuous measurements during the summer of 2003 along the axis of predominant airflow (i.e., roughly southwest to northeast). They utilized two transport assessment sites at Big Hill and Echo Summit, along with other monitoring sites at various locations on the western slope of the Sierra Nevada, plus four in-Basin monitoring sites. Also incorporating aircraft data, they concluded that pollutants from upwind regions act to raise background concentrations entering the Tahoe Basin to the extent that local contributions do not need to be large to cause exceedances of air quality standards.

While the prior Tahoe Basin studies noted above are most

Table 1
Sampling locations equipped with both active monitors and passive samplers.

Location	Code	Latitude (degrees)	Longitude (degrees)	Elevation (masl)	Site description
Angora Lookout	AGL	38.8817	−120.0548	2218	Steep hillside near top of ridge; extensive fire damage
Echo Summit (CARB site)	ECHO	38.8116	−120.0331	2250	Flat clearing/parking lot along U.S. Hwy. 50
Folsom[a] (CARB site)	FOL	38.6833	−121.1644	108	Suburban location near green open space
Genoa Peak 7000	GP7	39.0789	−119.9091	2232	Small clearing on mild slope; thick grass
Genoa Peak 8000	GP8	39.0504	−119.9072	2449	Open clearing on moderate slope; heavy fire damage
Genoa Peak 9000	GP9	39.0438	−119.8834	2734	Rocky outcropping near summit; excellent exposure
Incline Village[a] (SLAMS site)	IVL	39.2504	−119.9567	1957	Rooftop in residential/commercial neighborhood
Lower Blackwood Creek	LBC	39.1098	−120.1901	1948	Flat open meadow with wet grass
Placerville[a] (CARB site)	PLA	38.7253	−120.8219	612	Semi-rural location in Sierra foothills
Sacramento[a] (CARB site)	SAC	38.5684	−121.4931	15	Rooftop near downtown Sacramento
Sugar Pine Point State Park	SPP	39.0419	−120.1448	1951	Flat open meadow; a few nearby trees
Thunderbird Lodge	THB	39.1739	−119.9316	1915	On the roof of a shed at the base of a steep incline
Upper Incline	ICN	39.2856	−119.9241	2523	Wide, open, steep slope with lots of green plants
Valhalla	VAL	38.9360	−120.0448	1906	Flat sandy terrain with low scrub; near CA Hwy. 89
Watson Creek	WC	39.2294	−120.1251	2293	Flat open meadow with leafy green plants

[a] These four long-term monitoring sites did not collect any passive sampler data.

Table 2
Sampling locations equipped only with passive samplers.

Location	Code	Latitude (degrees)	Longitude (degrees)	Elevation (masl)	Ave. O_3 in 2010 (ppb)	Ave. O_3 in 2002 (ppb)
64 Acres	64A	39.163	−120.143	1900	39.8	44.1
Barker Pass	BPS	39.071	−120.230	2344	52.8	60.7
Blodgett	BLOD	38.897	−120.664	1298	54.7	58.7
Cave Rock	CR	39.044	−119.948	1902	N/A	52.3
Clear Creek	CCK	39.126	−119.884	2099	49.5	52.4
Desolation Wilderness	DW	38.934	−120.122	2436	53.9	N/A
Diamond Peak	DIP	39.258	−119.901	2571	55.5	54.4
Forest Hill	FH	39.085	−120.741	1252	58.0	68.5
Heavenly Gun Barrel	HGB	38.929	−119.931	2509	56.0	57.1
Heavenly Ridge Bowl	HRB	38.918	−119.915	2782	55.2	57.5
Heavenly Sky Express	HSE	38.917	−119.903	3043	56.7	57.0
Hobart Mills	HM	39.409	−120.185	1806	35.9	44.8
Kelly Lake	KLAKE	39.313	−120.574	1816	51.9	58.0
Little Valley	LIL	39.253	−119.877	1956	47.0	44.2
Loon Lake	LLK	38.988	−120.334	1927	47.6	66.7
Riverton Ridge	RT	38.779	−120.428	1227	46.1	66.2
Serene Lakes	SLAKE	39.323	−120.360	2246	57.1	61.7
Sly Park	SPK	38.708	−120.593	1067	42.6	61.0
Tahoe Regional Park	TRP	39.252	−120.051	1962	40.8	49.9
TB2 Buoy	TB2	39.108	−120.006	1897	63.5	N/A
Upper Blackwood	UBW	39.079	−120.216	2179	51.1	56.2
Watson Mtn. Road	WMR	39.193	−120.166	2187	50.3	54.4
White Cloud	WHC	39.316	−120.847	1279	56.8	66.6
Woodford's	WF	38.772	−119.836	1811	54.8	60.2

relevant to the results presented in the present report, it should be noted that the more general topics of surface ozone (i) in alpine environments and (ii) near large bodies of water with persistent "lake breeze" (onshore flow) or "land breeze" (offshore flow) conditions have been thoroughly investigated in recent decades. Readers interested in a review of surface ozone measurements at high elevation sites should consult section 4.2 of Burley and Bytnerowicz (2011), which compares high-elevation results from the White Mountains along the California–Nevada border to similar sites across North America, Europe, and Asia. Other recent studies of interest might also include the paper from Ambrose et al. (2011) on results from the Mt. Bachelor Observatory (2763 m) in central Oregon, or the paper from Macdonald et al. (2011) on data collected at Whistler Mountain (2180 m) in British Columbia, Canada. Readers looking for more background on surface O_3 measurements where "lake/sea breeze" or "land breeze" conditions are prevalent are similarly encouraged to consult the recent papers from Goldberg et al. (2014), Stauffer et al. (2012), and Cleary et al. (2014).

This report presents ozone data measured in 2010 by portable ozone monitors deployed at ten different sites surrounding the lake, plus simultaneous data from long-term monitors at Incline Village and Echo Summit. It also presents two years (2002, 2010) of ozone data from passive samplers that were deployed across a more extensive network of sites that included both the Tahoe Basin and the area immediately to the west. (Three of the sites from this extended network of passive samplers also measured ozone in 2006.) Additional passive sampler data from 2010 for ozone precursors such as NO_x and volatile organic compounds (VOC) are also utilized to better understand the factors that influence ambient ozone levels within the Lake Tahoe Basin. In addition to mixing ratio data for O_3, NO_x, and VOC, an analysis of local winds is presented to help identify some of the meso-scale phenomena that can influence temporal and spatial variations in ozone. Back trajectories using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model are also utilized to highlight the long-range transport patterns that can bring ozone into the Tahoe Basin.

2. Experimental methods and procedures

2.1. Sampling locations

Sampling locations where ozone concentrations were measured using both portable monitors and passive samplers are listed in Table 1, along with the long-term monitoring stations at Echo Summit (ECHO) and Incline Village (IVL). Three additional sites – Sacramento (SAC), Folsom (FOL), and Placerville (PLA) – that are used to provide simultaneous comparison data are also included. Table 2 presents analogous information for the sampling sites where ozone was measured only with passive samplers. A map of the sampling locations used in this study is presented in Fig. 1.

The eleven sites equipped with both active monitors and passive samplers span the complete circumference of the lake, with lower elevation locations typically positioned within a few hundred meters of the shoreline and higher elevation sites usually located within a few kilometers of the shoreline. While most of these active sites were in relatively remote locations with minimal and/or infrequent exposure to vehicular emissions, some locations – Valhalla (VAL), Echo Summit (ECHO), Incline Village (IVL) – were adjacent to busy highways. At all of the measurement sites the sampling hardware was installed, whenever possible, so as to minimize potential impacts from nearby vehicular emissions or other local sources of pollution. For those sites equipped with both portable monitors and passive samplers the two different measurements were typically positioned within approximately 10 m of one another, with similar sampling heights (~1.75 m above ground level for the portable monitors; ~2.0 m above ground level for the passive samplers).

The sites equipped only with passive samplers included approximately a dozen locations that were located within ~10 km of the shoreline plus another ten locations that extended data collection further to the west (~75 km), north (~20 km), and south (~30 km). These outermost sites lie outside the Tahoe Basin, and enable direct in-Basin vs. out-of-Basin comparisons.

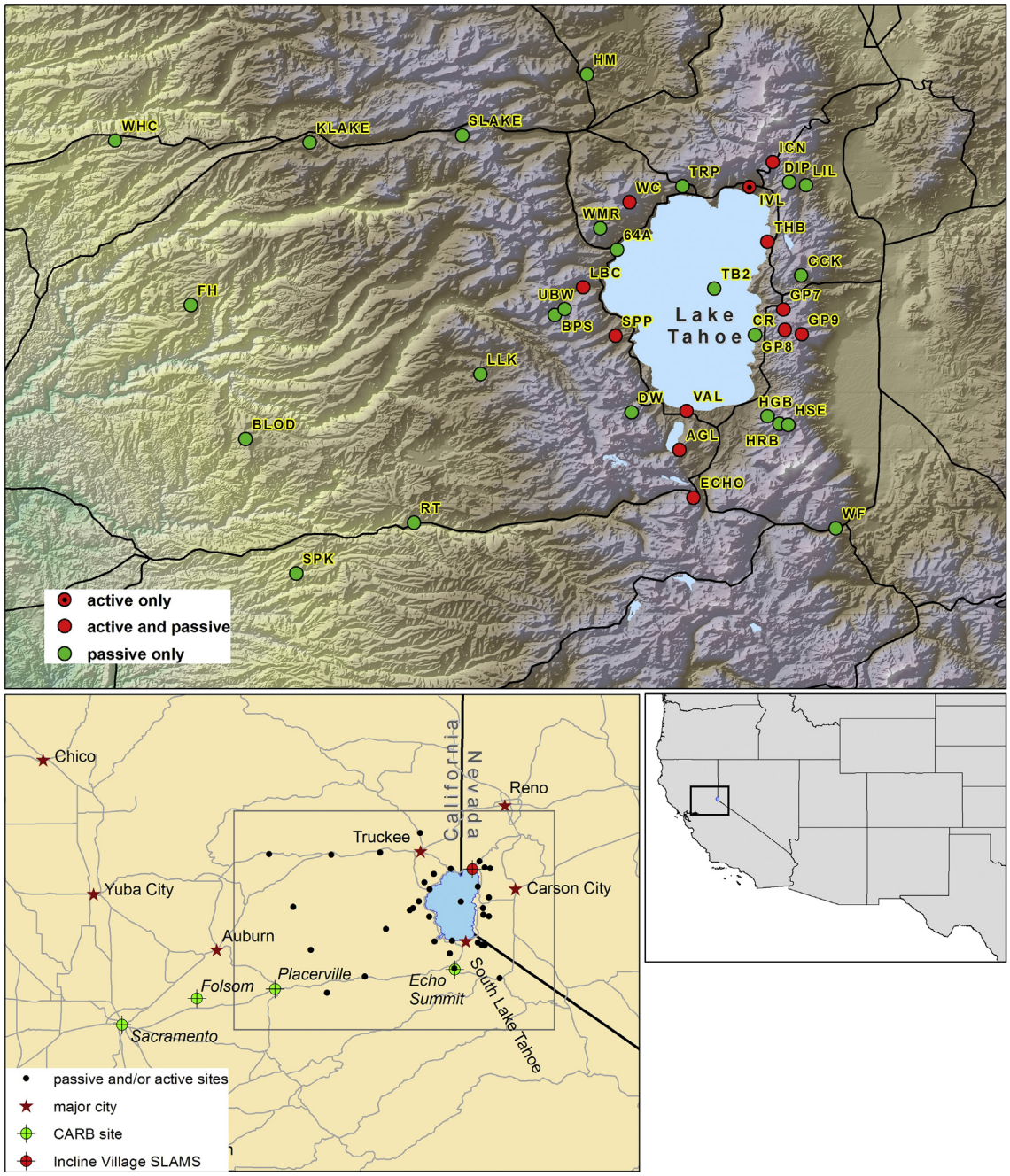

Fig. 1. Map of the sampling sites utilized in this study. Corresponding latitude/longitude/elevation data for each sampling site are presented in Tables 1 and 2

2.2. Sampling timelines

Although data collection in 2010 commenced at some locations in mid-June, the hourly data used to calculate daily averages, daily maxima of 8-h averages, and average diurnal cycles have been restricted to 12:00 PST on July 14 through 11:00 PST on September 22, which corresponds to exposure periods #3 through #7 for the passive samplers. Restricting the hourly data in this manner facilitates direct comparisons between the active ozone monitors and the passive samplers within a uniform 70-day window. Calculations of ozone exposure indices, however, utilized all available hourly data, with simple linear extrapolations to either a four-month period of June through September (a 24-h index calculated across an interval of 120 days, or 2880 h in total), or a three-month period of July through September (a 12-h index calculated across an interval of 90 days, or 1080 h in total). Along these lines, a preliminary 24-h exposure index based upon 2300 h of continuous ozone data would be multiplied by a factor of 2880/2300 = 1.252 in order to obtain the appropriate value for the four-month exposure period.

