Seasonal and Diurnal Variations in Aerosol Concentration on Whistler Mountain: Boundary Layer Influence and Synoptic-Scale Controls

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ABSTRACT

A mountain air chemistry observatory has been operational on the summit of Whistler Mountain in British Columbia, Canada, since 2002. A 1-yr dataset of condensation nuclei (CN) concentration from this site has been analyzed along with corresponding meteorological data to assess the frequency and patterns of influence from the planetary boundary layer (PBL). Characterization of air masses sampled from the site as either PBL influenced or representative of the free troposphere (FT) is important to subsequent analysis of the chemistry data. Median CN concentrations and seasonal trends were found to be comparable to other midlatitude mountain sites. Monthly median number concentrations ranged from 120 cm$^{-3}$ in January to 1601 cm$^{-3}$ in July. Using well-defined diurnal cycles in CN concentration as an indicator of air arriving from nearby valleys, PBL influence was found to occur on a majority of days during spring and summer and less frequently in late autumn and winter. Days with PBL influence were usually associated with synoptic-scale weather patterns that were conducive to convective mixing processes. Although more common in the warm season, vertical mixing capable of transporting valley air to the mountaintop also occurred in February during a period of high pressure aloft. In contrast, an August case study indicated that the more stable character of marine air masses can at times keep the PBL below the summit on summer days. Considerable variability in the synoptic-scale weather conditions at Whistler means that careful analysis of available datasets must be made to discriminate FT from PBL periods at the observatory.

1. Introduction

Mountain air chemistry observatories have been established in numerous locations worldwide to monitor background levels of aerosols and trace gases and to detect long-range transport (LRT) of atmospheric pollutants. High-elevation observatories provide a cost-effective means of sampling the free troposphere (FT) over long time periods, but even the highest mountains are at times prone to the influence of air from the planetary boundary layer (PBL) that is transported upward from adjacent valleys (e.g., Hindman 1995). The PBL air can bring with it pollutants of local origin, thereby confounding observations meant to sample air masses of more distant provenance. Thus, it is useful to determine which atmospheric layer is represented by particular mountain observatory measurements (Henne et al. 2008). This will vary with time and synoptic weather situation. Herein, the PBL will be considered to be the layer of well-mixed air that is affected by the earth’s surface through exchanges of energy, mass, and momentum on time scales of a day or less (Oke 1987). A daytime PBL that is enhanced by free convection is referred to as the convective boundary layer (CBL).

The frequency with which a particular mountain observatory is influenced by PBL air from the lowlands depends on the mountain’s size, shape, geographical location, and local climate (Kleissl et al. 2007). Therefore, research aimed at distinguishing airmass types tends to be site specific. In all cases, however, investigators can examine the data for indicators of PBL air and/or driving forces of vertical transport and subsequent PBL influence at the site (Henne et al. 2008).
Water vapor has often been used as an indicator of PBL air because of its origin at the earth’s surface and tendency to become well-mixed in the PBL, with substantially lower concentrations found in the FT. Obrist et al. (2008) used diurnal cycles in water vapor mixing ratio to estimate the timing of nearly daily transitions between free-tropospheric and PBL air masses at the Storm Peak Laboratory in Colorado. Weiss-Penzias et al. (2006) also used water vapor as a PBL indicator at the Mount Bachelor Observatory in Oregon by comparing water vapor observations with moisture profiles from the two nearest radiosonde sites. Enhanced water vapor at the mountaintop as compared with an equivalent altitude in the free atmosphere was considered to be a signal of PBL influence on the mountain.

Like water vapor, temperature is expected to show regular diurnal cycles in the PBL but not in the FT. For the Mount Washington Observatory in New Hampshire, Grant et al. (2005) used the timing of daily extreme temperatures to identify days on which the summit was affected by boundary layer (BL) processes. Days with early morning minima and afternoon maxima in temperature were classified as “radiative” days exhibiting BL behavior, whereas days with temperature extremes at the beginning and end of the day were assumed to be dominated by horizontal advection. In the case of temperature, however, diurnal cycles may be produced by heating and cooling of surfaces that are very local to the mountaintop site without input of air from the lowlands.

Particulate matter originating at the surface typically exhibits a vertical profile similar to that of water vapor, such that diurnal cycles can often be attributed to vertical transport. At the Mauna Loa Observatory in Hawaii, Bodhaine (1996) found that daily increases in condensation nuclei (CN) concentration corresponded closely to upslope winds that carried polluted island air up to the site from lower elevations. Analysis of aerosol data has been used extensively for studies of vertical transport and airmass discrimination at the Jungfraujoch Observatory in Switzerland (Baltensperger et al. 1997; Lugauer et al. 1998; Nyeki et al. 1998; Collaud Coen et al. 2011). Daytime increases in aerosol parameters at the site were mainly attributed to CBL growth that is enhanced by slope winds acting within a certain catchment area in the Alps (Baltensperger et al. 1997).

