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REPORT

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OZONE AND METEOROLOGICAL PROFILES IN THE LOWER FRASER VALLEY OF BRITISH COLUMBIA

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For several weeks in the summers of 1992 and 1993 balloons carrying meteorological and ozonesondes were released in the Lower Fraser Valley region of British Columbia when ground-level ozone concentrations were elevated. The 1992 program was a precursor to the more intensive field program, Pacific 93, conducted from July 15th to August 12th, 1993.

At the Clearbrook site in 1992 the vertical profiles indicate ozone forming near the ground, and being transported up the valley by the sea breeze, is trapped under a temperature inversion less than one kilometre above the surface. Ozone concentrations within the boundary layer increase rapidly during the day then decrease during the evening and overnight. Some of the ozone mixes into the free tropopause during the day causing a general increase in ozone concentration above the boundary layer during the episode.

Introduction

In the lower troposphere ozone occurs naturally and also as a result of man-made activity. Stratospheric ozone may intrude downwards into the troposphere or natural volatile organic compounds (VOCs) may combine with oxides of nitrogen (NOx) in sunlight to produce ozone. Ozone levels reached during these natural processes are considered the background ozone concentration. Ozone can also form in complex reactions of anthropogenic NOx, VOCs and, from these sources, ozone is considered a form of pollution. Elevated levels of this pollution have been shown in well documented studies to produce adverse effects on the health of man, animals and vegetation making ozone a serious environmental problem.

Ozone formation associated with large urban areas was first identified in the 1940s in the Los Angeles basin.[1] Chemical theories have been developed to explain the photochemical formation of ozone in the boundary layer or free troposphere from precursor pollutants emitted at ground level. The formation of ozone is fastest when solar radiation is strongest and temperature is highest. The most important factors are the concentration of NOx and temperature, this combination of factors results in distinct seasonal and diurnal changes in ozone concentration.

The formation of ozone is also very dependent on meteorological conditions. High pressure systems produce high temperatures, light synoptic scale winds and subsidence aloft. High temperatures and sunshine are necessary for ozone production. Subsidence aloft causes a temperature inversion that traps the ozone near the ground. The light winds with the sea breeze advect precursor pollutants and ozone to areas downwind of the primary pollutant source.

In 1988 the Canadian Council of Ministers of the Environment (CCME) identified increases in the concentration of ground-level ozone as the primary air quality problem in Canada.[2] The Lower Fraser Valley of British Columbia was targeted as one of three non-attainment areas in Canada where ozone concentration exceeded the maximum acceptable air quality objective of 82 ppb.[3] The CCME Management Plan for Nitrogen Oxides and Volatile Organic Compounds, Phase I (November 1990) is a plan to reduce emission of ozone forming pollutants. To successfully reduce these pollutants, much more

needs to be known about the distribution of ozone at the surface and aloft downwind of urban areas. Until now there has been little information on the typical ozone profile in the Fraser Valley from the ground level to about 12 km at different times of the day and during different weather conditions. It was not known with any certainty the depth and variability of the ozone concentration near the ground.

Project Equipment and Description

From July 31st to August 25th, 1992 balloons carrying meteorological and ozonesondes were released in the Lower Fraser Valley of British Columbia. The sonde releases were a precursor to the more intensive field program, Pacific 93. Free ascent balloon soundings were chosen as they have less restrictions for release and can attain a much high altitude.

It was decided that when an episode of elevated ground-level ozone was expected balloons carrying the meteorological and ozone sondes would be launched five times a day at 5 am, 11 am, 2 pm, 5 pm and 8 pm Pacific Daylight Time.[4] All times in this report are in Pacific Daylight Time (GMT + 7 hrs) and all heights are measured from above the ground (AGL).

The VIZ W-9000 Meteorological Processing System was used for this study. This system is PC based, using a 386DX-33 computer to process the meteorological and ozone data received from the sonde. The VIZ model 1543-523 Mark II meteorological sonde with an ECC-5A interface card is used for the ozonesonde flights. Meteorological and ozone data is transmitted at just over one second intervals from the balloon rising at 150-200 m/min. This data frequency provides excellent height resolution. The sonde used a LORAN receiver to determine its position. For this project balloons were only tracked to about 12 kilometre in altitude.

