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ELEVATED OZONE LAYERS AND VERTICAL DOWN-MIXING OVER THE LOWER FRASER VALLEY, BC

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Abstract—Vertical profiling data, including lidar, are used to illustrate elevated layer development during two days of the Pacific '93 field study. Results indicate that multiple processes may produce layers. The "chimney effect", where pollutants are vented along the heated sidewalls of the valley, is shown to be important, while evidence is also shown for "convective debris" contributing to elevated layer development. These processes are similar to those observed in the Los Angeles Basin. However, the study identified a site-specific process in which a strong elevated layer developed as a result of the propagation of a coastally trapped disturbance (manifested as a low-level marine stratus surge). In addition to distinct elevated layers associated with inversion at the top or above the planetary boundary layer, pollutants (including ozone) are shown to persist overnight in the nocturnal residual layer (RL) that caps the stable boundary layer. In order to investigate the effects of vertical down-mixing on surface ozone concentrations, a transilient turbulence model was applied to vertical profile data for 6 August 1993. After sunrise, this showed significant down-mixing of ozone from the nocturnal RL layer. Furthermore, down-mixing was also shown to contribute to surface concentrations in the early afternoon when the growing mixed layer intercepted the elevated layer created by the coastally trapped disturbance. The mechanisms and structures described show strong similarities to those found in the Los Angeles Basin and suggest that these phenomena likely exist in other polluted coastal environments where they may contribute significantly to the observed ground-level concentrations via vertical mixing processes. © 1997 Elsevier Science Ltd.

Key word index: Ozone, vertical mixing, layers aloft, lidar, air quality.

INTRODUCTION

Distinct polluted layers in the lower troposphere have been shown to be important features of the air pollution distribution of coastal regions, most notably in Southern California (Wakimoto and McElroy, 1986; McElroy and Smith, 1986, 1991, 1993; Lu and Turco, 1994; Ulrickson and Mass, 1990). In the complex coastal terrain of the Los Angeles Basin, interactions between sea breezes, slope flows and convective activity give rise to elevated layers of pollutants which are usually "trapped" within or above elevated inversions. Pollutant concentrations within elevated layers may be several times greater than those within the lower boundary layer (McElroy and Smith, 1993). As such, these structures are of crucial importance as they may contribute significantly to ground-level concentrations through vertical mixing (McElroy and Smith, 1993). This process may partly explain the observed high temporal autocorrelation of daily surface ozone concentrations as pollutants may be stored aloft overnight and mixed to ground the following morning.

Possible mechanisms that explain the development of polluted layers are summarised in McElroy and Smith (1993) and Lu and Torco (1994) and include the following:

(1) *Convective debris* (pollutants) driven into the inversion layer that caps the mixed layer by convective plumes (Edinger, 1963). This may occur as a result of topographically forced convective activity (Wakimoto and McElroy, 1986) or in sea breeze convergence zones associated with particular topographic configurations (Edinger and Helvey, 1961; Ulrickson and Mass, 1990).

(2) Injection of material into inversion layers aloft by slope flows (Edinger, 1963; Wakimoto and McElroy, 1986; Blumenthal *et al.*, 1978; Ulrickson and Mass, 1990). In summer, this slope effect may take the form of a *chimney effect* where pollutants are vented into the "free" atmosphere above ridge level by strong convective activity along heated slopes and then advected back over the basin (Edinger and Helvey, 1961; Edinger *et al.*, 1972; Ulrickson and Mass, 1990).

(3) Undercutting of the existing mixed layer by clean marine air during sea breeze flow regimes (Blumenthal *et al.*, 1978; Edinger and Helvey, 1961; McElroy and Smith, 1993).

Using a two-dimensional mesoscale model to explore these mechanisms in a dynamic context, Lu and Turco (1994) demonstrate that pollutant transport over a mountainous coastal region is strongly controlled by the coastal configuration. In particular, the distance from coast to mountains, together with the height of the local topography, determines the nature of interactions between slope flows and sea breezes and hence the dynamic relationships that give rise to elevated pollutants layers. For example, with coastal mountains close to the coastline, sea breeze and slope flows are closely coupled and hence there is no distinctive sea breeze front. During the afternoon in this case, upslope flow is produced which may detrain polluted air into the inversion layer as a return circulation. An important aspect of Lu and Turco's (1994) study is the recognition of a strong diurnal cycle in the coastal environment with distinct stages that influence pollutant layer genesis.

In addition to the formation of polluted layers associated with inversions as described above for the Los Angeles Basin, pollutants may also persist overnight in a deeper residual layer (RL) that caps the nocturnal stable layer and represents the remnants of the mixed layer from the previous day (Stull, 1989). In this layer, stability is generally neutral and pollutants are effectively decoupled from the surface layer by the strong nocturnal inversion. Structures of this type have been shown to contribute significantly to ground-level concentrations of ozone in the early morning in the Swiss Alps (Neu *et al.*, 1994) and at a lowland rural site in the southeastern U.S.A. (Kleinman *et al.*, 1994).

Broad physiographic similarities between the Los Angeles Basin of Southern California and the Lower Fraser Valley (LFV) of British Columbia (Fig. 1) suggests that elevated layers of pollutants should also be important in the LFV. The deployment of both ground-based and airborne downward-looking lidar, as well as ozonesondes during the Pacific '93 field campaign presented the first opportunity to investigate details of the three-dimensional distribution of ozone in this region. By reference to two consecutive days during Pacific '93, this paper describes elevated layer structures observed and suggests possible mechanisms. It then describes in detail the effects of both an RL and a shallow pollutant layer associated with an inversion on ground-level concentrations.