In terms of drivers of PBL influence, convective uplift mechanisms are most commonly assumed to be responsible for the transport of valley air to high-elevation measurement sites. It has been found that thermal circulations common to mountainous areas can result in enhanced vertical transport and greater CBL heights than what is found over relatively flat terrain (De Wekker et al. 2004). The BL constituents can be lofted out of the primary CBL by mountain venting mechanisms, creating an injection layer of surface-based pollutants over the mountains (Henne et al. 2005). In a similar way, at nighttime during light wind conditions, a residual layer of BL constituents often remains above the nocturnal BL (Whiteman 2000) for all or part of the night.

Mechanical and dynamic lift can also play a role in transporting lowland air to mountain observatories. For the Pico Mountain Observatory in the Azores Islands, Kleissl et al. (2007) calculated how often wind flows impacting the mountain were able to force marine BL air over the top of the mountain. This form of lift is expected to be most important for relatively small, isolated peaks and to be less prevalent for sites in large mountain ranges. Dynamic lift can also at times bring PBL air to summits through upward motions associated with cyclones, fronts, or mountain waves (e.g., Lugauer et al. 1998; Forrer et al. 2000).

In this study, a 1-yr aerosol dataset is examined in conjunction with meteorological data to investigate the question of airmass discrimination for the Whistler Mountain Observatory. Meteorological explanations are posited for observed seasonal and diurnal patterns in aerosol concentration. This study follows on the work of Nseir (2007), who examined diurnal cycles of temperature, water vapor, and ozone at the Whistler site for two springtime periods in 2005 and 2006. In that study, an atmospheric stability parameter was used to estimate daily transition times between FT and PBL conditions at the mountain summit. This study uses a longer data period to allow evaluation of seasonal differences in the frequency of PBL influence. Case studies that incorporate supplementary local and regional observations are included to add detail to the vertical mixing analysis.

2. Site description

The Whistler Mountain air chemistry observatory is located on the summit of Whistler Mountain (2182 m MSL) in British Columbia (BC), Canada, at 50.06°N, 122.96°W. Operated by the Air Quality Research Division (AQRD) of Environment Canada since 2002, the facility measures numerous trace gas and aerosol parameters and is situated to observe episodes of trans-Pacific Ocean pollution transport. In addition to LRT from industrial sources, dust plumes from Asian deserts have been observed from this site (e.g., McKendry et al. 2008).

Located in the Coast Mountains, Whistler is approximately 100 km north of Vancouver, Canada, and less than 35 km from Pacific coastal inlet waters at the head of Howe Sound. Figure 1 shows Whistler’s location on a regional map. The Resort Municipality of Whistler occupies the Whistler Valley at the base of Whistler and
Blackcomb Mountains. The Whistler Blackcomb ski area is located on the two mountains, and thus they contain considerable infrastructure in the form of ski lifts, trails, and buildings. Trees, mainly conifers, and undergrowth are found up to approximately the 1820-m level on the mountain. The summit area is mostly exposed rock and soil with limited alpine vegetation.

Whistler’s location near the west coast of BC results in a climate characterized by frequent precipitation-producing, synoptic-scale disturbances in the autumn–spring seasons, followed by a much drier summer period dominated by the east Pacific high. The upper mountain receives heavy snowfall in winter, and the summit area is typically snow covered 8–9 months of the year. Wind flows tend to be topographically channeled below the ridgetops such that inflow winds are southwesterlies from the coast and outflow winds are northeasterlies from the BC interior.

3. Data and methods

A 1-yr study period from December 2008 through November 2009 was selected to maximize the availability of overlapping datasets. During this time, much supplementary meteorological instrumentation was deployed in the Whistler area by Environment Canada in preparation for the 2010 Winter Olympic Games. Data from mountainside weather stations and special radiosonde observations (described below) related to the Olympic Games were used in this study.

a. Data from Whistler Mountain

The primary datasets for the study are from the AQRD site at the summit of Whistler. A suite of meteorological sensors measures temperature $T$, pressure $P$, and relative humidity (RH). Hourly means were calculated from 1-min data such that each hour’s value represents an average of the preceding 60 min. The temperature and RH sensors are housed in an unaspirated radiation shield. Water vapor mixing ratio $w$ (g kg$^{-1}$) was calculated from $T$, $P$, and RH using Tetens’s formula and related equations in Stull (2000). Diurnal cycles were analyzed by calculating hour-of-day means and medians for the time periods in question.