The ozonesonde, model ECC-5A, is manufactured by Science Pump Co. of Camden, N.J.. The ozonesonde uses a constant volume pump to circulate ambient air through two cells containing dilute potassium iodide (KI) and potassium bromide (KBr) solutions. Within each cell is a platinum grid, one a cathode, the other an anode, linked together by means of an ion bridge. The presence of ozone in the air generates a current proportional to the concentration of ozone present in the ambient air. This current is incorporated in the radiosonde transmission. At the ground receiver, the signal is translated into a partial pressure measurement in nanobars.

The partial pressure measurements are later reconverted into the units "parts per billion" (ppb). The conversion of the partial pressure in nanobars (nb) to parts per billion (ppb) was accomplished by taking the ratio of partial pressure to the atmospheric pressure in millibars (mb) at the measurement level times 1000 or

$$\frac{\text{(partial pressure)}}{\text{(atmospheric pressure)}} * 1000 = \text{ppb's}$$

The ozonesonde interface cards are calibrated electronically according to VIZ procedures. Prior to each flight the ozonesonde is conditioned as described in the N.O.A.A. Technical Memorandum ERL-ARL-149.[5] The sonde conditioning commences 3-7 days before the flights. The sonde cells are injected with the KI and KBr solutions, conditioned with ozone and left to stabilize. Twelve hours before flight, the chemicals in the sonde cells are changed and the cells re-conditioned with ozone. One hour prior to release, the sonde is again conditioned with ozone.

Site Description

The choice of sites for releasing ozonesondes was limited by several requirements. The site had to be in the downwind portion of the urban pollution plume that had historically high ozone concentrations and also exhibit a return circulation created by a sea breeze. A rural setting was desired

away from local anthropogenic sources of compounds that would react with ozone. The elevation of the site had to be representative of the surrounding terrain so the sondes would ascend through the full depth of the plume.

In the summer of 1992 the site chosen was the Agriculture Canada Agassiz Substation at 510 Clearbrook Rd. located 4 km south of Clearbrook at 49° 00' 40" N 122° 20' W. This site is approximately 50 acres of cultivated plots with a ring of tall trees around the edge and a house/office and machine shed near the southwest corner. Located 2 km to the northwest is the Abbotsford Airport, the site of a primary meteorological station and where a Greater Vancouver Regional District (GVRD) ozone monitor is in operation. The surrounding area from east to southwest is a mix of berry, chicken and dairy farms. The site lies in the centre of the Fraser Valley at an elevation of 60 m, typical of the surrounding area. A "bulls-eye" of high ozone concentration has been observed in the past in the Clearbrook/Abbotsford area. The airspace over the Clearbrook site is in the Abbotsford Airport Positive Control Zone. Approval to release atmospheric research balloons was gained from Transport Canada and a NOTAM issued. This approval was canceled Aug. 7-10 during the Abbotsford International Airshow.

Results and Discussion

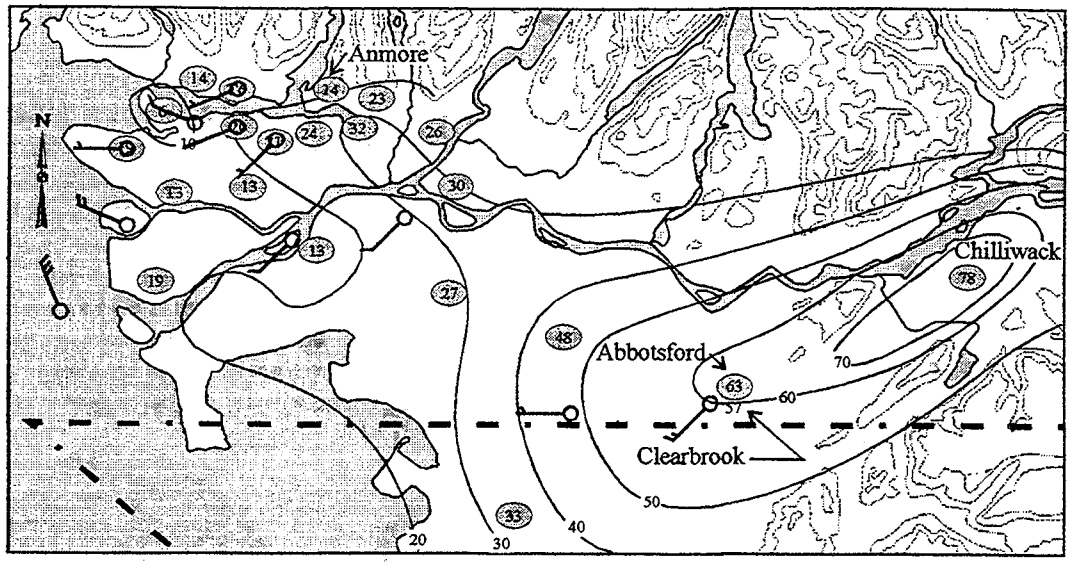
One definition of an ozone "episode" is when at least one station in a region reports three or more consecutive one hour average ozone values greater than 82 ppb[6], however, elevated ground level ozone concentrations are called episodes in this report. During the 1992 summer project, two episodes of elevated ground-level ozone concentration occurred.