METHODS

Lidar observations during Pacific '93 are described in Hoff *et al.* (1996). In summary, a 1.064 μm lidar, pointing downward at 8.2° of nadir, was operated from a Convair 580 aircraft. This infrared system has good sensitivity for particles of roughly 1 μm. To guarantee eye safety the aircraft was flown at approximately 4200 m. The lidar flight line used in this analysis is shown in Fig. 1. In addition to the airborne lidar, a ground-based doppler lidar system was operated from the Pitt Meadows Airport (Banta *et al.*, 1996). Backscatter from this infrared lidar (wavelength 10.59 μm) provides information on the concentration and radial velocities of aerosols. With different

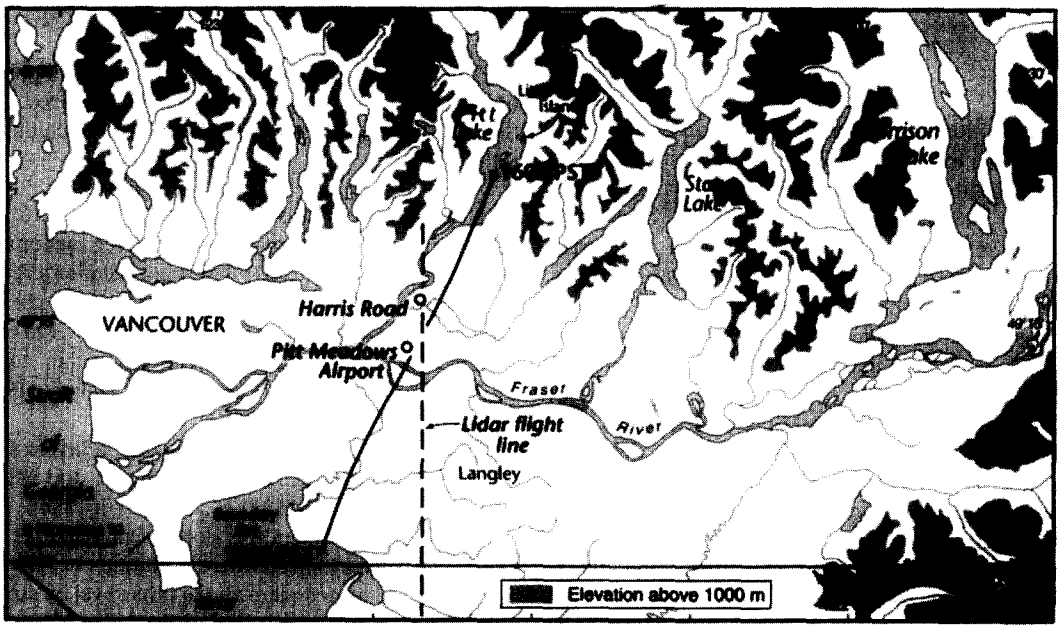

Fig. 1. Map of the Lower Fraser Valley showing sites mentioned in the text, the airborne lidar transect shown in Fig. 3, and the back-trajectory for the afternoon of 6 August.

scanning modes, horizontal representations of the flow or vertical profiles may be determined.

Tethered balloon profiles were obtained at both Harris Road and Little Goose Island on Pitt Lake. Soundings consisted of deployment of an Atmospheric Instrumentation Research Inc. (AIR) Tethersonde (TS-3A-SPH) with Ozonesonde (OZ-3A-T) beneath a 5 m^3 helium-filled balloon. Ascent and descent were controlled by an electric winch with a typical sounding reaching 1000 m AGL and taking approximately 45 min to complete an ascent and descent sequence. Finally, additional sounding data were available from Langley, where Model ECC-5A ozonesondes (together with a meteorological package), were released four times per day during Pacific '93.

Changes in ozone concentrations that occur at a site may be attributed to (a) horizontal advection, (b) vertical mixing, (c) deposition and (d) photochemical production/destruction (Neu *et al.*, 1994). In cases where elevated polluted layers exist or an RL does near the surface, vertical mixing may be an important process by which pollutants from an elevated layer may contribute to the observed concentrations in the mixed layer and at ground level. The effects of vertical mixing of ozone may be particularly important in the period soon after sunrise when the mixed layer is growing, but wind speeds are still light (hence advective effects are small) and photochemical ozone production is still low. In order to investigate the effects of vertical mixing on mixed-layer ozone concentrations on 6 August 1993, a simple transilient turbulence model (Neu *et al.*, 1994; Stull, 1993, 1989) is applied to Tethersonde data from the Harris Road site.

The transilient turbulence approach is a non-local form of turbulence closure in which unknown quantities at one point are parametrized using values of known quantities from many points in the vertical dimension (Stull, 1989). This approach assumes that turbulence in a superposition of eddies, each of which transports entities in a manner analogous to advection. Such a scheme is particularly appropriate to the daytime convective boundary layer where the stability of individual air parcels is not dependent on local lapse rates but on, for example, surface stability conditions. Hence, convective thermals encompassing the entire convective boundary layer typically exist in conditions in which most of the boundary layer is, in a local sense, characterized by neutral stability (Stull, 1989, 1993).

The transilient model used here is semi-empirical and relates a "mixing potential" to differences in meteorological quantities between discretely spaced heights which constitute a vertical column of grid boxes. One grid box can receive contributions (e.g. of ozone) from all others and likewise contribute ozone to all others. The "mixing potential" is expressed as a matrix k_{ij} of all possible exchanges between destination and source grid cells, and is called the transilient matrix. The components of the matrix can be parameterized from either the turbulent kinetic energy (TKE) equation or by a non-local analogy to the Richardson number (Stull, 1993; Neu *et al.*, 1994). The change in concentration C in a grid box in a time step Δt is given by

$$\overline{C_i}(t + \Delta t) = \sum_{j=1}^{N} k_{ij}(t, \Delta t) \cdot \overline{C_j}(t)$$

where C_i is the concentration in box i, k_{ij} is the amount of air transported between boxes i and j, t is the time and N the number of grid boxes. The dimensionless mixing potential is given by

$$k_{ij} = \frac{Y_{ij}}{Y_N} \quad \text{for } i \neq j, \quad k_{ii} = 1 - \sum_{j=1}^{N} k_{ij}$$

where Y_{ij}, based on the TKE equation, is given by

$$Y_{ij} = \frac{\Delta t \cdot T_0}{(\Delta_{ij} z)^2}\left[(\Delta_{ij}\bar{u})^2 + (\Delta_{ij}\bar{v})^2 - \frac{g}{\Theta_v} \cdot \frac{(\Delta_{ij}\Theta_v)(\Delta_{ij} z)}{R_c}\right] - \frac{D_Y \Delta t}{T_0}$$

where z is the height, u and v the horizontal wind speed components, and Θ_v the virtual potential temperature. The empirical parameters used are $T_0 = 10^3$ s, $D_y = 1$, and the critical Richardson number $R_c = 0.21$.

The values required for this scheme are easily obtained from atmospheric profiles, and the method is absolutely stable to numerical implementation. Using the scheme described above, the effect of vertical mixing (neglecting advection and photochemical production) on an initial ozone profile was calculated for 20 m deep vertical grid boxes. Transilient matrices were calculated every 30 s based on interpolated values from hourly vertical meteorological profiles.