The aerosol dataset analyzed consists of CN number concentrations measured by a TSI, Inc., 3025 Ultrafine Condensation Particle Counter (UCPC), which records counts of particles that are larger than approximately 3 nm in diameter, with near 100% detection efficiency beginning at ~6 nm (Wiedensohler et al. 1996). The TSI 3025 uses butanol as a condensing fluid to enlarge the particles to a size that can be detected by an optical sensor. Quality control and smoothing operations were performed on the CN dataset to remove short-term spikes that were likely caused by machinery related to ski-resort operations.

Slope and valley wind patterns were evaluated using data from automated weather stations that were installed on Whistler Mountain by Environment Canada. These stations composed the Olympic Autostation Network (OAN) and were located at various elevations on the mountain, primarily on west- to northwest-facing slopes. An OAN station was also collocated with the “NAV CANADA” surface weather observing site (International Civil Aviation Organization identifier CWAE) in the valley at a location known as Nesters (elevation 660 m MSL). Aviation routine weather reports (METAR) from CWAE were also used to assess local conditions.

b. Radiosonde data

Upper-air observations were conducted from the Nesters location during the period 5–23 February 2009 to support preparations for the 2010 Winter Olympics. Weather balloons carrying standard radiosonde packages were launched three times per day. The resulting profiles of temperature, humidity, pressure, and wind velocity were obtained from Environment Canada for this study.

Regional radiosonde observations were also used to represent free-air conditions at the three upper-air sites nearest to Whistler: Kelowna, BC; Quillayute, Washington; and Port Hardy, BC (Fig. 1). These datasets were downloaded from the University of Wyoming Department of Atmospheric Science Internet site (http://weather.uwyo.edu/upperair/).

c. Model reanalysis data

Synoptic weather maps were produced by plotting numerical model reanalysis data on regional maps. The
model data used in this study consist of National Centers for Environmental Prediction (NCEP) reanalysis products from the Physical Sciences Division Internet site of the National Oceanic and Atmospheric Administration Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/data/gridded/reanalysis). Gridpoint data originally on a 2.5° × 2.5° latitude/longitude grid were linearly interpolated to every 0.5° prior to display.

4. Results and discussion

a. Seasonal patterns

For the 1-yr study period, the annual mean CN number concentration at the Whistler mountaintop site was 872 cm\(^{-3}\) (\(\sigma = 853\)) and the median value was 635 cm\(^{-3}\), indicating a skewed dataset that contains numerous episodes of enhanced CN concentration. The highest hourly average of 7850 cm\(^{-3}\) occurred on 6 June during an episode of smoke from a forest fire. The lowest 10% of hourly concentrations in the dataset are represented by values below 95 cm\(^{-3}\), and the highest 10% are found above 1883 cm\(^{-3}\).

Median CN concentrations for each month of the study period are shown in the box plots of Fig. 2. The monthly medians varied over an order of magnitude from a low of 120 cm\(^{-3}\) in January to a high of 1601 cm\(^{-3}\) in July. The intervening months demonstrate a clear trend from low concentrations in winter to relatively high concentrations during the summer. The only interruption to this trend is manifested by February having a higher median value than March.

The observed seasonal trend in CN concentration at Whistler is similar to that of the Jungfraujoch Observatory in Switzerland. Data reported by Nyeki et al. (1998) showed a December minimum and a June peak in aerosol concentration at Jungfraujoch. The median CN concentrations at Whistler were higher for some months, however—in particular, in summer (e.g., 1273 cm\(^{-3}\) at Whistler vs 761 cm\(^{-3}\) at Jungfraujoch in June). In both cases the data are from 1-yr periods; therefore, the degree of interannual variability in aerosol concentration is not addressed here. Both Jungfraujoch and Whistler Mountain are situated in moist midlatitude mountain ranges, but the Whistler site is closer to the coast and at a lower elevation (2182 m vs 3454 m for Jungfraujoch).

b. Diurnal patterns

Daytime increases in aerosol number concentration at the mountaintop may be brought about by meteorological processes and/or other physical and chemical processes (e.g., nucleation or local dust generation). The assumption made here is that meteorological processes dominate the aerosol signal but it is recognized that—because of its sensitivity to fine particles—counts from the UCPC could be significantly affected by nucleation events (gas-to-particle conversion) that can occur from late morning to early afternoon. The process of nucleation and subsequent particle growth is often referred to as new particle formation (NPF; Nishita et al. 2008). For interpretation of the CN data, a concern is that NPF events rather than vertical transport of PBL air could be the cause of diurnal peaks.