For the passive sampler data from 2002, data collection commenced on June 5 and continued until October 7. However, to enable more direct comparisons to the 2010 results, the 2002 data presented here have been restricted to July 16 – September 24.

In addition to the data from 2010 and 2002, passive sampler data for ozone were collected in 2006 (June 1 – October 5) at a limited network of six sites, all in close proximity to the Lake Tahoe shoreline. The 2006 sampling locations included three sites used in

both 2002 and 2010—64 Acres (64A), Sugar Pine Point State Park (SPP), and Valhalla (VAL) — plus Cave Rock (CR), which was also sampled in 2002. The remaining two sites sampled in 2006 (Crystal Towers, Nevada Beach) were not utilized in either 2002 or 2010. The 2006 passive sampler data that are briefly discussed in Section 3.4 have been limited to the three sites that were sampled in all three years and are restricted to an observation window of July 13 through September 21 to facilitate comparisons with results from 2002 and 2010.

2.3. Sampling protocols and calibrations

2.3.1. Data from portable ozone monitors

Ozone concentrations were measured using Model 202 Ozone Monitors from 2B Technologies, which employ UV absorption (Beer's Law) at a wavelength of 254 nm. Ambient air was sampled approximately 1.75 m above ground level via a 2.5 m length of 6.35 mm (0.25 inch) o.d. Teflon tubing. The sampling inlet consisted of a downward-facing 47 mm diameter Teflon filter holder equipped with a 1–2 μm Teflon filter membrane, which was shielded from precipitation by a plastic rain shield. Power for the ozone monitors was provided by 12-V solar power systems at all locations except for Thunderbird Lodge (THB), where local AC power was employed. To ensure protection from the elements, the ozone monitors and accompanying electronics were enclosed in weatherproof plastic cases. Ozone concentrations were measured every 10 s, and were automatically recorded into internal monitor memory as 5-min averages. These 5-min averages were subsequently downloaded from the ozone monitors and converted into hourly averages.

Multi-point factory calibrations of the portable ozone monitors were conducted by 2B Technologies before deployment to the Lake Tahoe sites. While in the field, a mid-deployment calibration was performed at eight sites — all except Angora Lookout (AGL) and Thunderbird Lodge (THB) — using the model 306 Ozone Calibration Source from 2B Technologies. Extensive post-deployment calibrations were also carried out with the Model 306 after the conclusion of fieldwork. Based on these multiple comparisons, it is estimated that the hourly data from the portable ozone monitors have a precision of ±5 ppb and an accuracy of ±5%. Readers interested in prior field-based assessments of monitor performance should consult Burley and Ray (2007) or Burley and Bytnerowicz (2011).

2.3.2. Data from the CARB monitoring sites

Hourly data for the ozone monitors operated at Echo Summit along U.S. highway #50 (ECHO), 1309 T Street in Sacramento (SAC), Natoma Street in Folsom (FOL), and Gold Nugget Way in Placerville (PLA) by the California Air Resources Board were downloaded from the CARB website (California Air Resources Board, 2014a). Echo Summit, Sacramento, and Placerville lack hourly values for 04:00 PST because their daily calibrations occur at that time. The Folsom site is missing approximately half of the hourly values for 03:00 PST for a similar reason.

2.3.3. Data from the Incline Village monitoring site

Hourly data for the ozone monitor operated at Incline Village (IVL) by the Air Quality Management Division of the Washoe County Health District were downloaded from the Air Quality System (AQS) Data Mart website maintained by the United States Environmental Protection Agency (EPA, 2014a).

Both Incline Village and the CARB sites are subjected to rigorous quality assurance (QA) protocols that adhere to EPA-mandated criteria. Annual data quality reports indicate that the hourly ozone data from these sites typically have an accuracy of ±2%, and an approximate precision of ±3% (California Air Resources Board, 2014a). Readers who are interested the specific QA procedures that are employed at these sites should consult the EPA and CARB web pages for further information.

Diurnal plots prepared from data sets that have a recurring gap at a specific time have been interpolated to fill in the missing data. In these cases the ozone concentration for the missing hour is set equal to the average of the values on either side.

2.4. Data from passive samplers

Ogawa passive samplers for O_3 (Koutrakis et al., 1993) were deployed for 2-week intervals throughout the 70-day sampling period. Samplers were hung on wooden stands 2.0 m above ground level, suspended beneath PVC plastic caps that provided protection from direct sunlight and rain. Each sampler contained two cellulose filters coated with a nitrite solution, which is oxidized by ozone to nitrate (Ogawa, 2014). The nitrite-coated filters were extracted in a lab and the extracts were analyzed quantitatively for nitrate using ion chromatography. The rate of NO_3^- formation (amount of NO_3^- formed on a filter divided by time of exposure) served as a measure of average O_3 concentration. Whenever possible, the raw results from the passive samplers were compared to the real-time O_3 concentrations determined by the co-located portable ozone monitors. These comparisons yielded empirically derived calibration coefficients that were then averaged across multiple exposure periods to produce a single calibration coefficient for the entire season. The average calibration coefficient for the entire season was then applied to the raw passive sampler data to yield the 2-week average O_3 concentrations for each site and exposure period. The average calibration coefficients from 2002 and 2010 indicated excellent reproducibility, with magnitudes of 677.8 and 675.8, respectively (a difference of less than 0.3%). The average difference between the 2-week averages measured in 2010 by the passive samplers and those recorded by the portable O_3 monitors was 6.7% (or 3.4 ppb for an ambient ozone concentration of 50 ppb). The overall precision/reproducibility of the O_3 passive samplers, measured as the coefficient of variation (CV) of replicate samples, was 3%.

Volatile organic compounds (VOC) were collected using passive VOC Radiello samplers. Radiello diffusive samplers consist of stainless steel mesh cylinders (3×8 μm mesh, 4.8 mm diameter x 60 mm length) packed with Carbograph 4 (adsorbing cartridge code R145, used for all VOC except isoprene and 1,3-butadiene) and Carbopack X (cartridge code R141, used for isoprene and 1,3-butadiene). The cartridges were deployed in the diffusive sampling bodies according to the manufacturer's instructions (Radiello, 2014). After sample collection cartridges were analyzed by the thermal desorption-cryogenic pre-concentration method, followed by high-resolution gas chromatographic separation and mass spectrometric detection (GC/MS) of individual compounds (Mason et al., 2011). Thirteen anthropogenic (1,3-butadiane, n-hexane, cyclohexane, n-octane, n-nonane, n-decane, n-undecane, benzene, toluene, ethylbenzene, styrene, m/p-xylene, 1,2,4-trimethylbenzene) and two biogenic (isoprene and α-pinene) VOC were monitored.

2.5. Spatial interpolations of data from passive samplers

Interpolated contour plots of ozone concentrations (Fig. 5a and b) were prepared using the Geostatistical Analyst, an extension of the ArcGIS software (Environmental Systems Research Institute, Redlands, California, USA). Point data were converted into continuous interpolated surface values by application of the inverse distance weighted (IDW) method with 0.5 smoothing (Johnston et al., 2001). Interpolation parameters were

selected so that the number of points included in the interpolation was limited to the five nearest values, all of which had to be within a range of 200 km. No adjustments were made to compensate for the presence of topographic features that can impede (or promote) the transport of O_3 across the interpolated surface.

2.6. Ozone exposure indices

Selected ozone exposure indices were calculated with the Ozone Calculator Program (Jackson, 2014) at the ten sites equipped with portable ozone monitors. The SUM00 index is an exposure dose obtained by multiplying all hourly concentrations (ppm) by a uniform time interval of one hour (h). Indices SUM06 and SUM07 indicate the integrated doses of all O_3 concentrations at or above 0.06 ppm and 0.07 ppm, respectively. The W126 index is a sigmoidally-weighted value (Lefohn and Runeckles, 1987) in which higher concentrations receive greater weighing. These four O_3 exposure indices were calculated for 24-h periods using all available hourly data and then extrapolated (as discussed in Section 2.2) to the 4-month (120-day) interval of June through September. Among the calculated indices, SUM00, SUM06 and W126 are most commonly used in the United States for the evaluation of potential phytotoxic effects (Musselman et al., 2006). The SUM00 index has been successfully used for predicting O_3 phytotoxic effects on ponderosa and Jeffrey pines throughout California (Arbaugh et al., 1998). In addition to the values calculated for 24-h periods, the W126 index was also determined for a 12-h window between 8:00 and 20:00 PST for the 3-month (90-day) period of July–September. The use of a 12-h W126 calculation, applied to the highest 3-month period of ozone during a given year, has been proposed as a secondary federal ozone standard that would focus upon ecological effects (Environmental Protection Agency, 2014b).