An episode occurred at the beginning of the 1992 study on July 30th, one day prior to the instrumentation setup being complete. Ozone concentrations were beginning to subside by July 31st when three vertical profiles were obtained. On July 30th, an hourly mean ozone concentration of 101 ppb was recorded at the Chilliwack Works Yard. By the next day ozone concentrations only reached 73 ppb at Anmore just north of Burrard Inlet.

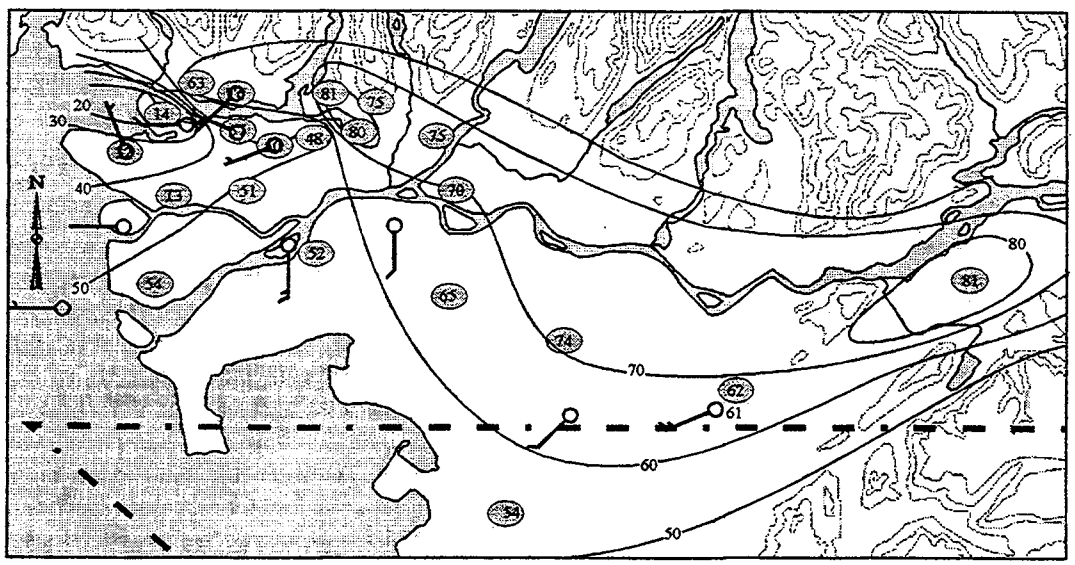
The second episode in 1992 began building on August 11th, the highest ozone levels occurred in the eastern and central valley. Chilliwack Works Yard and Downtown Abbotsford had maximum one hour concentrations in the mid to upper seventies. By August 12th, maximum readings remained high at Chilliwack and climbed even more in the Abbotsford and Langley areas to be in the upper seventies also. On August 13th the area of high ground level ozone became more widespread. Both Anmore and Chilliwack reported maximum concentrations of 81 ppb with most stations in the Fraser Valley recording values in the seventies. By the next day the weather pattern had changed and ozone concentrations in the entire valley did not reach above the mid forties. Figure 1 shows surface ozone data and wind data from stations operated by the B.C. Ministry of the Environment, the Greater Vancouver Regional District, the FCC for Custer, Washington and from a monitor operated by the Measurement and Analysis Division (ARQM) of Environment Canada. The ARQM ozone analyzer was co-located with the ozonesonde release site.

Five ozonesondes were released each day at Clearbrook on August 12th and 13th, and the profiles produced show the distinct diural pattern of ozone concentration above the surface. Full meteorological data is also available for the Lower Fraser Valley during this period. The 12th meets most of the meteorological prerequisites for high ozone concentrations, the 13th is the last day of the episode and certain changes in the meteorology can be seen that announce its end and result in a redistribution of the vertical ozone concentration. This two day period will be assumed to be representative of a typical episode of elevated ozone in the Lower Fraser Valley and will be looked at in more detail.