At Storm Peak Laboratory in Colorado, NPF events were found during 52% of 474 measurement days, consistently occurring in midafternoon (Haller et al. 2011). Because the Storm Peak site is thought to experience nearly daily transitions from FT to PBL air near midday, it is possible that mixing of condensible vapors from the PBL provides some of the necessary conditions for the nucleation events. At a mountain site in Japan, Nishita et al. (2008) found that concentrations of nucleation-mode particles were strongly correlated with water vapor mixing ratio. Rapid concentration increases of fine particles were concurrent with increases in \(w\) and periods of upslope winds, leading the investigators to conclude that nucleation had occurred in PBL air, which was subsequently transported to the site.

The possible contribution of nucleation has also been addressed for the Jungfraujoch Observatory. Baltensperger et al. (1997) found that aerosol concentrations were correlated well with concentrations of black carbon and the radon daughter \(^{210}\)Pb. Because both of these entities

![Fig. 2. Monthly box plots of CN number concentration data. The horizontal line through each box represents that month’s median value, and the lower and upper edges of the boxes mark the 25th and 75th percentiles, respectively. The “whiskers” extending above and below the boxes end at the adjacent values (the most extreme values that are not considered to be outliers). Outliers are not shown.](image-url)
are considered to be PBL tracers, it was concluded that vertical transport accounted for the diurnal aerosol cycles. In a later study NPF was considered to be an important contributor to CN diurnal cycles at Jungfraujoch, however, especially in winter during clear weather (Collaud Coen et al. 2011).

Determining the importance of NPF to CN number concentrations at Whistler would require analysis of additional aerosol and chemical parameters, exceeding the scope and data availability of this study. The CN concentration is used here as a starting point for meteorological analysis; the assumption that vertical transport dominates the diurnal signal is bolstered on days on which CN and water vapor are strongly correlated.

To identify diurnal patterns in the Whistler CN data, median values were calculated for each hour of the day. These hour-of-day medians were computed for each month of the study period as well as each 3-month season. The seasonal medians are shown in Fig. 3.

The previously mentioned seasonal differences in aerosol concentration are also evident in Fig. 3. Winter concentrations were generally low and were lacking any well-defined diurnal pattern. The other three seasons all had similar diurnal trends: a morning minimum in CN concentration followed by a late afternoon or early evening peak. The timing of the concentration maxima and minima showed slight seasonal variation, with the diurnal peak in CN occurring later in the day during summer (1900 LST) than in spring or autumn. These diurnal trends are consistent with the progression of convective turbulent mixing that is typical of days with substantial solar heating—that is, increasing CBL depth during the daytime heating period followed by stabilization and downslope flows overnight. Data from two previous springtime periods at Whistler indicated that daily trends of $w$ were anticorrelated with atmospheric stability, supporting the premise that diurnal increases of PBL constituents are related to convective mixing (Macdonald et al. 2011).

Although the median CN concentrations were highest in summer for all hours, the highest-amplitude median diurnal cycle occurred in the springtime. When relative amplitude is considered (diurnal variation as a percentage of the daily mean), it becomes apparent that the summer diurnal cycle was considerably dampened relative to those of both spring and autumn. This can be explained by nocturnal residual layers of aerosol being more common in summer than during the other seasons, as was found to be the case at Jungfraujoch (Collaud Coen et al. 2011). The long diurnal heating periods and light synoptic-scale winds of summer high pressure systems favor residual layer development and persistence. Thus, the nighttime aerosol concentrations remain relatively high, which dampens the diurnal cycle and contributes to the overall higher median concentrations of summer.

As the time frame analyzed decreases, more variability in the median diurnal cycles of CN concentration becomes apparent. For example, Fig. 4 shows the median cycles from the three individual months that compose the springtime trace in Fig. 3. While the concentration values and diurnal trends were very similar for April and May, the March data indicate considerably lower concentrations and less diurnal variation, suggesting that vertical transport processes and PBL influence at the summit were less prevalent in March.

A much greater degree of variability exists in the CN data on a day-to-day basis. Although numerous factors can influence the aerosol concentration measured at any given time, much of the variability can be attributed to frequent changes in synoptic-scale weather conditions. The synoptic-scale situation can provide an environment that is either favorable or restrictive toward mesoscale vertical transport processes, which can in turn control PBL influence at the site. The synoptic-scale weather also affects aerosol concentration via wet scavenging processes.