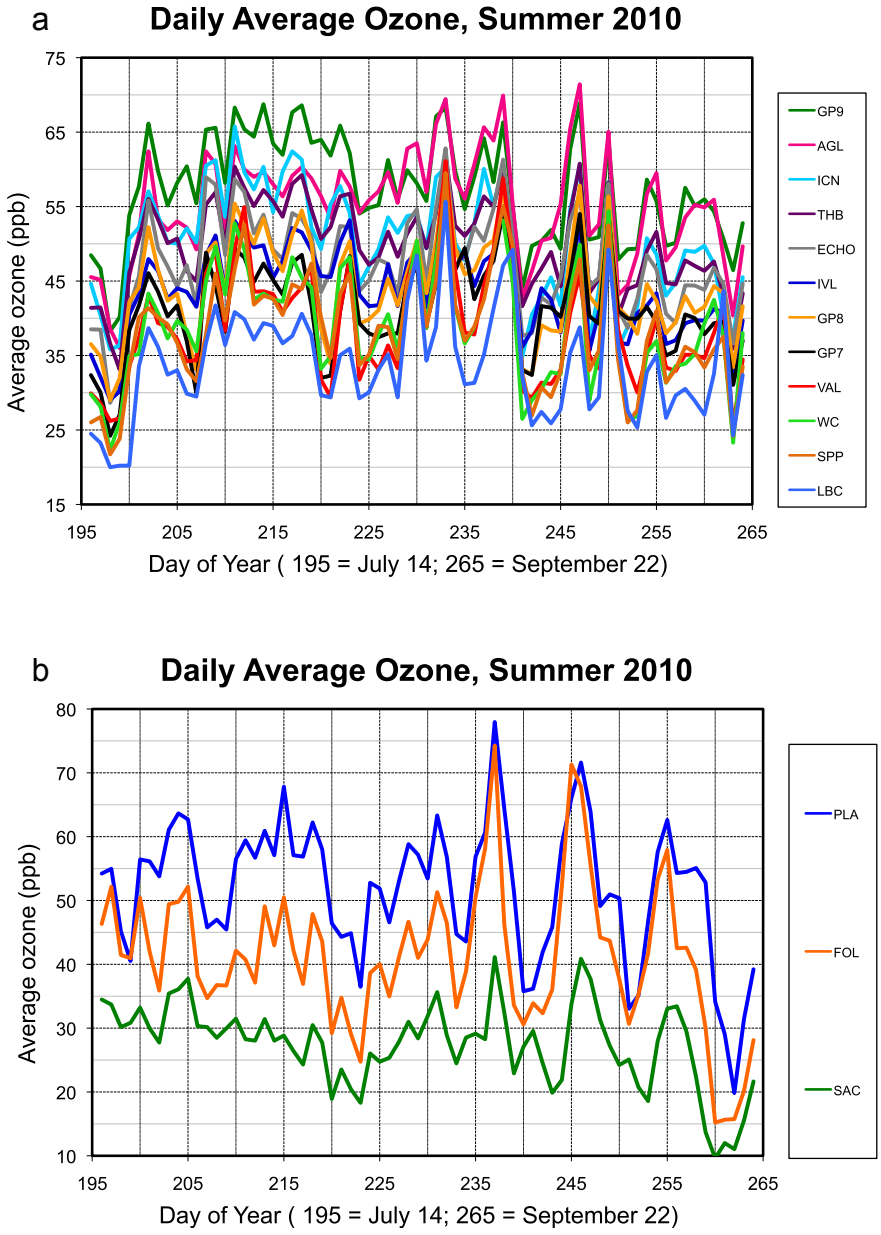

Fig. 2. Daily average ozone concentrations (ppb) measured by active monitors, 15 July to 21 September, 2010: (a) Tahoe sites; (b) Sacramento, Folsom, and Placerville.

2.7. Meteorological analyses

Meteorological data were obtained through the National Weather Service's National Centers for Environmental Prediction (NCEP). NOAA's Air Resources Laboratory (ARL) routinely uses NCEP model data for air quality transport and dispersion modeling calculations (Air Resources Laboratory, 2014). Site-specific wind roses for the present study were calculated using archived wind data from the North American Mesoscale (NAM) 12 km meteorological model. The NAM 12 km model was chosen because it provided the best possible resolution and could be verified against the National Climatic Data Center (NCDC) observational cooperative data site, Tahoe Valley. The NAM model outputs data at three-hour intervals starting at 00:00 UTC. For the present analysis, the data are restricted to July 1st through September 23rd, 2010, which is approximately coincident with the July 14 – September 22 timeframe for the collection of ozone data. The daily data intervals correspond to three-hour increments, starting at 01:00 PST, with eight intervals within every 24-h period.

2.8. HYSPLIT calculations

Regional–scale transport patterns responsible for bringing elevated ozone concentrations into the Lake Tahoe Basin were investigated by conducting back-trajectory calculations with the online version of the HYSPLIT model (Draxler and Rolph, 2014; Rolph, 2014). Calculations were performed using the 40 km EDAS (Eta Data Assimilation System) archived meteorological data, with a run time of 30 h, and arrival heights of 100, 500, and 1500 m above ground level.

3. Results and discussion

3.1. Daily average ozone concentrations, summer 2010

Daily average ozone concentrations calculated from hourly data are presented in Fig. 2. Fig. 2a shows results from the 12 active monitors that operated at Lake Tahoe, while Fig. 2b shows results from comparison sites in Sacramento (SAC), Folsom (FOL), and Placerville (PLA). Average ozone concentrations measured at most of the Tahoe sites are roughly similar to those recorded at Folsom and Placerville—in the range of 40–60 ppb – and higher than those recorded in downtown Sacramento (20–40 ppb). However, two of the high elevation Tahoe sites – Genoa Peak 9000 (GP9) and Angora Lookout (AGL) – frequently have higher ozone than the upwind comparison sites, especially for days 200–240. As discussed in Section 3.9, this result likely reflects the predominance of regional transport at these two locations, which are also expected to experience diminished dry deposition due to steep topography and sparse vegetation. Fig. 2 also indicates that the timing of the minima and maxima at the Lake Tahoe sites deviates from the timing observed at the comparison sites. For example, the local maximum occurring on days 204–205 for Sacramento, Folsom, and Placerville is not present in the Tahoe data. The sharply resolved maximum from day 237 for the three comparison sites (Fig. 2b) does not occur concurrently at the Tahoe sites (Fig. 2a), but is instead diminished and delayed (to day 239).

The observation of generally similar average ozone values combined with poorly correlated temporal patterns in the daily averages is consistent with the previous work of Dolislager et al. (2012b), who found that intact 1- or 2-day transport of pollutants from upwind air basins to Lake Tahoe occurs very infrequently. Instead of direct transport of intact air masses, they concluded that emissions from upwind regions were acting to raise background concentrations of pollutants that were subsequently transported into the Tahoe Basin.

While most of the O_3 that is transported into the Tahoe Basin originates from the Central Valley of California, it is very likely that there are also contributions from Asian sources, and possible episodes of down-mixing of ozone-rich air from the upper troposphere/lower stratosphere. The importance of long distance transport of Asian O_3 (and/or ozone precursors) to western North America has been addressed in many prior studies, including Jaffe et al. (2003), Jaffe and Ray (2007), Macdonald et al. (2011), and Ambrose et al. (2011). In the latter report, measurements at the Mt. Bachelor Observatory (2763 m) in central Oregon identified a total of 25 high-ozone events (defined as 8-h average O_3 > 70.0 ppb) between 2004 and 2009, all of which occurred between early March and late September. Of those 25 high-ozone events, 18 could be explicitly analyzed in terms of ozone sources, and it was found that subsidence of ozone-rich air from the upper troposphere/lower stratosphere played a role in 78% (14/18) of the high-ozone episodes, while long-range transport from Asia played a role in 56% (10/18) of those events (Ambrose et al., 2011). Compared to the well-exposed Mt. Bachelor, the Lake Tahoe sites utilized in the present study should experience fewer episodes of subsidence from the upper troposphere/lower stratosphere because of their lower elevations and more sheltered topography. The Tahoe sites should also be less impacted by direct long-range transport from Asia because the Sierra Nevada crest located to the west of the Tahoe Basin will act as a barrier that inhibits westerly transport. Another key difference between the two locations is the presence of upwind emission source regions (San Francisco Bay Area, Sacramento, Central Valley) for Lake Tahoe, while Mt. Bachelor is largely unaffected by local anthropogenic emissions.

3.2. Exceedances of the 8-h NAAQS and CAAQS

Fig. 3 presents the daily maximum values for the 8-h averages calculated from hourly ozone data. Presentation of the results in this format allows for direct comparisons with both the National Ambient Air Quality Standard (NAAQS) for ozone, which is currently 75 ppb (EPA, 2014c), and the California Ambient Air Quality Standard (CAAQS), which is currently 70 ppb (CARB, 2014b). Of the 12 Tahoe sites, only three exceeded the NAAQS for ozone: Genoa Peak 9000 (GP9), which had 6 days with exceedances; Angora Lookout (AGL), which had 4 days with exceedances; and Upper Incline (ICN), which had 1 day with an exceedance. Two of the three upwind comparison sites also exceeded the NAAQS: Folsom (FOL), which had 15 days with exceedances; and Placerville (PLA), which had 6 days with exceedances. If the CAAQS is used as the threshold, then four of the Tahoe sites show exceedances: Genoa Peak 9000 (16 days with exceedances), Angora Lookout (11 days), Upper Incline (2 days), and Watson Creek (WC), which had 1 day with an exceedance. All of the upwind comparison sites exceeded the CAAQS at least once: Folsom (18 days with exceedances), Placerville (16 days), and Sacramento (1 day).

The observation that Genoa Peak 9000 (GP9, the highest elevation Tahoe site) experienced essentially the same number of CAAQS exceedances as the most polluted comparison site (Folsom, FOL) but significantly fewer violations of the NAAQS further supports the hypothesis that Tahoe exceedances primarily reflect elevated levels of background ozone rather than transport of intact air masses from source regions. Folsom is well-positioned – approximately 30 km downwind of downtown Sacramento – to see frequent NAAQS exceedances because the travel time from the upwind emission sources is sufficient to allow the required photochemistry to convert primary pollutants into ozone, but not so lengthy as to allow for significant dilution

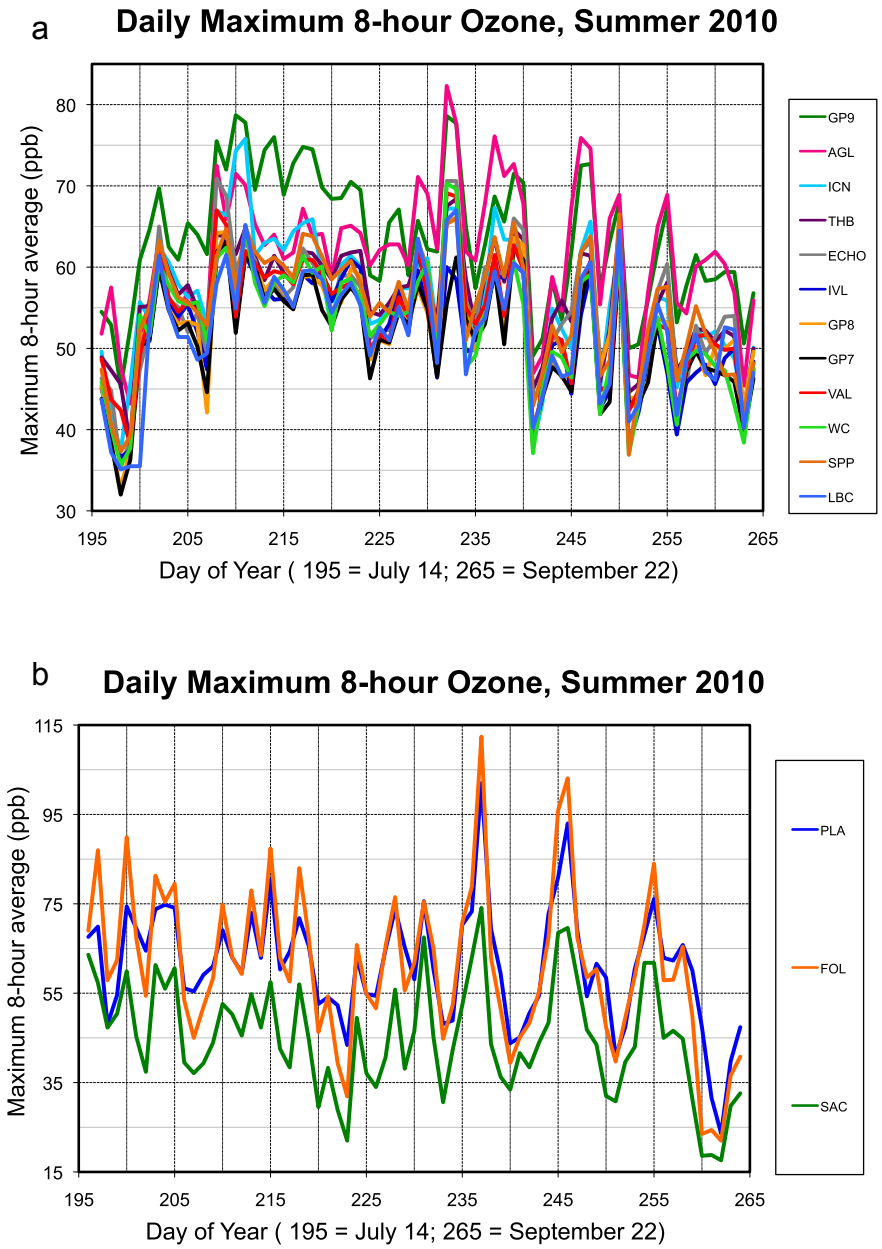

Fig. 3. Daily maxima of the 8-h average ozone concentrations (ppb) measured by active monitors, 15 July – 21 September, 2010: (a) Tahoe sites; (b) Sacramento, Folsom, and Placerville.

of the "Sacramento plume." Genoa 9000, in contrast, lies roughly 150 km downwind of downtown Sacramento, so there is much greater likelihood that the plume will be diluted/dispersed before arriving. Compared to Folsom there are thus fewer violations of the 75 ppb NAAQS, but a similar number of violations of the 70 ppb CAAQS.