Persistent ozone episodes in the Lower Fraser Valley occur during specific synoptic and mesoscale meteorological conditions. The highest ozone concentrations occur under a stationary high



Ozone concentration contours (ppb) 5 p.m. August 12, 1992.



Ozone concentration contours (ppb) 5 p.m. August 13, 1992.

Values at Stations = Average Hourly Ozone Concentration (ppb)
Ozone Concentration Contour Interval = 10 ppb
Height Contour Interval = 300 metres
Windspeed in kmh

0 10 20 km

Figure 1. Ozone concentration contours (ppb) for 5 p.m. PDT August 12th and 13th, 1992.

pressure centre where pressure gradients are weak and where solar radiation and temperature is high. With these conditions the low wind speeds and subsidence aloft create a stagnant air mass.

On August 12th an upper ridge of high pressure extended in a north/south line through the southern interior of the province. The thickness ridge in the same orientation lagged slightly and was over the Lower Mainland. The upper ridge remained strong through the day as it edged slightly eastward. A surface area of high pressure was established east of the Rockies. A thermal trough of low pressure, extending up the Oregon and Washington coast from northern California had reached the south end of Vancouver Island. A small thermal low that, in the morning, had developed on the southern Washington coast reformed over the Juan de Fuca Strait late in the afternoon.

By the morning of the 13th the slow moving upper ridge began depressing over the south coast as a weak disturbance moved through from the southwest in the upper flow. By late afternoon the ridge rebounded over the area as the disturbance moved eastward toward Alberta. The surface high remained west of the Rockies. The thermal trough of low pressure steadily moved inland to lie in the southern interior by late afternoon. This change in the surface pressure pattern allowed a surge of cooler Pacific air to push out the photochemically aged air.

Ozone concentration in the boundary layer and evidence of a sea breeze

Early morning. The early morning meteorological profile at 5 a.m. is available both days, unfortunately, the lowest 1000 m of the ozone profile is missing on the 12th. At 5 a.m. the surface ozone readings are 1 ppb on both days. Ozone near the surface has diminished overnight by chemical reactions and deposition to the surface. Just above the surface ozone concentrations rise steeply to 30 ppb at the top of the nocturnal inversion.

The winds at the surface are calm, but in the middle of the stable layer the winds blow from the NE-E at approximately 15 knots both mornings.

Late morning. By late morning (11 a.m.) convection is beginning to homogenize the ozone distribution between the ground and the base of the elevated inversion (former nocturnal inversion). Some ozone production is taking place as temperatures near the surface climb to be near 25° C. Ozone concentrations at the surface both days are now only 4-5 ppb less than those at the base of the elevated inversion. Above the inversion ozone values continue to increase steadily. (Surface ozone at 11 a.m.: August 12 = 18 ppb; August 13 = 20 ppb.)

Some differences are beginning to appear in the surface wind pattern on these two mornings. On the 12th the surface winds are still from the northeast with peak wind speeds of 16 kts in the elevated inversion. On the 13th surface winds are light southwesterly, the thermal trough is moving inland to reform east of the Coast Mountains changing the surface pressure gradient. Overhead, winds gently swing through north to blow briefly from the east before shifting back to blow from the SSW above the inversion. The synoptic pattern on the 13th will not allow a true reversing onshore/offshore sea breeze pattern to develop.

Monthly sea breeze statistics over a ten year period indicate the average time of onset was 12 p.m. at the Abbotsford Airport with a duration of 8 hours. The mean surface wind before onset, during this period, was from 040° (NE) at 2 kts (3.7 kmh) and during the sea breeze mean winds were from 230° (SW) at 6 kts (11.1 kmh).[7]

Early afternoon. Ozone concentrations are increasing rapidly both days with ozone formation and advection playing a larger role. Convective mixing is keeping the ozone in the layer beneath the elevated inversion (near 650 m AGL) well mixed with concentrations at the surface and beneath the