METEOROLOGICAL CONTEXT

On the afternoon of 5 August 1993, a strengthening mid-tropospheric ridge over the LFV brought subsidence, clear skies, and warm temperatures. However, at the surface, a low-level surge of marine stratus was propagating northward along the west coast and by 0530 PST on 6 August it had reached the southern LFV. The appearance of the surge at 0400 PST at Langley was marked by southeasterly winds and a moist layer beneath a strong inversion at about 300 m. Such shallow coastally trapped disturbances are relatively common along the North American west coast in summer and generally mark the transition from warm, sunny conditions which are conducive to ozone exceedance in the LFV to cool cloudy conditions with winds from the south (Reason and Steyn, 1990, 1992; Reason and Dunkley, 1993; Mass and Albright, 1987).

Low-level flow patterns in the region showed a switch from southwesterly winds in the western LFV on the afternoon of 5 August to south-to-southeasterly winds that prevailed early on 6 August. The ground-based lidar wind profiles from Pitt Meadows (Fig. 2) show a $\sim$ 1000 m deep surface-based layer of southeasterly winds accompanying the low-level stratus surge and a shift to low-level southerly and then southwesterly winds through to the afternoon of 6 August. Of importance to the discussion that follows is the easterly flow at approximately 700–900 m evident at 0400 PST. This indicates that in the early morning of 6 August there were relatively light winds (2–3 m s^{-1}) out of the LFV at this level, thereby permitting short trajectories that could keep pollutants within the region over the period of a day.

A detailed discussion of spatial and temporal patterns of ozone pollution in the LFV as well as conditions observed during Pacific '93 is provided in Steyn *et al.* (1996). With westerly winds over the city on 5 August and high temperatures, the maximum ground-level ozone concentrations for Pacific '93 were recorded with highest concentrations in the central LFV (83 ppb) and over Pitt Lake (111 ppb). The following day, in the relatively cool marine air associated with the low-level stratus surge, ground-level ozone concentrations reached 52 ppb with highest concentrations along the northern side of

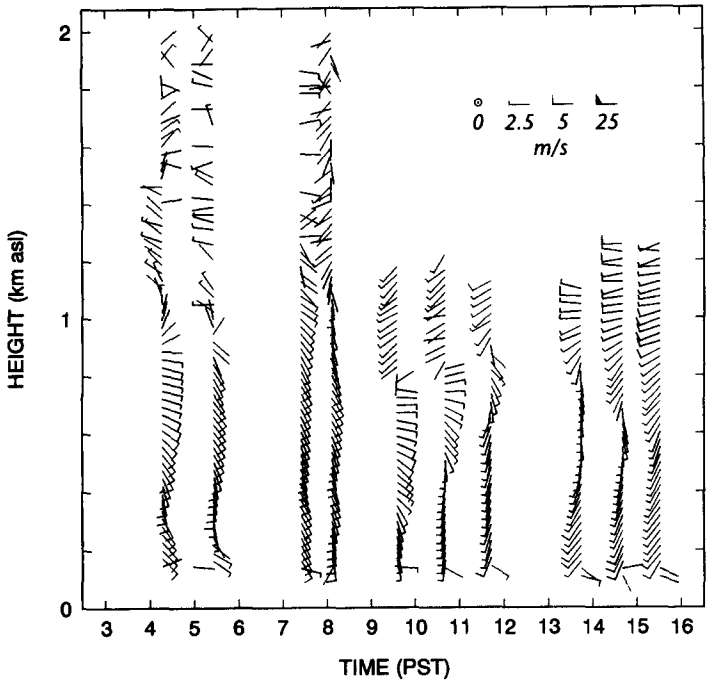

Fig. 2. Profiles of horizontal wind for 6 August 1993, derived from 5° lidar PPI scans at Pitt Meadows Airport.

the LFV in the vicinity of Pitt Meadows. The extent to which advection and vertical down-mixing contributed to this spatial distribution is the focus of the remainder of this paper.

RESULTS

Lidar observations

Lidar images along the north–south track (shown in Fig. 1) for the afternoon of 5 August and morning of 6 August 1993 are shown in Fig. 3. The colours represent backscatter with dark colours (e.g. blues) showing clear air while bright colours (e.g. yellows, reds) represent aerosol laden air. The dark shading at the bottom of the plate is the terrain surface. Important structures evident in these images are labelled.

The afternoon flight on 5 August shows several layer structures, some of which were apparent on more than one day and on multiple flight legs. The top of the mixed layer is clearly defined by the backscatter and shows an increase in elevation from about 500 m in the south to about 800 m adjacent to the mountains along the northern edge of the LFV. Within the mixed layer, the polluted urban plume from Vancouver to the east is clearly apparent (A) as are what appear to be individual plumes of aerosol (B). The latter, which are associated with individual sources such as the trans-Canada highway, appear to be mixed through the full depth of the boundary layer with the plumes having an horizontal scale of similar magnitude to their vertical scale. This is consistent with the scales of thermal convective plumes (Stull, 1988) and raises the possibility that convective activity over the LFV may inject pollutants through the top of the boundary layer via the "convective debris" mechanism. Although this convective mechanism cannot be confirmed by the lidar imagery, the effect of strong convective activity along the heated sidewalls of the valley is unambiguous. A layer of aerosol is shown rising up the heated northern slopes with a plume of material ejecting into the free atmosphere to about 1500 m (C). This is identical to the "chimney effect" observed over San Gabriel mountains in the Los Angeles basin (Wakimoto and McElroy, 1986) and modelled by Ulrickson and Mass (1990). At this level, winds were light ($< 2.5\ m\ s^{-1}$) with a slight northerly component. It is therefore possible that layer (D) evident at 2500 m was also generated by this slope venting mechanism.

Between 1500 m and the top of the mixed layer, relatively weak backscatter with some layering (E) is evident despite winds which were westerly. With no northerly component to the flow at this level it is difficult to attribute this aerosol to material injected into the return flow of slope flows below ridge level as modelled by Lu and Turco (1994). A more likely explanation is that this material is the result of convective activity and/or material which has persisted from the previous day. Evidence for the latter comes from the 0400 PST ozonesonde from Langley, which shows residual ozone concentrations of up to 50 ppb, up to an elevation of 1.5 km (Fig. 4a).