3.3. Diurnal cycles

Average diurnal cycles calculated from hourly data are presented for the 12 Lake Tahoe sites in Fig. 4a, while the cycles for the comparison sites of Sacramento (SAC), Folsom (FOL), and Placerville (PLA) are presented in Fig. 4b. The Tahoe sites display great site-to-site variability during the evening and pre-dawn hours of 19:00 to 07:00 PST, but consistent maxima of 50–55 ppb from 10:00 to 17:00 PST. Genoa Peak 9000 (GP9) and Angora Lookout (AGL) differ from other Tahoe sites because of their very small diurnal cycle magnitudes and the observation of increasing ozone between the hours of 17:00 to 20:00 PST. This latter result – an increase in O_3 despite the shutdown of photochemical production pathways – is seen only at these two locations. The comparison sites of Sacramento, Folsom, and Placerville also show great variability in their evening and pre-dawn behavior, but their afternoon maxima differ significantly from what is seen at the Tahoe sites. Rather than flat-topped maxima of 50–55 ppb that commence by 10:00 PST and last for approximately eight hours, the diurnal maxima for the comparison sites do not arrive until approximately 14:00–16:00 (Sacramento, Folsom) or 16:00–17:00 (Placerville), and they last for only 1–3 h, at values ranging from ~67 ppb (Folsom) to ~50 ppb (Sacramento).

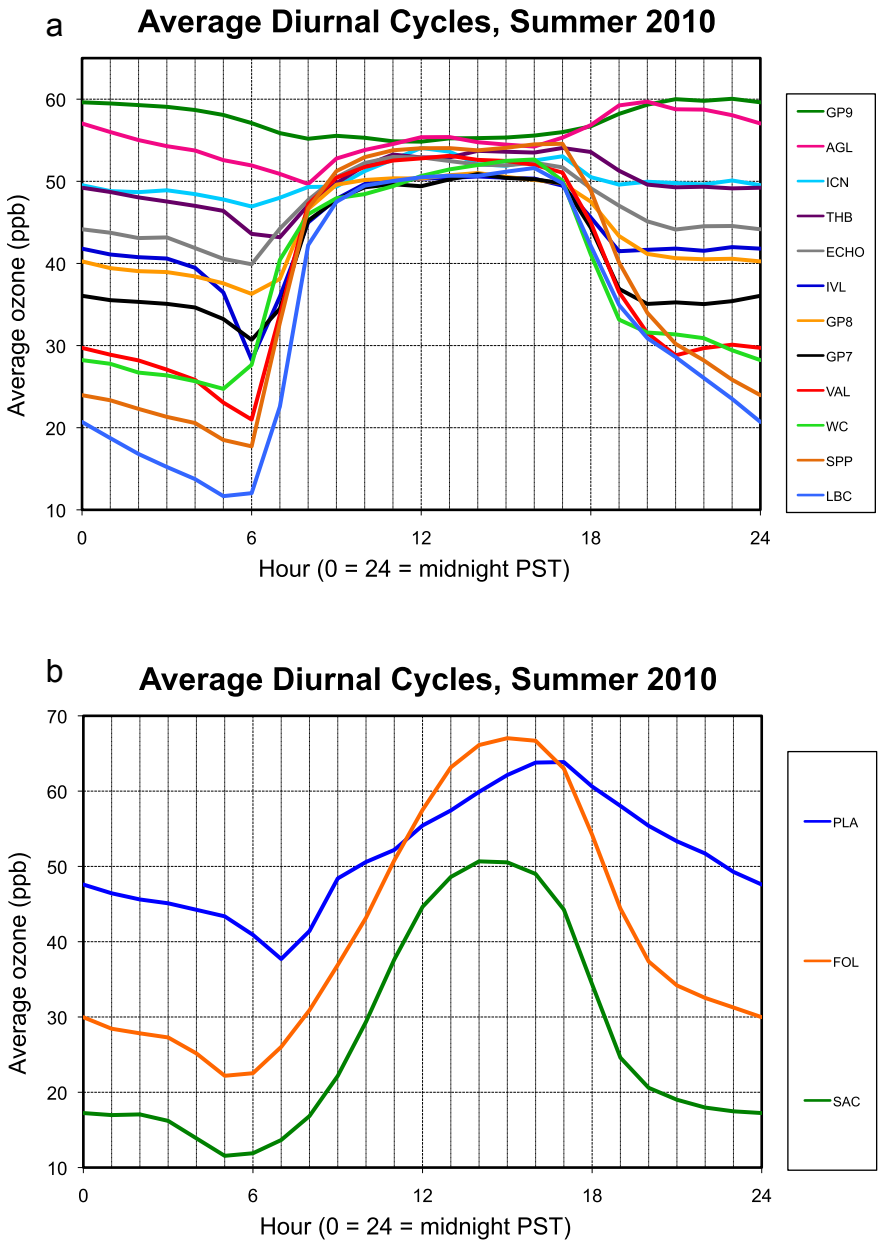

Fig. 4. Average diurnal cycles of observed ozone (ppb), based on data collected from 12:00 PST on July 14 through 11:00 PST on September 22, 2010: (a) Tahoe sites; (b) Sacramento, Folsom, and Placerville.

3.4. *Spatial distributions of ozone from passive sampler data*

Ozone distribution maps for the 2002 and 2010 seasons (Fig. 5a and b, respectively, which present the average ozone concentrations listed in Tables 2 and 3) show the highest O_3 concentrations in the western portion of the monitoring domain, outside the Lake Tahoe Basin. These high O_3 levels reflect the closer proximity of the westernmost passive sampler sites to anthropogenic emissions of O_3 precursors from the Central Valley (which includes the greater Sacramento metropolitan area), and biogenic emissions from the Sierra Nevada foothills (Dillon et al., 2002; Dreyfus et al., 2002). Fig. 5a and b strongly suggest that high elevation mountain ranges west of the Basin (especially those in the Desolation Wilderness) act as an effective barrier in preventing movement of those polluted air masses eastward into the Basin. However, there is also evidence of elevated O_3 concentrations at high elevation sites adjacent to the Lake, especially Genoa Peak 9000 (GP9), which saw average values of 60.2 ppb in 2002 and 59.2 ppb in 2010. Within the Tahoe Basin in 2010, the highest mean O_3 concentration (63.5 ppb) was observed at the NASA buoy site in the middle of the Lake (TB2). This result, which was markedly higher than the closest onshore result of 47.2 ppb for Thunderbird Lodge (THB), likely reflects diminished dry deposition to the surface of the Lake, a phenomenon that has been observed in prior studies of surface O_3 above large bodies of water (Goldberg et al., 2014; Stauffer et al., 2012; Cleary et al., 2014).

While generally similar O_3 distribution patterns occurred in 2002 and 2010, the 2010 levels of O_3 were significantly lower ($p < 0.01$) than those measured in 2002 (Fig. 6). The differences between the two years were caused primarily by differences in August and September, while the July data were similar in both years. These differences in measured O_3 do not appear to result from differences in meteorology, as the average monthly

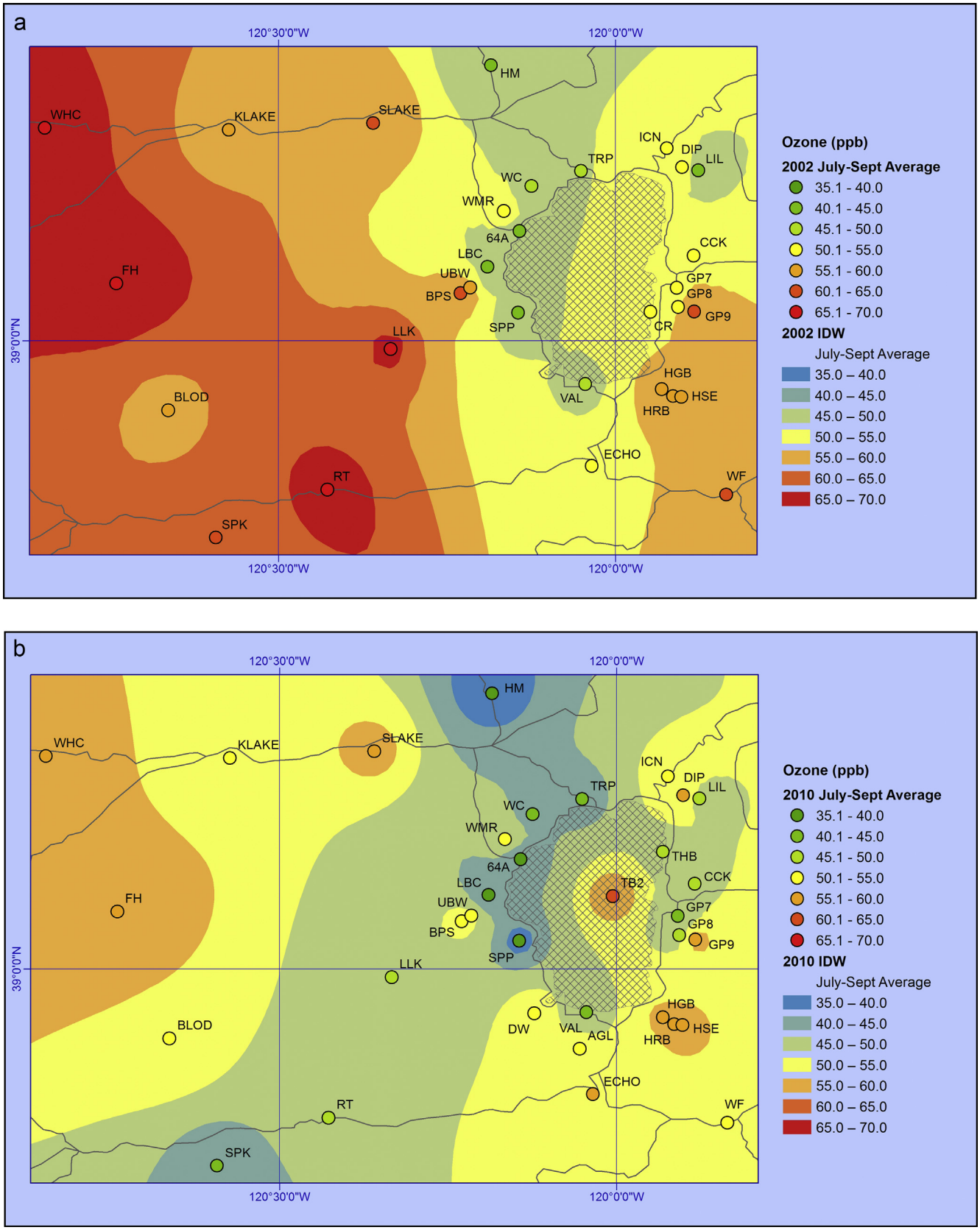

Fig. 5. Spatial distributions of O_3 concentrations in and around the Lake Tahoe Basin, based on the passive sampler data presented in Tables 2 and 3: (a) 2002 summer seasonal averages for July 16 – September 24; (b) 2010 seasonal summer averages for July 14 – September 22. Individual site concentrations are specified using the colored circles shown in the upper part of the legend, while interpolated concentrations are expressed using a different color scheme shown by colored rectangles in the lower part of the legend.

temperatures measured in 2002 (July = 18.1 °C, August = 16.1 °C, September = 13.4 °C) were very similar to the average monthly temperatures measured in 2010 (July = 17.6 °C, August = 16.1 °C, September = 13.6 °C). A direct comparison of average O_3 concentrations in 2002, 2006 and 2010 for three representative lakeshore sites yields 44.1, 42.2 and 39.8 ppb for 64 Acres (64A), 44.3, 43.2 and 37.0 ppb for Sugar Pine Point State Park (SPP), and 46.7, 46.5 and 43.3 ppb for Valhalla (VAL), respectively. All of these inter-annual comparisons are consistent with the previously reported decrease of ambient O_3 concentrations in the western US (Lefohn et al., 2008).