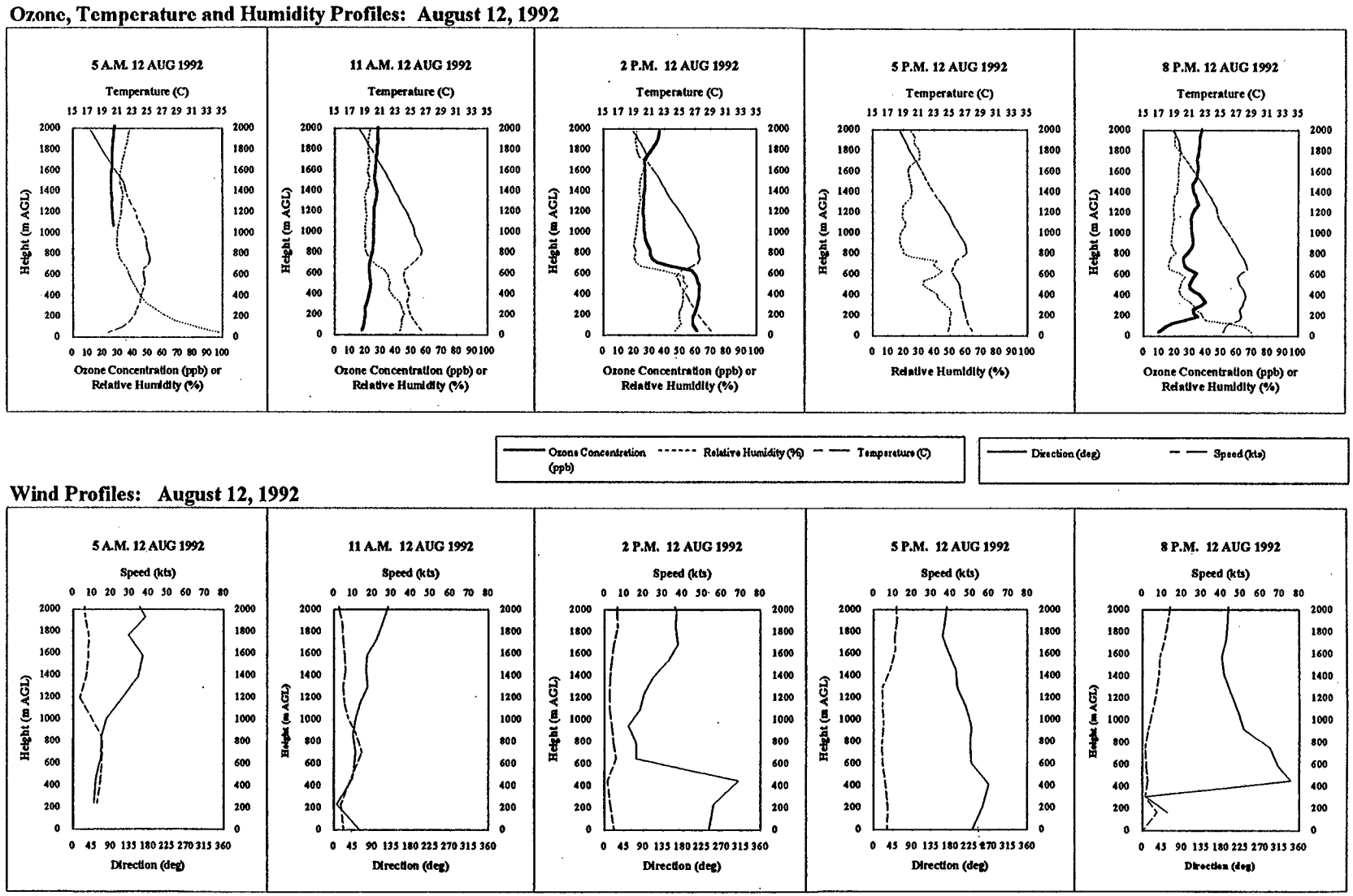


Figure 2. Ozone, temperature, humidity and wind profiles for Clearbrook, B.C.: August 12, 1992