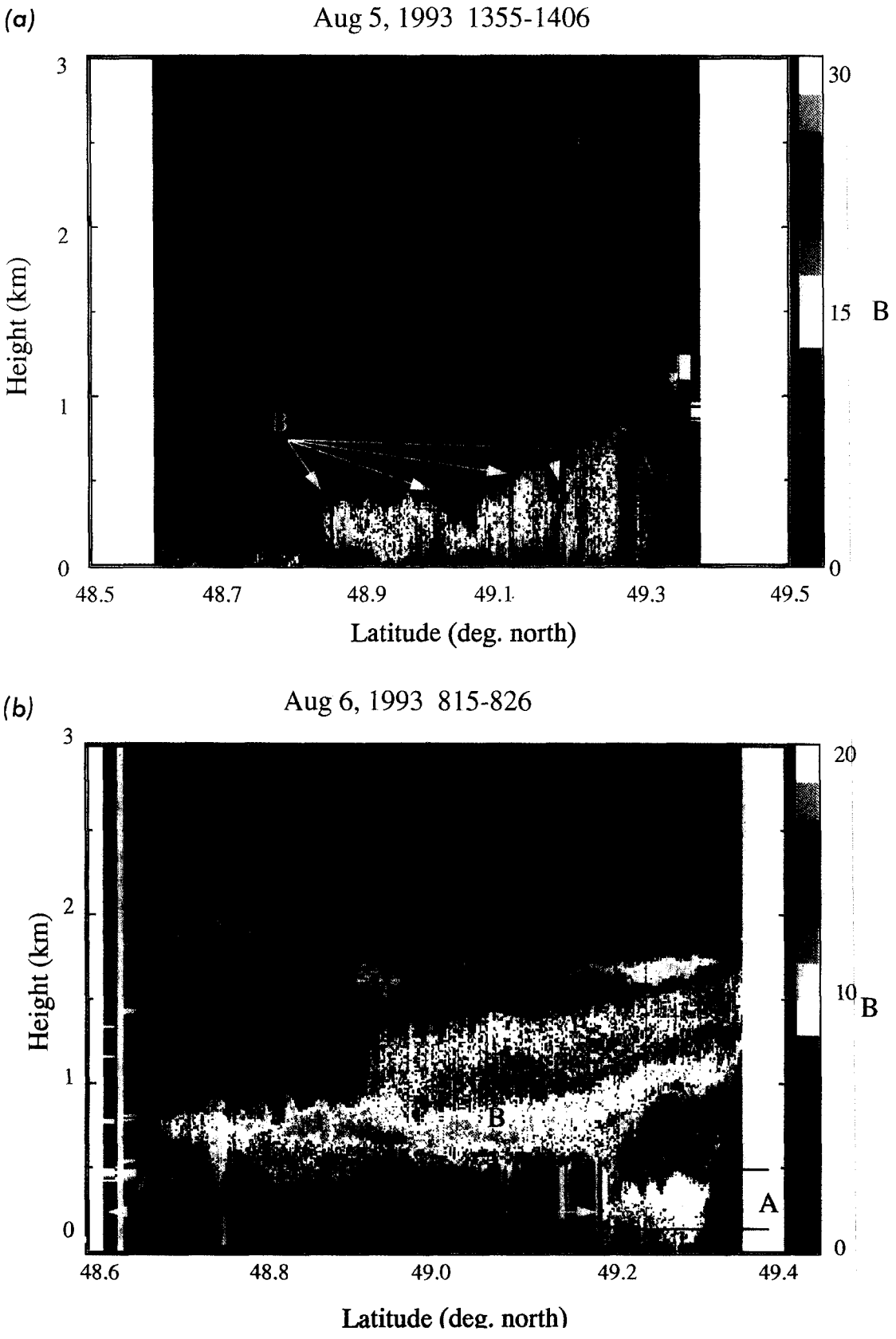

Fig. 3. Aircraft lidar north–south transect showing aerosol backscatter for (a) 5 August, 1355–1406 PST and (b) 6 August, 0815–0826 PST. Prominent features discussed in the text are labelled. The colour scale represents the ratio of total backscatter to that of clear air (Rayleigh).

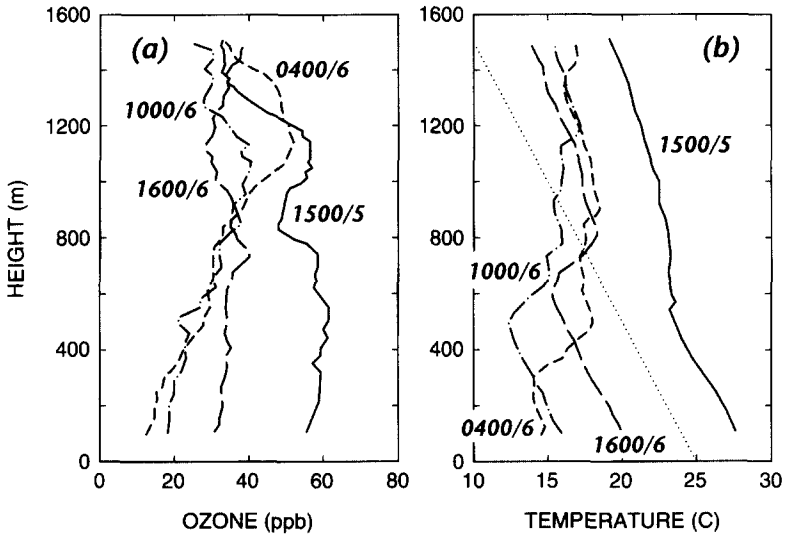

Fig. 4. Vertical profiles of (a) ozone and (b) temperature for 5 and 6 August from Langley.

The lidar flight leg at 0800 PST on 6 August (Fig. 3b) presents a marked contrast to that associated with the strongly convective boundary layer on the previous day (Fig. 3a). The salient feature is what appears to be a well-defined aerosol layer from 300–500 m AGL (A) associated with a strong low-level inversion that was evident at 0400 and 1000 PST at Langley (see Fig. 4). To the south of 49.2° latitude very strong returns from the top of this layer indicate the top of the stratus cloud deck associated with the overnight marine surge. On the basis of observations in Southern California (Blumenthal *et al.*, 1978) and aircraft observations in the LFV (Fig. 5c), a peak in ozone concentrations would be expected to coincide with the layer (A) if it were composed of aerosol. However, ozone profiles from the measurement site at Harris Road at this time show no such low-level ozone peak (Fig. 6). This suggests that the layer to the north of 49.2° latitude represents an extension of the cloud layer and is either hydrated aerosols or a relatively low density of condensing droplets, rather than a heavily polluted layer with anthropogenic origins.