3.5. Passive sampler results for volatile organic compounds (VOC)

Table 4 (sites with active ozone monitors) and Table 5 (sites without active ozone monitors) show the average 2010 concentration sums of thirteen anthropogenic VOC (1,3-butadiane, n-hexane, cyclohexane, n-octane, n-nonane, n-decane, n-undecane, benzene, toluene, ethylbenzene, styrene, m/p-xylene, 1,2,4-trimethylbenzene), two biogenic VOC (isoprene and α-pinene), and their ratios (anthropogenic/biogenic, A/B). It is important to note that the absolute A/B ratios are not meaningful, since only limited numbers of anthropogenic species were measured (primarily those representative of fossil fuel combustion). Instead, the site-to-site variability of this ratio is more important. In general, biogenic species are more abundant than anthropogenic species (A/B < 1) at all sites with the exception of TB2 Buoy (TB2), which is situated in the middle of the Lake (A/B = 1.6). This site also shows the highest average ozone concentration measured at any site in either 2002 or 2010. The observation of a higher A/B ratio at the TB2 site may indicate the influence of local spark ignition and diesel engine emissions (for example from large boats), and/or emissions from developed areas that are located near the shoreline, and/or the absence of biogenic VOC emissions from the Lake itself. Overall, with the exception of the TB2 site, higher A/B ratios are frequently

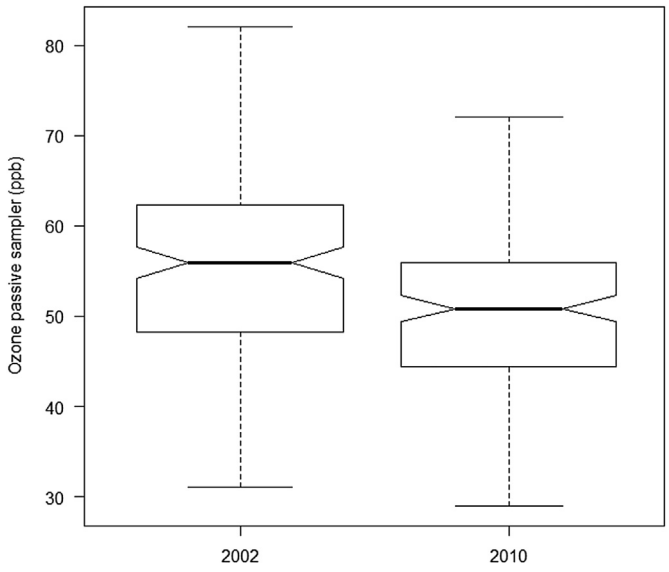

Fig. 6. Box-plots of the passive sampler ozone data for 2002 (July 16 – September 24) and 2010 (July 14 – September 22), combining data from all of the sampling sites. The overall summer seasonal median is represented by the thick horizontal bar, while the quartiles (25th & 75th percentiles) are denoted by the extremities of the box) and the ranges are denoted by the extremities of the whiskers. There is a significant difference in the mean O_3 values between 2002 and 2010. The 2010 values are, on average, 5.6 ppb less than the average in 2002 (*P*-value = 0.00016). At the 95% confidence level the difference between 2002 and 2010 varies between 3.6 and 7.6 ppb.

Table 3
Ozone data for Lake Tahoe sites equipped with active ozone monitors in 2010.

Location	Active O_3 (ppb)[a]	Diurnal magnitude (ppb)[b]	Passive O_3 (ppb)		Site topography	Ground cover
	2010		2010	2002		
Angora Lookout	55.1	5.7	53.3	N/A	Very steep hillside near the top of a ridge	Heavy fire damage; low scrub/bushes
Echo Summit	47.4	12.6	56.1	50.2	Flat site near the base of an incline	Paved parking lot, gravel, sparse grass
Genoa Peak 7000	41.2	19.5	44.1	54.1	Open meadow with gentle slope	Thick grass
Genoa Peak 8000	44.2	14.4	45.4	54.1	Gentle slope on western side of Genoa Peak	Extensive fire damage; mostly ash and dirt
Genoa Peak 9000	57.3	~0	59.2	60.2	Exposed outcropping just below Genoa Peak	Mostly rocks interspersed with tufts of grass
Incline Village	43.8	22.2	N/A	N/A	Gentle slope facing towards the southwest	Rooftop inlet, with some tall conifers nearby
Lower Blackwood Creek	33.8	39.0	35.1	41.0	Large, flat open meadow	Grassy and very wet
Sugar Pine Point State Park	38.3	36.3	37.0	44.3	Flat open meadow	Mostly grass, a few mountain mules' ears
Thunderbird Lodge	49.9	9.7	47.2	N/A	At the base of a steep hillside near the Lake	Rooftop inlet; building surrounded by thick brush
Upper Incline	50.3	6.7	52.2	52.2	Broad, steep hillside with good exposure	Dry soil with extensive mtn. mules' ears coverage
Valhalla	39.0	32.1	43.3	46.7	Flat, near the shoreline of Lake Tahoe	Dry, sandy soil with thick low scrub/bushes
Watson Creek	38.6	26.7	43.2	47.2	Flat open meadow	Gravel with nearby mountain mules' ears

[a] Average hourly ozone for 12:00 PST on July 14, 2010, through 11:00 PST on September 22, 2010.
[b] Diurnal magnitude is defined as (the diurnal average concentration at 13:00 PST) − (the diurnal average minimum); see Fig. 4.

Table 4
2010 NO_x and VOC passive sampler data for sites equipped with active ozone monitors in 2010.

Location	Ave. NO (ppb)	Ave. NO_2 (ppb)	Ave. NO_x (ppb)	Ave. Anthropogenic VOC (ppb)	Ave. Biogenic VOC (ppb)	(Anthropogenic/ Biogenic) Ratio
Angora Lookout	2.05	1.39	3.44	0.14	0.64	0.22
Echo Summit	2.55	0.88	3.43	0.12	0.64	0.19
Genoa Peak 7000	2.70	0.96	3.66	0.14	0.64	0.22
Genoa Peak 8000	2.16	0.95	3.11	0.12	0.43	0.29
Genoa Peak 9000	2.04	0.94	2.98	0.13	0.33	0.41
Incline Village	N/A	N/A	N/A	N/A	N/A	N/A
Lower Blackwood Creek	2.80	1.29	4.09	0.24	1.44	0.25
Sugar Pine Point State Park	2.83	0.88	3.71	0.17	0.81	0.21
Thunderbird Lodge	2.25	1.40	3.65	0.17	0.50	0.39
Upper Incline	2.29	0.82	3.11	0.23	0.36	0.65
Valhalla	3.15	2.57	5.72	0.36	0.72	0.49
Watson Creek	1.11	0.73	1.84	0.20	0.71	0.28

observed for sites with main roadways nearby: TB2 Buoy > Desolation Wilderness (DW) > Tahoe Regional Park (TRP) ≈ Upper Incline (ICN) > Valhalla (VAL).

3.6. Wind rose data

The daytime (07:00 to 16:00 PST) wind roses (Fig. 7) show a dominant southwesterly flow. Lower Blackwood Creek (LBC) and Sugar Pine Point State Park (SPP) on the western side of the Lake have a stronger easterly component than the other sites. Genoa Peak 9000 (GP9) on the eastern side of the Lake has more of a westerly component than southwesterly, and also shows a small northwesterly component that is also observed at Angora Lookout (AGL) and Valhalla (VAL). The nighttime (19:00 to 04:00 PST) wind roses (Fig. 8) show a dominant westerly component except for the southern sites of Angora Lookout and Valhalla, which show a more southwesterly component. Angora Lookout and Valhalla also show a small southeasterly component. The nighttime wind rose for

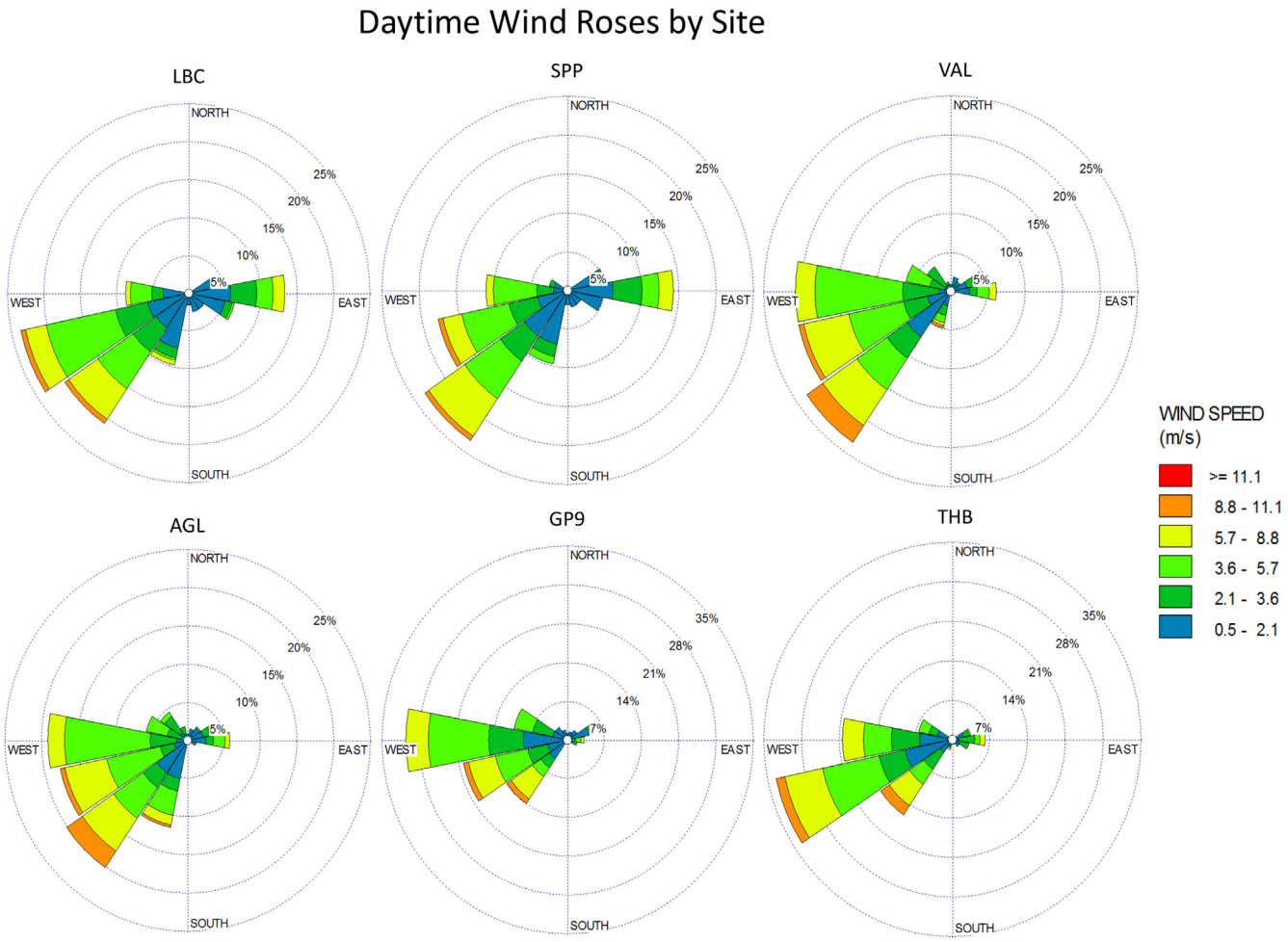

Fig. 7. Daytime wind roses for six Tahoe Basin sites equipped with portable ozone monitors. Results are based upon data for 07:00, 10:00, 13:00 and 16:00 PST, calculated from 12 km NAM data for July 1 – September 23, 2010.