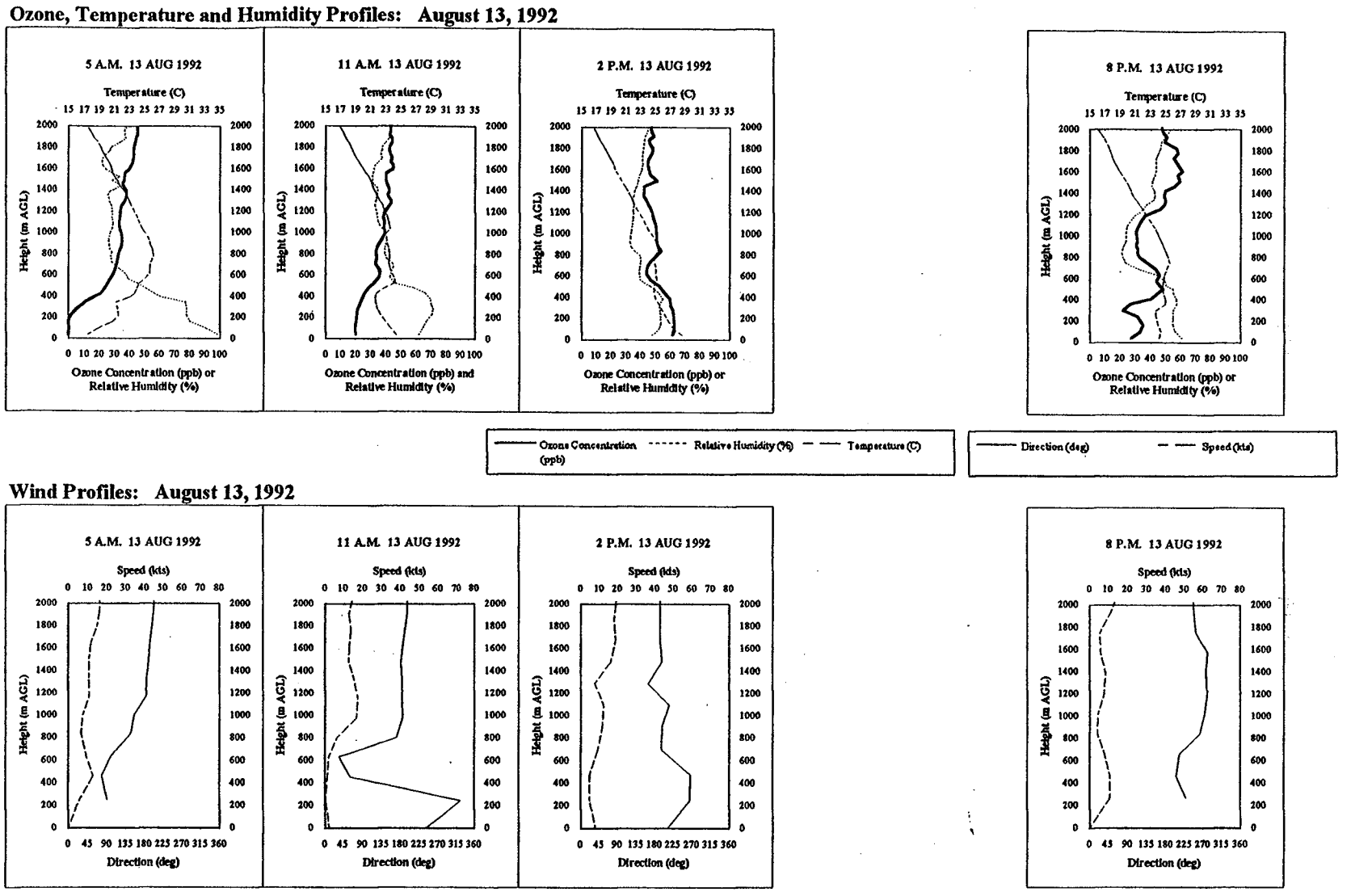


Figure 3. Ozone, temperature, humidity and wind profiles for Clearbrook, B.C.: August 13, 1992.

inversion varying only by a few ppb at most. (Surface ozone 2 p.m.: August 12 = 60 ppb; August 13 = 56 ppb.)

The wind profiles in the boundary layer on the 12th and 13th continue to differ from each other. The surface winds are from the southwest both days, however, on the 12th the winds aloft swing through NW to ENE by the top of the inversion. This is evidence of a sea breeze return circulation, one of the necessary conditions for an ozone event to occur. On the 13th the southwesterly surface winds shift to the south then back to the southwest with speed steadily increasing off the surface. There is little evidence of a return circulation.

Late afternoon. The 5 p.m. flight on the 12th produced a meteorological profile only and the 5 p.m. flight on the 13th failed completely. On the 12th there is some evidence of a sea breeze. Surface winds remain southwesterly and shift to the west to be 7-8 knots in the middle of the boundary layer. In the subsiding layer above the boundary layer the winds shift through south to briefly blow from the southeast. This may be the return flow which is advecting NE in the upper flow or the return flow may be so weak as to be difficult to see. (Surface ozone 5 p.m: August 12 = 57 ppb; August 13 = 60 ppb.)