To categorize this day-to-day variability and begin to describe the frequency of PBL influence at Whistler, each day’s observations were evaluated based on conformance to a model of a “typical” diurnal pattern. This scheme was based on that of Baltensperger et al. (1997) for Jungfraujoch and was adjusted to better fit the data from Whistler. The main aspects of the model are that the daily course of CN concentration approximates a sinusoidal pattern and that a well-defined peak in

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**Fig. 3.** Median values of CN concentration for each hour of the day computed over each 3-month season of the study period (December–February = DJF, March–May = MAM, June–August = JJA, and September–November = SON).
concentration occurs in the afternoon or evening hours. For the months of March–October, 3-h means ending between 1400 and 2300 LST were used as the allowable window for the diurnal peak. For the “winter” months of November–February, a narrower window of 1300–2000 LST was used to reflect the shorter daylight period, which tends to produce earlier peaks in diurnal signals. The scheme for defining a typical diurnal cycle was found to be in generally good agreement with subjective evaluations of daily CN data plots. Days with sharp peaks in CN concentration will often be rejected by this scheme, however. It is also expected that PBL air occasionally affects the summit at atypical times such that, for example, a peak in CN concentration occurs before noon. Therefore, the scheme used here can be considered to be conservative, because it was designed in accordance with an idealized model of diurnal PBL expansion.

Results of this analysis are given in Fig. 5, which shows how many days per month met the criteria. Overall, 127 out of 344 days analyzed (37%) were classified as exhibiting typical diurnal variations of CN concentration. There are clear seasonal differences in the results, with relatively few days qualifying in late autumn and early winter. In the April–September period, all months but August had slightly more than 50% of the days meet the criteria. Note that CN data were unavailable from 12 to 24 November; thus, only 17 days from that month were included in the analysis.

The results for August appear not to fit the overall trend of well-defined diurnal cycles being most common in the warm season. August 2009 was generally a hot and dry month at Whistler, which is normally considered to be favorable for vertical mixing. However, it may be that dynamic subsidence from strong high pressure aloft suppressed the convection on some days. Furthermore, closer inspection of the summer weather reports revealed another possible explanation for the low number of days with typical cycles in the CN data: smoke was frequently reported in the Whistler area during August. The abundance of wildfire emissions into the atmosphere during portions of the 2009 summer greatly influenced aerosol concentrations in the region (Takahama et al. 2011). Elevated smoke layers that moved through the Whistler area at various times caused peaks in the measured concentrations that often did not fit the timing expected if aerosol movement was dominated by vertical transport (e.g., McKendry et al. 2010). Days with peaks in CN concentration that did not occur in the afternoon or evening hours did not qualify as typical cycle days, even though there may have been PBL influence at the mountaintop.

February is the other month that appears to be in conflict with seasonal trends found in Fig. 5. February had a high frequency of diurnal CN cycles for a winter month, with 11 of 28 days (39%) meeting the criteria. In this case, the synoptic-scale conditions particular to February 2009 point to a plausible explanation. The month was characterized by drier-than-normal weather, including a 15-day period without measurable precipitation. The large number of sunny days with light synoptic-scale pressure gradients in February may have facilitated convective mixing capable of transporting PBL air to the summits. In a “normal” February, frequent stratiform precipitation events would tend to limit CBL growth and also to reduce aerosol concentrations through washout of particles. Additional datasets are examined in the following section to evaluate whether
Convective transport was indeed vigorous enough during this period to mix valley air up to the mountaintop.

c. Vertical-mixing case studies

Aerosol data from the mountaintop have been used for a first estimate of the frequency of PBL influence at the Whistler site. On the basis solely of the available summit data, however, it cannot be known whether there is a deep CBL extending from the valley floor to the mountaintops and beyond or whether diurnal cycles are merely a reflection of more-local upslope flows that have their origins above the valley BL. This uncertainty arises because none of the variables measured at the site are perfect tracers of valley air. In this section, vertical-profile data from winter and summer case studies are used to investigate further the nature of PBL influence at the site.

1) Winter PBL-influence case: 20 February 2009

Comparisons between readings from the mountaintop and free-air profiles of meteorological variables from radiosondes are normally of limited utility for the Whistler Observatory because the nearest sites of routine upper-air observations (marked in Fig. 1) are all greater than 250 km from Whistler. Thus, the upper-air data collected from soundings that were conducted from Whistler Valley in February 2009 are particularly valuable for investigating the vertical structure of the local atmosphere. Figure 6 shows average temperature profiles from the 5–23 February special observing period for each of the three daily observation times. The profile comparison indicates that considerable warming and some destabilization occurred in the low levels between the morning and afternoon observation times. Slight diurnal warming is evident up to the height of Whistler Mountain, supporting the notion that synoptic conditions during this period facilitated thermal circulations that at times resulted in diurnal variations through the depth of the valley atmosphere.