Above the low-level saturated layer, a secondary layer with weak backscatter (B) does appear to be associated with aerosol emanating from upslope flows along the northern side of the LFV. Langley profiles from 0400 and 1000 PST (Fig. 4a) on 6 August do show peaks in ozone concentrations (at around 1100 m). However, the early morning profiles from Harris Road were not high enough to penetrate the layer (B) shown in Fig. 3b. It is possible that light northerly winds which persisted until around 0600 PST overnight at this level (from ground-based lidar profiles) may have transported material in this layer southward over the valley. Whatever the mechanisms operating, it is clear from the lidar images that on the morning of 6 August there were substantial amounts of pollutant that persisted above the surface layer.

Vertical profiles from Langley

The sequence of vertical soundings of ozone and temperature from the measurement site at Langley for the period 5–6 August are shown in Fig. 4 and provide a useful background to the description of the polluted layer observed on 6 August in the vicinity of Harris Road.

On the afternoon of 5 August, near-surface temperatures in the LFV were in excess of 30°C. Highest ground-level ozone concentrations of the observation period were recorded on this day. Profiles at 1500 PST show a weak isothermal layer marking the top of the mixed layer (at approximately 500 m) and an associated ozone peak of 60 ppb near the base of this layer. Ozone concentrations above the mixed layer remained relatively high with a secondary peak in ozone at around 1100 m corresponding to layer (E) in Fig. 3a. The rapid low-level cooling that occurred with the surge of cool marine air into the valley late on 5 August is shrinkingly apparent in the 0400 PST profiles. The temperature profile shows a strong inversion with base at 300 m (temperature increased 4°C over 100 m, the strongest inversion observed during Pacific '93) and shallower inversions at 700, 850 and 1300 m. Within this deep stable layer, ozone concentrations increase with height to a maximum of 51 ppb at 1100 m. At this height, winds in the valley were westerly, suggesting that material in this layer was still being advected up-valley at this time rather than being advected out of the valley by southeasterly flow at the surface. By 1000 PST on 6 August the mixed layer had increased to approximately 500 m in depth and was capped by a stable layer extending to 1200 m, in which several shallow inversions were embedded. Peak ozone concentrations at this time

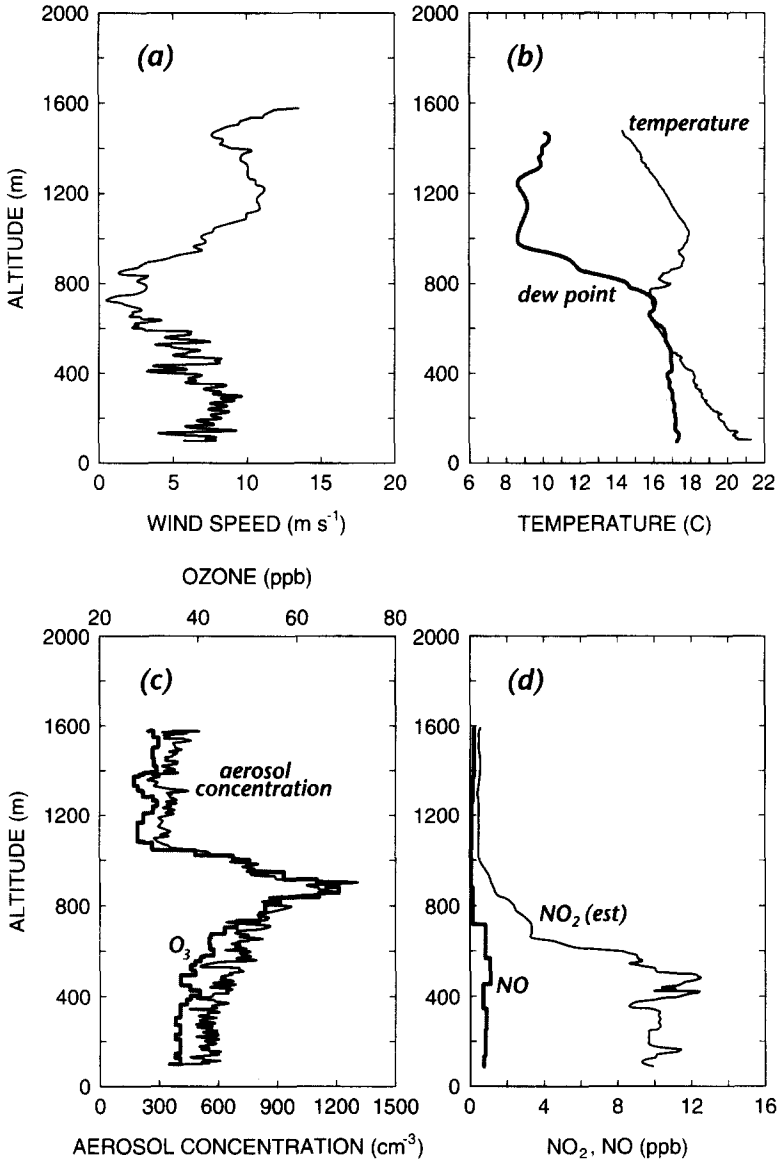

Fig. 5. Aircraft-derived vertical profile over Pitt Meadows for 6 August 1993 (1607–1612 PST) showing (a) wind speed, (b) aerosol and ozone concentrations, (c) temperature and dewpoint and (d) NO and NO_2.

were at 1100 m and were lower than concentrations observed overnight. By later afternoon on 6 August the mixed layer was 600 m deep and capped by a single strong inversion with top near 800 m and in which a minor peak in ozone concentrations was evident. The temperature profile at this time presents a marked contrast to the previous day when only a weak capping inversion was evident at the top of the mixed layer.