Evening. Surface ozone concentrations are falling as the ozone deposits to the surface or reacts with other substances near the ground. Surface temperatures are falling and a surface inversion is beginning to from. Smaller inversion layers are forming beneath the weak elevated inversion the persisted all day, the air is becoming more stable and stratified. The ozone profile is becoming less uniform as photochemical reactions have ceased and the ozone is dimishing. On the 13th a minimum of 22 ppb of ozone at 300m is in a layer where south-southwest winds are blowing at 11 knots. This structure indicates the possible presence of thin layers from different upwind sources overlying each other that, in this case, may be carrying ozone reactive substances. (Surface ozone 8 p.m.: August 12 = 20 ppb; August 13 = 20 ppb.)

At 8 p.m.on both days the surface winds are calm. On the 12th the sea breeze has ended within the previous hour and within the stratified layers beneath the old inversion NE winds to 8 knots have developed. Near the top of the inversion the winds gradually back to become light southwesterly. Winds on the 13th, above the surface, blow from the SW at 10 knots then briefly shift to west before returning to blow from the southwest quadrant above the inversion.

Ozone concentration the lower troposphere above the mixed layer

The concentration and distribution of ozone in the boundary layer is of primary interest in studies of smog formation. It is also of interest to see how the ozone concentration above the boundary layer varied as time and meteorological conditions change since clouds play an important part in the vertical distribution of ozone.[8] During August 12-13 ozone concentrations increased steadily in the airmass just above the boundary layer (see figure 4). This nearly linear increase with time in the layer 1000 to 2700 m can clearly be seen in figure 5. The rates that the ozone values are increasing are similar for both days despite the lack of a capping subsidence inversion on the 13th. On the 12th from 5 am to 8 pm the average concentration increases by 6.9 ppb (from 28.6 to 35.4 ppb), during the same period at the same level on the 13th the concentration increases by 7.2 ppb (from 42.5 to 49.7 ppb). In the 39 hour period that ozonesondes were released average concentrations increased from 28.6 ppb to 49.7 ppb in the airmass above the boundary layer.

Under areas of high pressure, air slowly sinks, compresses and warms. If the sinking rate is fast enough, subsidence inversions will form. These inversions act as a cap to vertical motion in the atmosphere through which air parcels have difficulty in passing. Subsidence is a necessity for widespread and prolonged ozone episodes. The air over the Fraser Valley had been subsiding and warming for several days prior to the ozone episode. On August 12, above the boundary layer to about 4000 m,