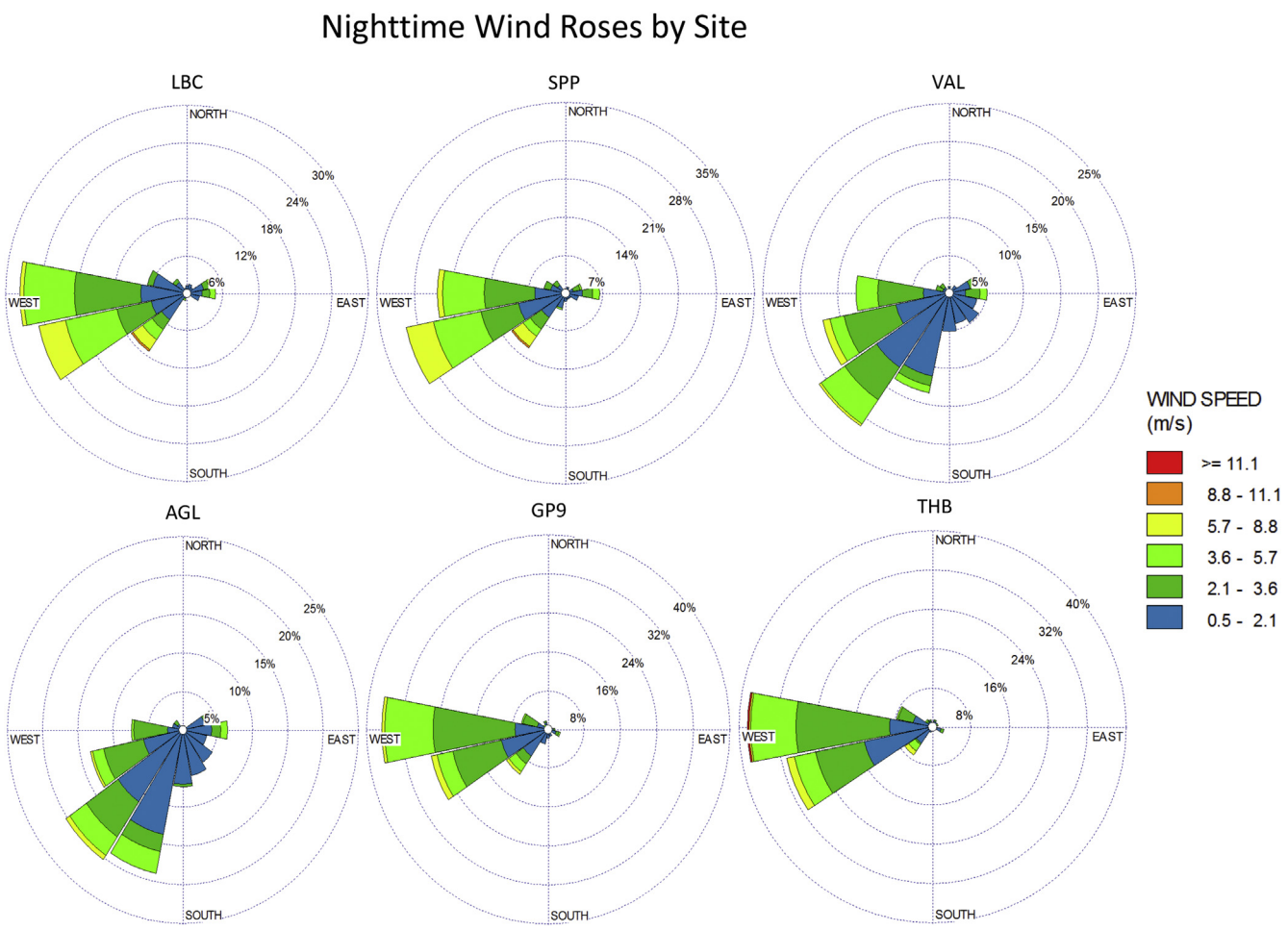

Fig. 8. Nighttime wind roses for six Tahoe Basin sites equipped with portable ozone monitors. Results are based upon data for 19:00, 22:00, 01:00 and 04:00 PST, calculated from 12 km NAM data for July 1 – September 23, 2010.

Genoa Peak 9000 is very similar to the one obtained during daytime hours.

The wind rose data presented in Figs. 7 and 8 suggest the presence of a "lake breeze" during daytime hours, and/or a "land breeze" during nighttime hours, at some of the Tahoe sites situated close to the shoreline. During periods of insolation the land surface is heated and its temperature increases, whereas the water surface remains at a relatively constant temperature due to its very high heat capacity. The surface temperature influences the overlying air and as a result there is warmer and less dense air over land, while the air over the water is cooler and denser. Near the shoreline a pressure gradient is established due to the buoyant effects created by the temperature differences. Thus, if the prevailing conditions are such that the synoptic-scale wind is light, the local buoyant force is the dominant force and an on-shore lake breeze is established (Biggs and Graves, 1962). Lyons and Olsson (1973) showed that the lake breeze may favor the occurrence of high air pollution in shoreline areas. This is due to three factors: (1) formation of low-level temperature inversions as cool lake air moves inland, (2) continuous fumigation of elevated plumes from shoreline pollution sources, and (3) recirculation of pollutants within the lake breeze circulation pattern. All of these factors are a consequence of the unique features of the lake breeze temperature and wind structure. At night, the solar insolation of the land surface is diminished, and the air over the land becomes cooler and more dense relative to the air over the water. If the prevailing conditions are again such that the synoptic-scale wind is light, an off-shore land breeze is established.

Fig. 7 indicates an easterly component of wind coming off the lake during daytime hours at Lower Blackwood Creek (LBC) and Sugar Pine Point State Park (SPP). Since both of these sites are located on the western side of the Lake and have eastern-facing exposures, these components likely correspond to on-shore lake breezes. This feature is less apparent, however, for the western-facing Thunderbird Lodge site (THB), which is located near the shoreline on the eastern side of the Lake. In this case the lake breeze would come from the west and would be obscured by the dominant westerly winds. The nighttime wind rose data (Fig. 8) show a southeasterly component at Valhalla (VAL) that could indicate a nighttime land breeze. Lower Blackwood Creek and Sugar Pine Point State Park might also be experiencing a nighttime land breeze, but once again the wind rose evidence is obscured by the dominant westerly wind flow. Thunderbird Lodge does not show a nighttime land breeze; in this case the elevated nocturnal ozone concentrations (Fig. 4a) may instead suggest onshore transport of ozone during evening hours – a possibility that is consistent with the elevated ozone concentrations measured by passive samplers at the TB2 buoy (Section 3.4, Table 2, Fig. 5b).

It should be emphasized that the wind rose results shown in Figs. 7 and 8 – which are based upon calculations that have limited spatial and temporal resolution – are not intended to rigorously reproduce the meso-scale circulation patterns that are

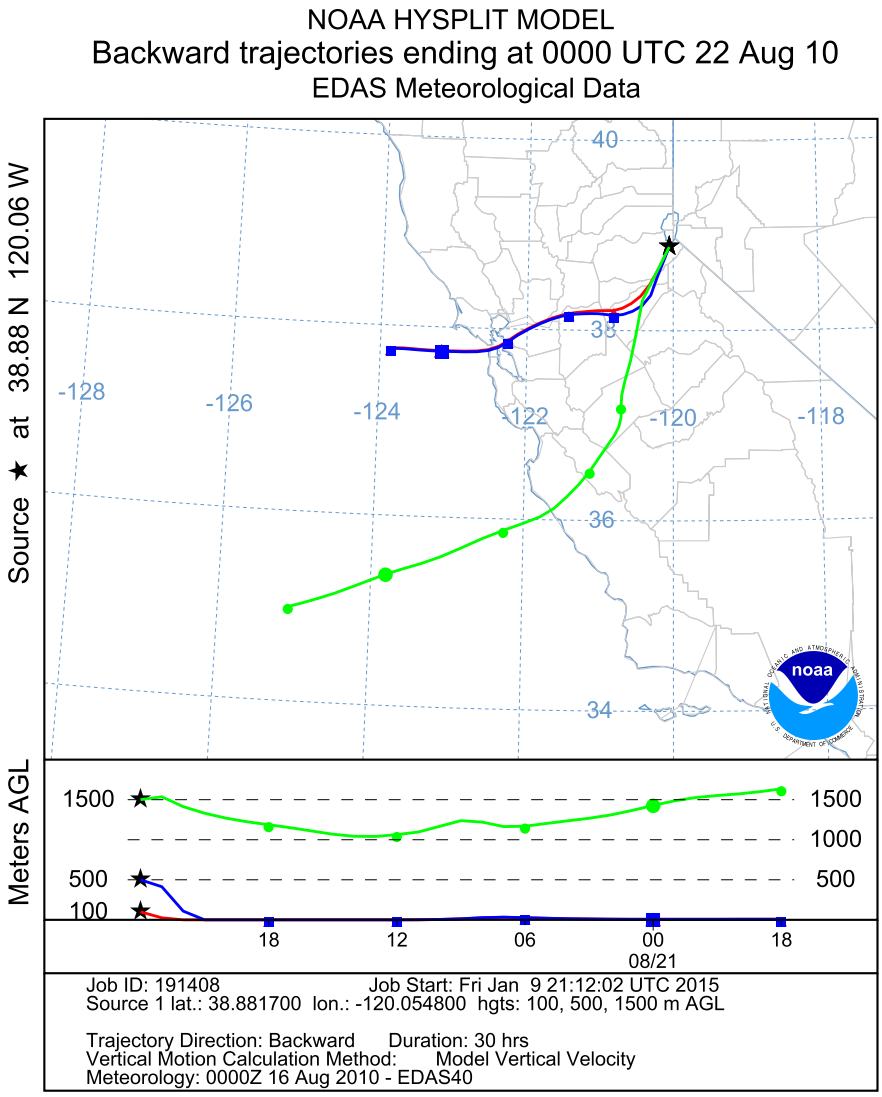

Fig. 9. Air mass back-trajectories at 100, 500, and 1500 m above ground level for the high-ozone day of August 21, 2010. The arrival time at the Angora Lookout site (AGL) is 16:00 PST (00:00 next day UTC).

actually present within the Lake Tahoe Basin. Instead, these results are intended to serve as a stand-in for the lack of *in situ* wind data from the sampling sites and provide potential insight into the differences/distinctions that might exist between the different sampling locations. Because of the limited resolution of the input data, the wind rose patterns in Figs. 7 and 8 tend to be dominated by the synoptic-scale winds coming from the west and southwest, with an underestimation of the meso-scale lake breeze and land breeze contributions. (This underestimation of local onshore and offshore flows will likely be a bigger problem for those sites that are close to the shoreline and less of an issue for the higher elevation sites that are further away from the Lake.) While this underestimation of meso-scale behavior diminishes the accuracy and usefulness of the wind rose results, the resolution of the calculation nonetheless appears to be good enough to identify the sites (LBC, SPP) that are more likely to experience sustained onshore or offshore flows. Readers who are interested in a rigorous review of the meso-scale wind patterns that have been measured within the Lake Tahoe Basin – at sites (mostly along the shoreline) that differ from those used in the current study – are encouraged to consult Pederson (2005) and VanCuren et al. (2012).