The twentieth of February 2009 exemplifies a day during the winter season for which well-defined diurnal cycles could be found in meteorological data from Whistler Mountain. The criteria for a typical diurnal cycle in CN concentration were met, and the CN values were well correlated with water vapor mixing ratio (Fig. 7). Potential temperature profiles from the morning and afternoon radiosonde observations (Fig. 8) show that a diurnal transition occurred from a highly stable surface-based inversion in the morning to a warmer, only slightly stable valley atmosphere in the afternoon. The top of the diurnally affected layer at 1600 LST was very near the mountaintop level, which is marked with an “X” in Fig. 8.

METAR observations from CWAE indicated that 20 February had abundant sunshine with just scattered cirrus clouds over Whistler. Winds were light, and the surface temperature reached 5°C by the time of the afternoon upper-air sounding. The primary synoptic-scale feature responsible for these conditions was a strong high pressure ridge aloft (Fig. 9a). Because Whistler was directly under the upper ridge, it can be assumed that the synoptic-scale vertical motion was downward, which gave the region nearly clear skies. At the surface, high pressure was centered over southeastern BC, providing a weak offshore pressure gradient to the Whistler area (Fig. 9b). This quiescent pattern on the synoptic scale allowed daytime heating to produce local and mesoscale thermal gradients. The presence of snow cover may have increased the lapse rate up the mountainside: assuming
the conifers on the lower mountain were mostly free of snow at this time, absorption of solar radiation would have been greater on the forested lower slopes than at the snow-covered summit area (Whiteman 2000).

Convective thermals and upslope flows mixed air upward from the valley, redistributing heat as evident in the profiles of Fig. 8. Observations from OAN weather stations on Whistler Mountain showed winds with a westerly (upslope) component during the afternoon and winds with an easterly (downslope) component at nighttime. On such days, the thermally driven vertical transport and the synoptic-scale vertical motion are of opposite direction, which is what Lugauer et al. (1998) and Collaud Coen et al. (2011) found to be the most common situation for PBL influence at Jungfraujoch.

In this case, mesoscale uplift was strong enough to work against synoptic-scale subsidence, bringing PBL air to the summits. Common in the summer months, this scenario was able to occur on this late winter day because of the prevailing synoptic-scale conditions. Although an afternoon peak in aerosol concentration could conceivably be caused by horizontal advection of a pollution plume or by new particle growth, the strong correlation between CN and water vapor in this case and the preceding evidence for diabatic processes support the idea that convective uplift resulted in diurnal intrusions of PBL air at the mountaintop. The measurement site was then representative of a mixture of PBL and FT air until several hours after mesoscale uplift had ceased, allowing FT air from upstream to displace the PBL constituents through horizontal (synoptic scale) advection.

2) SUMMER FT CASE: 13 JULY 2009

Although surface heating and convective mixing are generally more pronounced in the summer months, the results of daily CN analysis presented in Fig. 5 indicate that days during the summer without well-defined diurnal cycles are common. One such day, 13 July 2009, is analyzed here as an example of synoptic-scale conditions limiting vertical transport in the Whistler area.

On 13 July no rainfall was reported at Whistler, but CN concentrations at the summit generally declined through the day (Fig. 10). Water vapor mixing ratio was unsteady through the morning, with some increase between 0800 and 1200 LST, followed by decreasing values through the afternoon and evening. Neither of these variables showed an afternoon or evening peak as expected for a typical day with PBL influence, nor were they well correlated with each other.

Figure 11 shows the day’s temperature and pressure trends. A slight diurnal cycle is evident in the temperature
trend, but with the daily maximum occurring earlier than usual for the time of year (1300 LST). The temperature then fell through the afternoon and evening, ending the day about 5°C cooler than it began. Meanwhile, the pressure gradually increased by 3 hPa through the day. These changes in meteorological variables in the afternoon hours indicate that an airmass change was taking place. Rather than being an intrusion of humid, aerosol-rich air from the lowlands, however, this case appears to be more characteristic of a synoptic-scale change to cooler, drier air.

The synoptic-scale pattern of this day is summarized by the maps in Fig. 12. At 500 hPa, a trough had recently passed through southwestern BC and a high pressure ridge was approaching the area from the eastern Pacific. The rising pressure observed at Whistler can be attributed to this building high pressure ridge. It can be expected that dynamic subsidence was present in this upper-level pattern, but in this case Whistler did not have clear skies. Broken-to-overcast cloud cover was reported throughout the day with ceilings of 1500–3000 ft (450–900 m) above ground level (AGL).

Regional surface observations and the sea level pressure (SLP) pattern (Fig. 12b) provide an explanation for the cloud cover at Whistler. A moderate onshore pressure gradient was present across coastal BC. Brisk southerly winds of 5–10 m s⁻¹ at Squamish (30 km south of Whistler at the head of Howe Sound) and 4–6 m s⁻¹ at Whistler brought moist marine air up Howe Sound and the Cheakamus Valley toward Whistler, producing a layer of stratocumulus clouds in the region.