Vertical profiles of temperature, wind speed, dew point and atmospheric pollutants obtained by instrumented aircraft spirals over Pitt Meadows on the afternoon of 6 August (Fig. 5) show a well-defined ozone and aerosol layer associated with an inversion extending from 700–1100 m. Peak concentrations of ozone and aerosol occurred at 900 m within the layer and were approximately twice those near the surface. Near the base of the inversion winds were light (2–3 $m\,s^{-1}$) southwesterlies, and despite afternoon heating, the air was near saturation. Low NO and NO_2 concentrations within the layer suggest that the polluted air was chemically aged (Kleinman *et al.*, 1994) and likely originated from photochemical activity the previous day. At Langley at this time (Fig. 4a, b), the vertical profile of temperature was virtually identical to that shown by the aircraft at Pitt Meadows (Fig. 5c). However, ozone concentrations were considerably lower and showed only a slight peak in the concentrations within the inversion capping the top of the mixed layer. This suggests that the

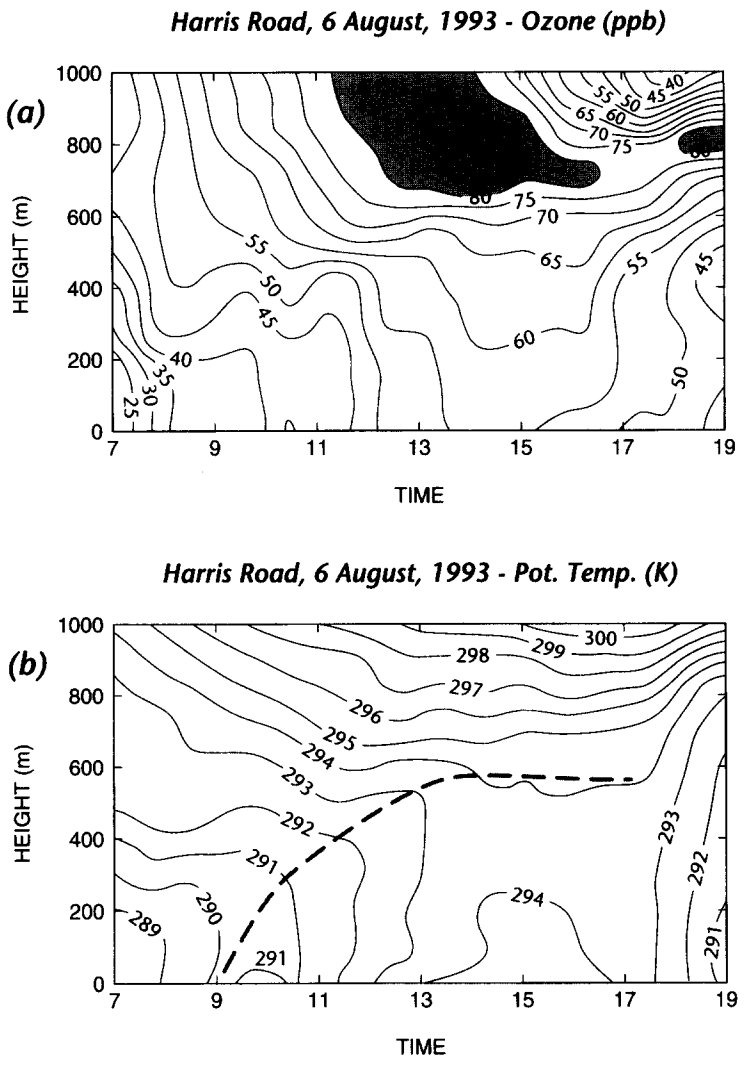

Fig. 6. Time–height plots showing isopleths of (a) ozone concentration and (b) potential temperature based on tethersonde profiles from Harris Road for 6 August 1993. In (b) the growing mixed layer is denoted by a dashed line.

polluted layer evident in the aircraft profile over Pitt Meadows was associated with relatively high concentrations advected from the southwest that did not reach eastward as far as Langley.

Tethered balloon observation from Harris Road

Regular tethered balloon surroundings at Harris Road during daylight hours on 6 August permit a detailed examination of the elevated pollutant layer shown in Fig. 5 and its impact on ozone concentrations in the lower troposphere. The temporal evolution of ozone concentrations and thermal structure in the planetary boundary is shown in Fig. 6. Ozone isopleths and isentropes are based on interpolated values from 22 vertical soundings throughout the day.

Observations early on 6 August show the mixed layer to be about 200 m in depth and capped by an inversion of 2°C over approximately 150 m. Ozone concentrations in the shallow mixed layer were low and increased through the inversion to virtually constant values of around 50 ppb through the top of the sounding. At this time the vertical structure is consistent with a RL with relatively high concentrations overlying the eroding nocturnal inversion below. There is no evidence at this time of the strong inversion with elevated ozone concentrations that was advected over the site later in the morning. This deep residual polluted layer coincides with the layer of backscatter extending from near the surface to about 1000 m AGL shown adjacent to the northern sidewalls of the LFV in Fig. 3b. As the mixed layer continued to grow during the morning in response to surface heating, highest ozone concentrations were maintained within the steadily rising capping inversion and the stable layer above it. Within the stable layer, ozone concentrations continued to increase

throughout the morning and by 1359 PST a distinct peak in concentrations was observed at around 750 m AGL with concentrations reaching 96 ppb. Maximum concentrations at ground level at the Harris Road site were approximately 55 ppb. By later in the afternoon, the stable layer incorporating the capping inversion and isothermal layer above it had become a single inversion that included the distinct and relatively shallow polluted layer shown by ozone isopleths and aircraft profiles (Fig. 5).

In order to determine whether increasing concentrations in the elevated layer that was apparent from late morning over Harris Road can be attributed to advection or photochemical production, examination of the meteorology of the layer is necessary. Figure 7 shows the mean maximum ozone concentrations in tethersonde profiles, the height of their occurrence and the accompanying mean wind speeds and directions at the level of the maximum. All means are based on the nine values centred on the peak ozone concentration (equivalent to an average over a depth of approximately 80 m). Ozone concentrations in excess of 80 ppb in the profiles were observed to occur around midday and were associated with a veering of wind direction from the predominant easterly out of the valley that prevailed in the morning to southeasterly and then southwesterly winds in late afternoon. With southwesterly flow prevailing in the afternoon in the elevated stable layer, ozone concentrations remained high and relatively constant through