3.7. HYSPLIT back-trajectories

In order to assess the effects of synoptic-scale atmospheric transport, 30-h air mass back-trajectories were performed with the HYSPLIT model (Draxler and Rolph, 2014; Rolph, 2014). August 21 (day-of-year = 233 in Fig. 3a) was chosen as the representative high-ozone day (Fig. 9), while August 29 (day-of-year = 241 in Fig. 3a) was chosen as the representative low-ozone day (Fig. 10). Angora Lookout (AGL) was selected as the arrival site because it had the highest ozone value for the high-ozone day. Trajectories were calculated for 100, 500, and 1500 m above ground level; the 100-m height (red triangles (in the web version)) approximates the lower part of the boundary layer and should experience many interactions with the surface, while the 1500-m height trajectory (green circles (in the web version)) approximates the top of the boundary layer.

While Figs. 9 and 10 indicate very similar trajectories at the 100-m and 500-m heights – originating over the Pacific Ocean to the west of Marin County, and then proceeding through the San Francisco Bay and Delta region and the Central Valley before ascending the western slope of the Sierra Nevada – they indicate very dissimilar trajectories at 1500 m above ground level. The high-ozone

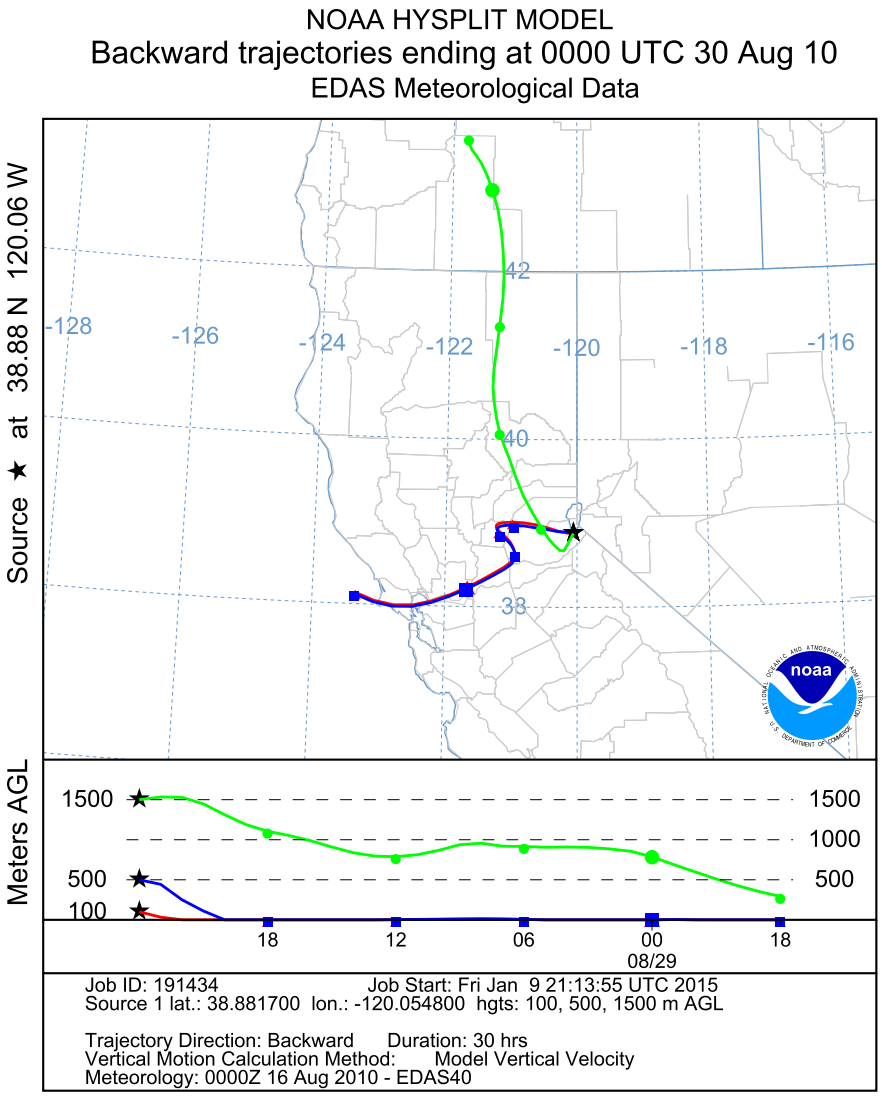

Fig. 10. Air mass back-trajectories at 100, 500, and 1500 m above ground level for the low-ozone day of August 29, 2010. The arrival time at the Angora Lookout site (AGL) is 16:00 PST (00:00 next day UTC).

trajectory passes through the heavily polluted San Joaquin Valley (located to the southwest of the Tahoe Basin) whereas the low-ozone trajectory approaches from the north, passing through the less polluted Lassen National Forest.

3.8. Factors that influence surface level ozone concentrations

Table 3 and Fig. 4a summarize the 2010 results from the 12 Tahoe sites equipped with active ozone monitors. These results indicate that the average ozone concentration measured at any given site depends primarily on the ozone mixing ratios observed during the evening and pre-dawn hours, rather than the mixing ratios measured during the hours of 10:00 to 17:00 PST. The observation that all of the Tahoe sites tend to rapidly reach the same middle of day maximum (of roughly 50–55 ppb) between the hours of 06:00 and 10:00 PST suggests that this initial rise in surface ozone is due primarily to the vigorous vertical mixing that occurs in the hours immediately after sunrise, when ozone-depleted air near the surface is warmed (via solar heating of the surface) while cooler, ozone-rich air from aloft is simultaneously mixed downwards. These well-mixed conditions persist throughout the Tahoe Basin until approximately 17:00 PST, when there is a marked decrease in solar insolation. During the evening hours, those sites that have good exposure to ozone-rich air from aloft, which is being transported in via regional-scale and long-range transport, continue to exhibit high ozone concentrations. Sites that are more conducive to the formation of nocturnal temperature inversions see a decrease in surface level ozone, primarily via dry deposition.

The extent to which a given site experiences elevated or diminished ozone concentrations during the evening and pre-dawn hours appears to depend on a combination of factors that include elevation, topography, and ground cover. Local emissions of NO can also play a role, as NO is known to “titrate” ozone very efficiently at night (Sillman, 1999). However, NO data collected in July 2012 with active monitors (Burley, 2014) indicate that ambient NO concentrations within the Tahoe Basin are typically $\leq$3 ppb, even at sites that are located near major roadways. Since nocturnal titration of ozone by NO is a stoichiometric (as opposed to catalytic) process where 1 ppb of freshly emitted NO can destroy no more than an equivalent 1 ppb of O_3, the observation of low NO mixing ratios would seem to limit the overall contribution of NO titration

Table 5
2010 NO_x and VOC passive sampler data for sites without active ozone monitors in 2010.

Location	Ave. NO (ppb)	Ave. NO_2 (ppb)	Ave. NO_x (ppb)	Ave. Anthropogenic VOC (ppb)	Ave. Biogenic VOC (ppb)	(Anthropogenic/biogenic) ratio
64 Acres	3.88	4.22	8.10	0.32	0.87	0.37
Barker Pass	2.87	0.68	3.55	0.17	0.54	0.32
Blodgett	1.86	1.61	3.47	0.33	0.96	0.34
Clear Creek	1.78	0.77	2.55	0.11	0.48	0.24
Desolation Wilderness	2.21	1.05	3.26	0.44	0.51	0.85
Diamond Peak	1.84	0.92	2.76	0.12	0.31	0.40
Forest Hill	2.34	0.92	3.26	0.17	1.05	0.16
Heavenly Gun Barrel	2.51	0.77	3.28	0.13	0.31	0.40
Heavenly Ridge Bowl	2.18	0.69	2.87	0.12	0.31	0.39
Heavenly Sky Express	2.11	0.64	2.75	0.09	0.26	0.36
Hobart Mills	2.99	2.13	5.12	0.28	1.13	0.25
Kelly Lake	2.96	3.43	6.39	0.19	0.68	0.21
Little Valley	2.59	0.90	3.49	0.18	0.75	0.24
Loon Lake	2.10	1.25	3.35	0.18	0.89	0.20
Riverton Ridge	2.31	1.45	3.76	0.28	1.33	0.21
Serene Lakes	3.25	1.25	4.50	0.23	0.66	0.35
Sly Park	2.57	1.62	4.19	0.32	1.64	0.19
Tahoe Regional Park	2.02	1.57	3.59	0.64	1.03	0.61
TB2 Buoy	2.41	1.44	3.85	0.73	0.45	1.60
Upper Blackwood	2.59	0.79	3.38	0.10	0.42	0.25
Watson Mtn. Road	1.94	0.80	2.74	0.15	0.35	0.42
White Cloud	2.36	1.38	3.74	0.18	0.89	0.21
Woodford's	2.18	1.17	3.35	0.22	0.55	0.39

to the diurnal cycle differences seen in Fig. 4a.

3.9. Site-by-site analysis of 2010 data from active ozone monitors

3.9.1. Genoa Peak 9000, Angora Lookout

Genora Peak 9000 (GP9, 2734 m) and Angora Lookout (AGL, 2218 m) see high levels of nocturnal ozone, typically around 60 ppb for 20:00 to 00:00 PST, followed by a gradual decrease in the early morning hours (Fig. 4a). For these two sites, the well-mixed hours of 10:00–17:00 PST therefore represent a broad minimum (Genoa Peak 9000), or an intermediate plateau (Angora Lookout), rather than a mid-day maximum in O_3. The efficient vertical mixing that takes place during this period decreases ozone at these two sites because of vigorous upward mixing of ozone-depleted air from lower elevations. At night, the effective mixing with lower elevations – which can be viewed in this context as an ozone "sink" – is shut off, while access to ozone-rich air from aloft continues.

Genoa Peak 9000 (GP9) and Angora Lookout (AGL) both possess features that will tend to promote mixing from aloft while simultaneously minimizing dry deposition of ozone during evening hours. These include high elevation, steeply slopped topography that will inhibit the formation of stable temperature inversions during evening hours, and dry/rocky ground cover that will be a relatively inefficient ozone sink (compared to wet, leafy green plant matter). While Angora Lookout is situated at a lower elevation than Genoa Peak 9000, it is also closer to the upwind pollution source regions of Sacramento and the Central Valley, and positioned along a main conduit – the south–southwest corner of the Basin, near Fallen Leaf Lake and the U.S. highway #50 corridor – for surface-level regional transport. It is possible that the positioning of the Angora Lookout site, coupled with observed shift in wind patterns – from a more westerly flow during the daytime (Fig. 7) to a more southwesterly flow at night (Fig. 8) – may contribute to the observed increase in nocturnal ozone at Angora Lookout. Shifting wind patterns do not, in contrast, appear to play a role at Genoa Peak 9000, as the daytime and nighttime wind roses are very similar to one another.

It should be emphasized that these two sites experience average ozone concentrations (57.3 ppb for GP9 and 55.1 ppb for AGL, Table 3) that are substantially higher than concurrent values measured at the polluted urban/suburban comparison sites of Sacramento (SAC, 27.5 ppb), Folsom (FOL, 41.4 ppb), and Placerville (PLA, 51.8 ppb). This result suggests nocturnal exposure to ozone-rich air from the "polluted background" of the free troposphere – rather than close proximity to emission or primary pollutants – is the most important factor in determining the average overall ozone exposure. This assessment agrees with the prior analysis from Van Ooy and Carroll (1994), who investigated the spatial variability of ozone climatology at six remote sites along the western slope of the Sierra Nevada. They concluded that local topographical characteristics and their effect on local three-dimensional transport of polluted air had a much greater impact on the diurnal ozone signature at a given site than the "remoteness" of the site from pollution source regions.