Although radiosonde observations are not available from Whistler for this case, the nearest coastal upper-air sites provide a representative picture of the relevant vertical structure. The afternoon observations from Quillayute (Fig. 13) show a clearly defined marine BL capped by a subsidence inversion at approximately 1300 m MSL. Saturated conditions near the top of the BL indicate cloud layers, whereas the FT air above was much drier. Sounding data from Port Hardy (not shown
here) depicted a very similar scenario, indicating that the moist marine BL was found throughout a broad region on this day. Cloud bases at Whistler were observed to be 3000 ft (900 m) AGL at 1600 LST. This corresponds to a height of 1560 m MSL, slightly higher than the BL height at Quillayute but well below the mountain summit. The summit level is marked on Fig. 13, showing that the site was well above the marine BL. In addition, the mountaintop temperature corresponded well to the FT temperature profile from Quillayute.

Winds above the BL at Quillayute showed backing with height, indicating cold-air advection. Thus, the cooling, drying, and rising pressure observed at the Whistler site on this day can all be explained by the synoptic-scale changes that were occurring in the FT. The strong subsidence inversion capping the PBL effectively kept the air at the mountaintop level decoupled from the valley air. Cloud cover limited surface heating such that convection was not strong enough to force the PBL top to the height of the peak. Therefore, in this case, the mountaintop site was likely representative of the FT all day, although brief PBL influence around midday cannot be ruled out without local vertical-profile data. These inland intrusions of marine air are an occasional feature of the summertime weather at Whistler and may represent a recognizable pattern that maintains FT conditions at the measurement site.

**d. Synoptic classification of PBL-influence days**

Although PBL influence at the mountaintop is assumed to be driven most often by thermally induced mechanisms such as slope winds and convective updrafts, the conditions supporting PBL influence can be difficult to assess or predict from limited local observations. For instance, a stability parameter based on potential temperature differences between the valley and summit of Whistler was found to be a poor predictor of which days exhibited typical diurnal cycles in aerosol concentration; that is, diurnal-cycle days occurred with a large range of stability parameter values.

On the basis of the observed day-to-day variability of conditions at Whistler, it is evident that the process of PBL air intrusion does not operate with the kind of regularity found at a site such as Mauna Loa, which is an isolated peak with relatively consistent synoptic weather conditions. Therefore, no single local-scale parameter (such as wind direction or stability) can be expected to describe the meteorological conditions that loft valley air to the summits. Rather, it may be more useful to classify the synoptic-scale conditions that are conducive to PBL influence. In this section, days with signals of PBL influence are examined to determine whether a common set of synoptic conditions describes them. This is the environment-to-circulation approach to synoptic classification as described by Yarnal (1993).

The days selected for synoptic analysis are those that met the criteria for typical diurnal CN cycles while also displaying strong correlations between water vapor and CN concentration. This subset of 59 “PBL-influence days” represents the days that best fit the conceptual model of PBL constituents traveling together through vertical transport mechanisms. The definition of a strong correlation between water vapor and CN number concentration was based on daily Spearman’s rank correlation coefficients $r_s$ between hourly values of the two variables. For days with positive correlations, $t$ tests were performed on whether the correlations were different from zero, and days with resulting $p$ values of $<0.01$ were retained as PBL-influence days. The distribution of PBL-influence days was as follows: 6 days in winter (DJF), 21 days in spring (MAM), 24 days in summer (JJA), and 8 days in autumn (SON).

Synoptic weather patterns were identified on the basis of 500-hPa and SLP maps from NCEP reanalysis data. Inspection of these fields for the 59 PBL-influence days led to a subjective categorization of the maps into six circulation pattern types. Composite maps were created for each pattern type by averaging the height and SLP values from all days that fit the pattern. The two most common pattern types are shown in Figs. 14 and 15.

The most common pattern associated with PBL influence, which we will call pattern A, is shown in Fig. 14. Representing 32 of the 59 PBL-influence days, pattern A is characterized by a high pressure ridge aloft (500 hPa) and a weak surface (SLP) gradient in the Whistler region. Several of the summertime pattern-A days featured...
weak surface thermal troughs along the BC coast. This pattern type appears to capture days with enough ridging aloft to support clear or partly cloudy skies but not such a strong high that CBL growth was severely restricted by dynamic subsidence. At the surface, weak regional pressure gradients favored convection and diurnal wind development.