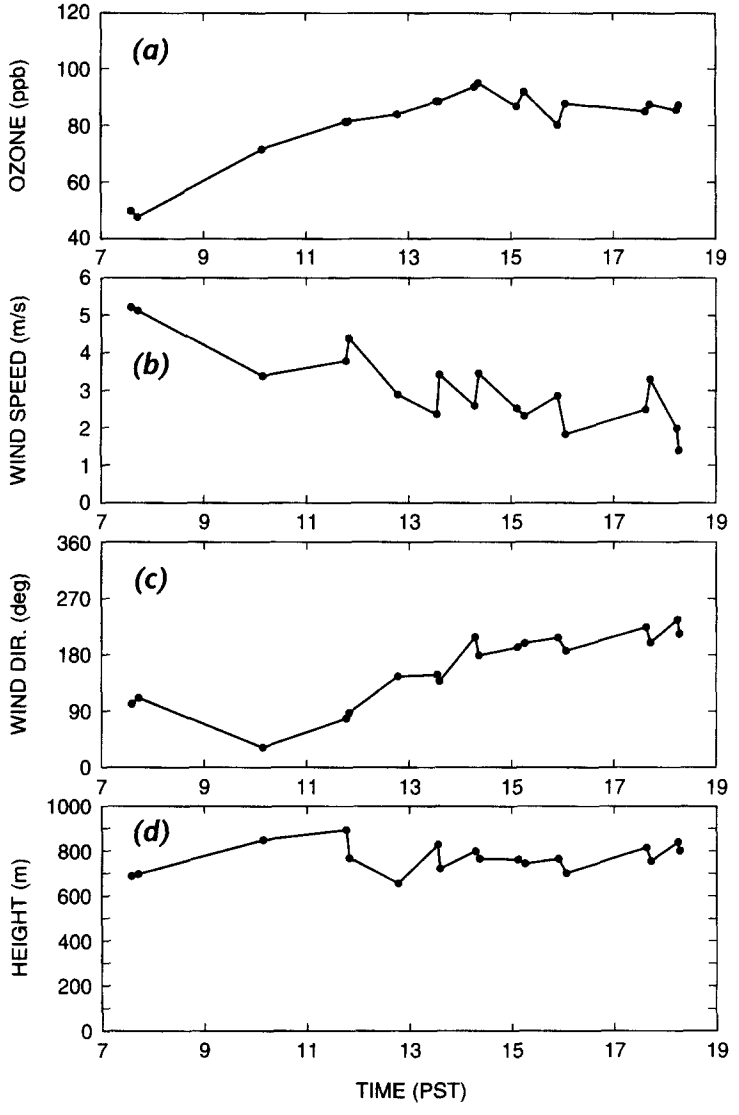

Fig. 7. Temperature evolution of the elevated layer observed on 6 August 1993 at Harris Road showing (a) ozone concentrations, (b) wind speed, (c) wind direction and (d) height. Values in a, b, and c are based on averages of the 9 values (approximately 80 m depth) around the peak ozone concentration observed in the vertical profile.

the late afternoon. If ozone production were dominating changes in ozone concentrations observed over Harris Road, a decrease in concentrations would be expected to occur after solar noon as photochemical activity declined. Persistence of high ozone concentrations within the layer, together with low temperatures (17°C) and low NO_x concentrations (indicative of a chemically aged air mass), all point to advection as the dominant process influencing changes in ozone concentrations over Harris Road on 6 August.

The exact origin of the pollutant layer shown in Figs 5 and 6 is difficult to determine on the basis of limited spatial observations. However, from observations discussed above, a likely explanation is that the layer originated from pollutants injected above the weak inversion on the previous day (most likely in the central LFV where highest concentrations existed). Available wind observations are consistent with a trajectory that advected the pollutant layer first eastward up the LFV and then overnight back out of the valley in the easterly winds observed in the layer around 800 m. On 6 August, the veering from easterly through to southwesterly (Fig. 2) would permit a trajectory that carried pollutants toward Pitt Meadows from the southwest, possibly from as far away as Boundary Bay or Georgia Strait. A simple back-trajectory (based on observed surface winds only) for this case is plotted on Fig. 1, and indicates that winds during the afternoon were sufficient to transport pollutants over the distances suggested here.

Impact of vertical mixing on ozone concentrations on 6 August

On 6 August, observations at Harris Road show a nocturnal RL in the early morning. Near midday, a distinct elevated layer associated with a strong inversion was then advected over the site. For both these layer structures, a transilient turbulent model (Stull, 1993; Neu *et al.*, 1994) is an appropriate tool to investigate the role of down-mixing on mixed-layer concentrations as it incorporates the effects of non-local mixing that typically characterise a convective boundary layer.

Neu *et al.* (1994) and Kleinman *et al.* (1994) describe a process by which pollutants can be entrained into the growing mixed layer from a nocturnal RL. In this case, the growing mixed layer in the hours after sunrise erodes the somewhat deeper nocturnal RL which is usually characterised by neutral stability and pollutants trapped within the RL are mixed to the surface.

Model results from the application of the transilient model to the early morning case are shown in Fig. 8a. The 0720 PST profile used to initialise the model is shown with the early afternoon profiles at the site. The morning profile reveals a deep RL with concentrations reaching 50 ppb in an adiabatic layer above 500 m. Below this concentrations decrease toward the surface due to the effects of surface deposition in the stable nocturnal boundary layer. The predicted afternoon profile based purely on vertical mixing processes and assuming no advection, deposition or photochemical production, is denoted by the solid line. At the surface, the change in concentration due to vertical mixing alone is significant and represents approximately one half of the observed total change in ozone concentrations. However, above about 300 m, vertical mixing actually reduces concentrations from those at the initial time (pollutants are mixed downward to nearer the surface resulting in a net loss from mixing in the layer above 300 m). The large change in concentrations from the morning to afternoon (i.e. the difference between the modelled and observed 1300 PST profiles) can be attributed primarily to advection as photochemical production was assumed to be low on this day due to relatively low temperatures. Finally, this estimate of down-mixing is conservative as an early morning profile (immediately after sunrise) was not available to initialise the model and thereby capture the steep increase in surface ozone concentrations observed at this time (Fig. 8c).

The impact of vertical mixing from the elevated layer that appeared over the Harris Road site in late morning is shown in Fig. 8b. In this case the transilient model is used to predict the effects of mixing of an initial profile at 1200 PST. The modelled profile at 1500 PST suggests that a substantial portion of the elevated layer was mixed downward into the boundary layer, thereby contributing significantly to the increase in concentrations observed at the surface in the period 1200–1500 PST. As in the early morning case, the difference between the modelled and observed profiles at 1500 PST can be attributed primarily to advection.