3.9.2. Upper Incline, Thunderbird Lodge, Echo Summit

Upper Incline (ICN), Thunderbird Lodge (THB), and Echo Summit (ECHO) all yield average ozone concentrations around 50 ppb, with small diurnal cycle magnitudes and elevated nighttime ozone concentrations in the range of 40–50 ppb (Table 3, Fig. 4a). While this outcome is not surprising for Upper Incline (2536 m, on a steep hillside with excellent exposure) or Echo Summit (2250 m, positioned in closer proximity to the emission sources located to the southwest of the Tahoe Basin), it is somewhat unexpected for Thunderbird Lodge, which lies at a much lower elevation (1915 m) near the Lake Tahoe shoreline. The observation of elevated levels of nocturnal ozone at the Thunderbird location may reflect (i) the steep topography of the sampling site, which prevents the formation of a stable nocturnal boundary layer; and (ii) an efficient onshore flow of ozone-rich air during evening hours (Fig. 8, Section 3.6). At Echo Summit, the relatively large difference between the average value measured in 2010 by the CARB monitoring station (47.4 ppb) and the concurrent value obtained by passive samplers (56.1 ppb) likely reflects the different locations of the two measurements. In this case the CARB monitor was located in a parking lot just off of U.S. highway #50, while the passive samplers were further removed from the highway by an additional 100 m or so, and positioned on top of a heavily forested hill. While both

locations had good access to the open sky, the lower elevation and closer exposure to fresh NO emissions likely reduced the O_3 concentrations measured by the CARB monitor compared to those recorded by the passive samplers. Since in this instance the active monitor and the passive samplers were not co-located, the CARB data from Echo Summit were not used to calibrate the passive samplers.

3.9.3. Incline Village, Genoa Peak 8000, Genoa Peak 7000

Incline Village (IVL), Genoa Peak 8000 (GP8), and Genoa Peak 7000 (GP7) all display somewhat lower ozone concentrations compared to the sites discussed above, with average mixing ratios in the range of 40–45 ppb (Table 3) and larger diurnal cycle magnitudes (Fig. 4a). All three of these sites possess gently sloping topography that is more amenable to the formation of nocturnal temperature inversions. The observation that Genoa Peak 8000 has higher average ozone and a smaller diurnal cycle magnitude than Genoa Peak 7000 reflects its higher elevation (2443 vs. 2232 m) and drier surface cover (ash and dirt vs. thick grass), which will reduce the likelihood of dry deposition during evening hours. The residential/commercial Incline Village site shows a pronounced diurnal minimum at 06:00 PST, which is probably the result of enhanced NO titration of ozone during the morning commute. This feature is not present at the Genoa Peak sites, consistent with their more remote locations.

3.9.4. Valhalla, Watson Creek, Sugar Pine Point State Park, Lower Blackwood Creek

Valhalla (VAL), Watson Creek (WC), Sugar Pine Point State Park (SPP), and Lower Blackwood Creek (LBC) have average ozone concentrations below 40 ppb, and display very large diurnal cycle magnitudes – in the range of 25–40 ppb. The key factor for these locations is the flat terrain, which supports the formation of stable temperature inversions during the evening hours.

While the flat topography is the dominant feature for these sites, other factors are also evident. Valhalla (VAL) is positioned along California state highway #89, which may provide slightly increased photochemical production of ozone during the afternoon hours and enhanced NO titration during the morning commute. Like Angora Lookout (AGL) and Echo Summit (ECHO), it is also closer to the main access point for regional transport of polluted air (generally from the southwest) into the Lake Tahoe Basin, which will increase observed ozone. Watson Creek (WC), in contrast, is a much more remote site, approximately 350 m higher in elevation, with very low average NO (Table 4). While the higher elevation and lack of NO will generally tend to favor higher ozone concentrations during evening hours, the flat terrain nonetheless predominates (with a likely assist from the leafy green ground cover), and the resulting diurnal cycle is very similar to what is observed at the lower, more heavily polluted Valhalla site (Fig. 4a, Table 3).

The two remaining sites, Sugar Pine Point State Park (SPP) and Lower Blackwood Creek (LBC), yielded the largest diurnal cycle magnitudes and lowest average ozone values of the 12 Tahoe sampling locations. This outcome reflects their low elevation, flat terrain, and leafy green ground cover that can enhance dry deposition of ozone during nighttime hours. The ground cover at the Lower Blackwood Creek site was grassy and very damp – characteristics that have been previously observed to correlate with large magnitude diurnal cycles and low average ozone at Tuolumne Meadows in Yosemite National Park (Burley and Ray, 2007) and the visitor center meadow at Devils Postpile National Monument (Bytnerowicz et al., 2013). These two sites may also experience mild enhancements in daytime ozone due to the presence of an on-shore lake breeze, as discussed above in Section 3.6.

3.10. Potential phytotoxic effects

Table 6 lists the exposure ozone indices that were calculated according to the methodology described in Section 2.5. The SUM00 values range from 96.1 ppm h (Lower Blackwood Creek) to 161.9 ppm h (Genoa Peak 9000). The SUM06 values range from 6.8 ppm h (Genoa Peak 7000) to 69.3 ppm h (Genoa Peak 9000). The SUM07 values range from zero at Genoa Peak 7000 to 15.1 ppm h at Genoa Peak 9000. The 24-h, 4-month W126 values range from 10.8 ppm h (Lower Blackwood Creek) to 46.6 ppm h (Genoa Peak 9000). The 12-h, 3-month W126 values range from 6.8 ppm h (Genoa Peak 7000) to 14.5 ppm h (Genoa Peak 9000).

The magnitudes of the SUM00 values for the Lake Tahoe sites are lower than those determined for a San Joaquin River transect across the southern Sierra Nevada in 2002 (148–192 ppm h; Cisneros et al., 2010), but somewhat above the values determined in 2007 and 2008 (110 and 98 ppm h, respectively) at the Devils Postpile National Monument (Bytnerowicz et al., 2013). In general, the present results for SUM00 are roughly similar to the values of 90–160 ppm h recorded in the San Bernardino Mountains of southern California in 2006 (Bytnerowicz et al., 2008). From this perspective, Angora Lookout and Genoa Peak 9000 can be viewed as sites that experience a high phytotoxic potential while the other Tahoe locations are more comparable to the low pollution sites in the San Bernardino Mountains or at the Devils Postpile National Monument. However, when the SUM00 calculation is replaced by SUM06 or W126, the results for Angora Lookout and Genoa Peak

Table 6
Ozone exposure indices.

Site	120 day (24-h) ppm h	120 day (24-h) ppm h	120 day (24-h) ppm h	120 day (24-h) ppm h	90 day (12-h) ppm h	120 day (24-h)	120 day (24-h)
	SUM00	SUM06	SUM07	W126	W126[a]	Percent complete (6/1–9/30)	Actual sampling period
Angora Lookout	154.0	50.1	11.2	37.8	13.3	79.5	6/15–9/23[b]
Genoa Peak 7000	116.5	6.8	0.0	11.2	6.8	80.0	6/16–9/22
Genoa Peak 8000	125.6	10.3	0.2	14.2	7.6	68.9	6/30–9/22
Genoa Peak 9000	161.9	69.3	15.1	46.6	14.5	68.8	6/30–9/22
Lower Blackwood Canyon	96.1	9.3	0.3	10.8	7.2	81.3	6/16–9/23
Sugar Pine Point State Park	107.6	19.3	0.6	15.7	10.4	68.9	7/1–9/23
Thunderbird Lodge	141.3	21.3	0.4	22.0	10.2	69.5	7/1–9/24
Upper Incline	142.4	27.5	1.8	24.6	10.1	68.8	6/30–9/22
Valhalla	109.6	14.5	0.3	14.4	8.7	81.8	6/15–9/23
Watson Creek	109.6	11.6	0.5	12.5	7.3	77.0	6/16–9/23

[a] Percent complete values for the 12-h W126 calculation are 89–90%.
[b] Angora Lookout is missing seven days of hourly data for 22:00 to 06:00 PST.

9000 (SUM06 values of 50.1 and 69.3 ppm h; W126 values of 37.8 and 46.6 ppm h, respectively) indicate that even these two most polluted Tahoe Basin sites have much lower phytotoxic indices than the western slope of the southern Sierra Nevada Mountains (SUM06 values of 140–150 ppm h and W126 values of 110–125 ppm h, respectively; Cisneros et al., 2010) or the sites in the San Bernardino Mountains that are most severely impacted by Los Angeles smog (SUM06 values of 85–105 ppm h and W126 values of 65–85 ppm h, respectively; Bytnerowicz et al., 2008). If Angora Lookout and Genoa Peak 9000 are excluded, then the remaining sites in the Tahoe Basin have SUM06 and W126 indices that are similar to the low values determined for Devils Postpile National Monument (SUM06 values of 29 and 23 ppm h; W126 values of 21 and 19 ppm h, in 2007 and 2008, respectively; Bytnerowicz et al., 2013).

The hypothesis that Angora Lookout and Genoa Peak 9000 are more likely to experience phytotoxic impacts is also supported by the 12-h (daytime) W126 results calculated over the 90-day interval of July through September, which show both Genoa Peak 9000 (14.5 ppm h) and Angora Lookout (13.3 ppm h) to be above the 13 ppm h threshold associated with phytotoxic damage. Since the present results for the 12-h W126 calculation correspond to the months of July–August–September, with data unavailable for other possible intervals (e.g., May–June–July, June–July–August), the 12-h W126 values reported here probably underestimate the values that would have been obtained if the calculation had been applied to the highest 3-month period for the entire year. The restriction of the 12-h W126 calculation to daytime data is also likely to produce an underestimation of the overall ozone exposure at these two particular sites because both Angora Lookout and Genoa Peak 9000 frequently see higher ozone values during at night, with lower values during daytime hours (Fig. 4a).

4. Conclusions

Data from passive samplers and active monitors indicate that the Lake Tahoe Basin experiences elevated concentrations of surface-level ozone. Different locations within the Basin generally experience similar mid-day maxima of ~50–55 ppb, which suggests that the Basin is well mixed during daytime hours. During the night there are large site-to-site variations in observed ozone; higher elevation sites that possess steeply sloped topography and maintain good exposure to “polluted background” air from the free troposphere experience high ozone concentrations, while lower elevation sites with flat topography experience much lower nocturnal ozone concentrations. Because of their good exposure to nocturnal ozone, many of the higher elevation Tahoe locations experience average ozone concentrations that exceed those measured in heavily polluted upwind source regions (Sacramento, Folsom, Placerville). The observation of high average ozone on a NASA research buoy in the middle of the Lake likely reflects diminished dry deposition to the surface of the Lake, a phenomenon that has been observed in prior studies of surface O_3 above large bodies of water. Wind rose analyses of archived NAM 12 km meteorological data for the summer of 2010 suggest that some of the sampling sites situated near the shoreline may have experienced on-shore “lake breezes” during daytime hours and/or offshore “land breezes” during the night. Back-trajectory analysis with the HYSPLIT model suggests that much of the ozone measured at Lake Tahoe results from the transport of “polluted background” air into the Basin from upwind pollution source regions (e.g., Sacramento, San Joaquin Valley). Given the high elevation of the Tahoe Basin, it is likely that this “polluted background” also included ozone transported from Asia. Ozone exposure indices indicate that the two most polluted sites (the highest Genoa Peak site, and Angora Lookout) sampled by portable ozone monitors during the summer of 2010 likely experienced some phytotoxic impacts, while the other Tahoe Basin locations experienced lower ozone exposures.

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