The scenario defined as pattern B features either a trough or zonal flow aloft, rather than a ridge (Fig. 15a). Similar to pattern A, however, the surface pressure gradient was weak on these days, usually with a high pressure ridge over the region (Fig. 15b). A review of surface observations and additional synoptic maps for the relevant days found that, on most of the pattern-B days, the Whistler area was in a convective postfrontal environment. There were 13 days that fit pattern B, all in the spring and summer months. On these days, a mix of sunshine and cloud was observed at Whistler. On nearly all of the pattern-B days, convective clouds were reported by the observer, with towering cumulus reported on six of the days. Surface heating was usually less intense on these days than for the pattern-A days, but the destabilizing effect of cold air aloft enhanced convective mixing enough to transport PBL constituents to the summits.

Most of the 14 remaining PBL-influence days not fitting either pattern A or B exhibited some version of an offshore flow for the southern Coast Mountains, which tends to bring dry conditions to Whistler. Thus, the synoptic pattern analysis in conjunction with a manual inspection of surface weather reports confirms that diurnal cycles of PBL indicators usually occurred on days with abundant insolation and relatively weak regional pressure gradients. This is consistent with convective uplift being the primary driver of PBL influence at the site. However, two PBL-influence days (17 March and 27 June)
5. Conclusions

A 1-yr aerosol dataset from the Whistler Mountain air chemistry observatory has been analyzed. At the seasonal scale, mean and median CN concentrations were highest in the summer months and lowest from late autumn through early winter, with number concentrations similar to other midlatitude mountain sites. Diurnal cycles with morning minima and afternoon or evening maxima in particle counts were found to occur throughout the year but were most common in the spring and summer months. Using well-defined diurnal cycles in CN concentration and water vapor mixing ratio as signals of PBL air from lower elevations, it was found that PBL influence occurred primarily on days on which the synoptic-scale situation was conducive to strong convective mixing. Synoptic patterns frequently associated with PBL-influence days included 1) a high pressure ridge aloft over the region coupled with a weak pressure gradient near the surface and 2) a postfrontal convective situation with atmospheric instability enhanced by cold air aloft. Ample insolation and light synoptic-scale winds found on such days allow thermally induced flows to drive vertical transport of PBL air to the mountaintop level. However, two of the identified PBL-influence cases occurred on days with cloud cover, precipitation, and apparent frontal passages, which suggests that dynamic lift can also at times force PBL air to the summit. Further research using a gaseous tracer of local valley-based pollution would help to determine the frequency of such events.

Considerable day-to-day variability was found in the trends of aerosol and meteorological variables at the Whistler Observatory, reflecting the frequently changing synoptic-scale weather conditions of this midlatitude coastal-range location. The Whistler site may be more susceptible to wintertime PBL influence than are other midlatitude sites at higher elevations, yet it is also expected to be more prone to summertime periods that—because of the effects of stable marine air—restrict the PBL to elevations below that of the observatory. A case study from February confirmed that a mixed layer can develop through the depth of the valley atmosphere during the winter season when synoptic-scale conditions are favorable. A July case study demonstrated how the regional weather situation can result in a relatively shallow PBL during the summer.

The high degree of synoptic-scale variability at Whistler makes air mass discrimination based on routinely available observations a challenging endeavor. Simple criteria, such as time of day, for separation of datasets into FT-influenced and PBL-influenced periods are likely not sufficient for broad application at this site. Analysis of a variety of datasets covering different scales of motion can lead to reasonable conclusions about conditions for particular short-term cases (~1 day). Vertical-profile data that enable evaluation of mixed-layer heights are particularly valuable in this context. Yet, a challenge still exists with respect to this and other mountain observatories to find a satisfactory and consistent method of determining which portions of a dataset time series are included in calculations of background concentrations. Data selection becomes particularly problematic for studies that aim to compare background/FT readings from different observatories (e.g., Andrews et al. 2011).

Despite these uncertainties, the Whistler Mountain Observatory constitutes a valuable component in the very limited network for observing trans-Pacific transport of pollution. As for many mountain observatories, frequent transitions among FT, PBL, and residual/injection-layer conditions mean that measurements from Whistler provide opportunities to study these tropospheric transition zones and related processes such as vertical transport, nucleation, and export of PBL constituents to the FT. This study underscores the importance of collecting and analyzing meteorological data to aid interpretation of physicochemical measurements. Ground-based remote sensing instruments, such as a lidar system that was installed at Whistler in April of 2010, will greatly assist air mass characterization efforts. Mixing heights derived from such platforms may also be used to assess and tune numerical models that predict BL depth over mountainous regions. Combining novel observations and high-resolution modeling in this way will advance the knowledge of boundary layer processes in complex terrain.

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