Although constrained by the data available for analysis, and the neglect of both photochemical and advective processes, the simple transilient model identifies two periods (after sunrise, and early afternoon) on 6 August when vertical down-mixing may have contributed significantly to observed ground-level concentrations. This provides a rational basis for interpretation of the surface ozone signal observed at Harris Road on 6 August (Fig. 8c). Ozone concentrations were observed to rise sharply after sunrise, especially from 0415 to 0600 PST when concentrations increased at 9.5 ppb h^{-1}. This increase may be attributed to vertical down-mixing from the nocturnal RL. Thereafter, the increase was only 3 ppb h^{-1}. From midday, the rate of change of ozone again increased (5.0 ppb h^{-1} from 1200–1545 PST), coincident with the advection of the elevated layer over the Harris Road site. Both increases in the rate of change of ozone are consistent with the observations of layer structures at these times and the down-mixing shown by the transilient model. Worth noting is the lack of a similar increase in ozone concentrations within the elevated layer during 1200–1600 PST period (Fig. 7a). This suggests that advection was not the primary cause of the increase in surface ozone concentrations observed at Harris Road at this time. Finally, model

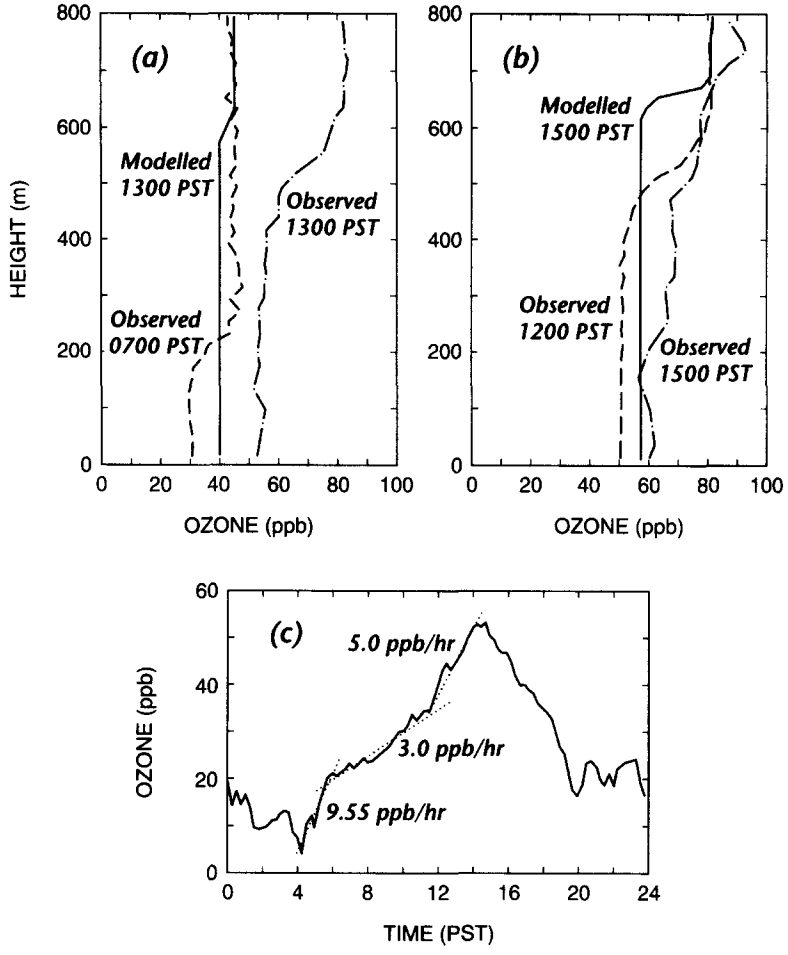

Fig. 8. The modelled effect of vertical down-mixing on boundary layer ozone concentrations at Harris Road based on initial profiles at (a) 0700 PST and (b) 1200 PST. Ground-level ozone concentration observed at Harris Road with observed rates of change are shown in (c).

results together with observed rates of change of ozone concentrations at Harris Road suggest that the early morning down-mixing may have a greater impact on surface concentrations than later in the day when the mixed layer is much deeper and pollutants mixed downward are diluted over a much greater depth.

DISCUSSION AND CONCLUSIONS

Results from two days show elevated layers to be an important component of the air pollution meteorology of the LFV and indicate that multiple processes may contribute to layer development in the LFV context. The mechanisms and structures described show strong similarities to those found in the Los Angeles Basin (e.g. Lu and Turco, 1994) and suggest that similar features will exist in other polluted coastal environments. The elevated ozone layer that developed on 6 August along the northern edge of the valley appears to be a site specific feature that has not been documented elsewhere. In this case, a particular sequence of events appeared crucial, notably:

(a) high ozone concentrations and strong convective activity the previous day left a residual polluted layer above the daytime mixed layer;

(b) nocturnal undercutting by a northward propagating coastally trapped disturbance produced a strongly stable layer effectively trapping the residual pollutant layer;

(c) relatively light, variable winds permitted the layer to persist within the valley for 12–24 h.

A simple transilient turbulence model suggests that down-mixing from the nocturnal residual pollutant layer present over the northern portion of the LFV in early morning contributed to about one half of the observed increase in surface ozone concentrations on 6 August. Both Neu *et al.* (1994) and Kleinman (1994), in quite different environments, also report that on

high ozone days about one half of the early morning increase in ground-level ozone could be attributed to down-mixing from aloft. The transilient model also indicates down-mixing associated with the elevated layer that was advected over the northern side of the LFV in the early afternoon. This phenomenon is similar to that described by McElroy and Smith (1993) in the Los Angeles Basin. Further work is required to investigate the effect of down-mixing of chemically aged air from an elevated layer (ozone rich but NO_x deficient) on the photochemistry of the boundary layer.

In conclusion, the interplay of convective activity and mesoscale circulations in the complex coastal terrain of the LFV gives rise to an air pollution meteorology in which elevated layers are commonplace. The mechanisms that produce these layers appear similar to those observed in Southern California with the notable exception of the role played by the coastally trapped disturbance in producing a layer at the end of the Pacific '93 field study. Such disturbances often signal the end of summertime pollutant episodes in the LFV and therefore the type of layer evident on 6 August may occur relatively frequently. Certainly there is considerable scope for further research to investigate the frequency, characteristics and formative mechanisms of elevated layers in the region. Finally, in the cases examined here, the persistence of a polluted layer from the previous day, subsequent vertical down-mixing of pollutants and the associated complex horizontal trajectories together present significant challenges for numerical modellers. These challenges must be met in order to achieve accurate simulations that are suitable for the determination of appropriate abatement strategies for the region.

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