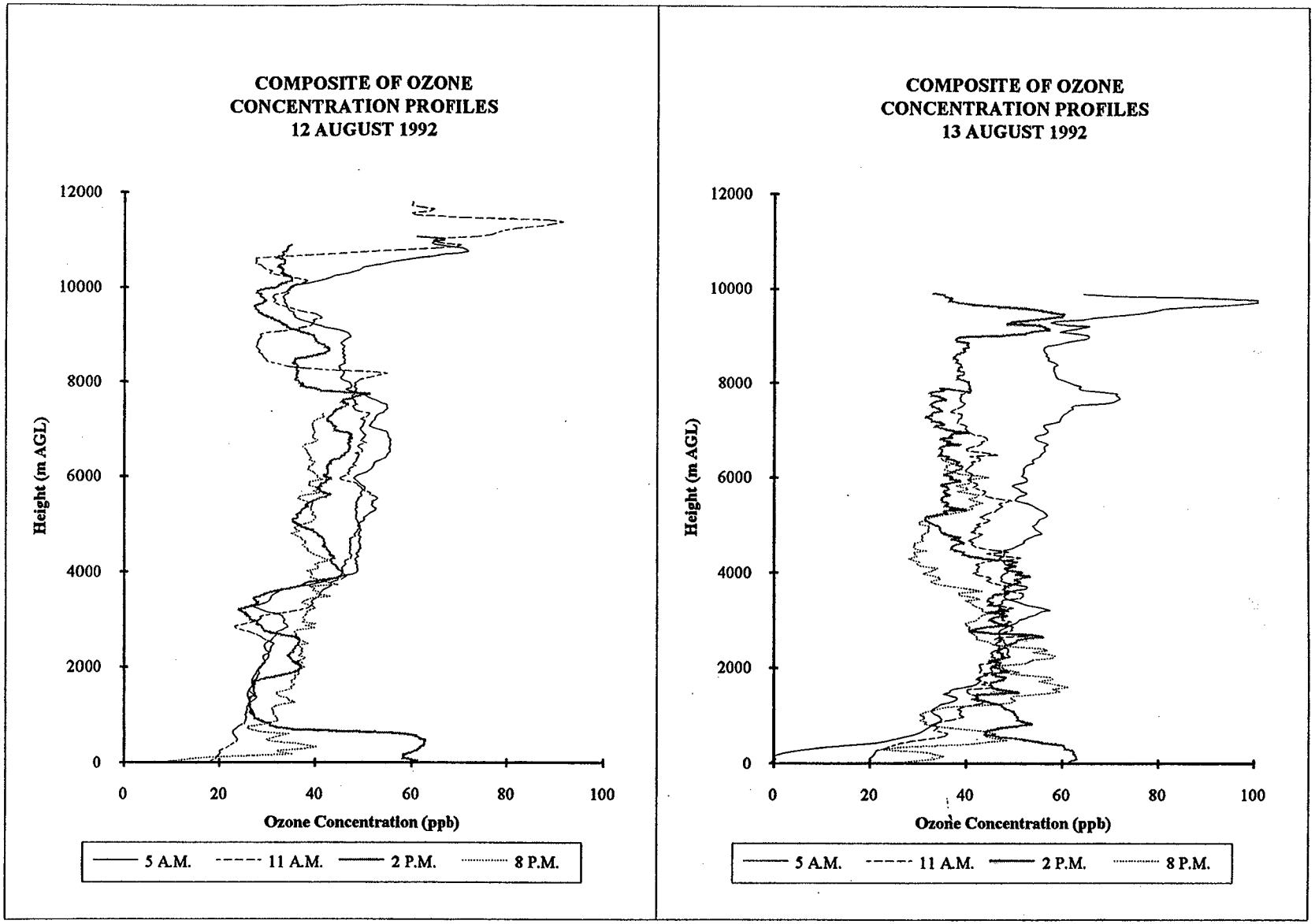


Figure 4. Vertical ozone profiles for August 12th and 13th, 1992 at Clearbrook, B.C..

warming occurred until about 2 p.m., the maximum warming in the layer over the past nine hours was 3.4° C at a height of 2700 m. A small subsidence inversion can be seen on the 2 pm sounding at this elevation. By August 13, subsidence has ended and a couple of small isothermal layers remain within 3000 to 4000 m layer.

Pollutants can vent from the mixed layer to the free troposphere under cumulus dynamics and raise the free troposphere pollutant concentrations above the background level.[9] Meterological reports from Abbotsford Airport indicate widely scattered cumulus cloud based near 2000 m covered one tenth of the sky on August 12th. These could be formed by several mechanisms. The cooler breeze off the sea during the day wedging under the warmer air over and land causes some lift. Lift occurs as the upper winds rise to cross over the Coast Range and also as a result of anabatic flow up the valley walls, all these mechanisms form convective clouds which are a visible indication of vertical mixing in the subsiding layer. It is also likely that dry thermal plumes are penetrating the weak elevated inversion above the boundary layer. On the morning of the 13th the convection was more active, (an isolated thunderstorm cell to the south of the airport produced some lightening) as the upper vorticty centre moved across the top of the ridge.

A possible source of the increasing ozone concentrations in the layer 1500 to 4000 m is from below as ozone rich air parcels break through the weak elevated inversion and release pollutants into the layer above producing local areas of higher ozone concentration. At first the areas of higher ozone concentration will be patchy and, in a capped airmass, ozone levels should increase and become more homogeneous through the day. On the 12th the weak subsidence inversion near 2700 m serves as an upper cap on dispersion, this feature was gone by the 13th. The ozone profiles on the 13th shows less vertical homogeneity than the previous day.

Some of the other ozone sources are from photochemical reactions taking place during the day in the lower troposphere (but temperatures at 2000 m stay below 19°C), from advection or from stratospheric instrusion above. Near the middle of August 1992 stratospheric intrusion was unlikely since average ozone values in the 4000 - 8000 m layer were similar both days and the rate of airmass sinking is not enough to bring in large amounts of ozone, it is also a process which usually occurs in the winter and early spring. The greatest change in the ozone concentration between August 12 and 13 occurs between 1500 - 4000 m. On average the winds at 2000 m blew from the south at 5 10 kts and slowly shifted to blow from the south-southeast at 15-20 kts by 4000 m.

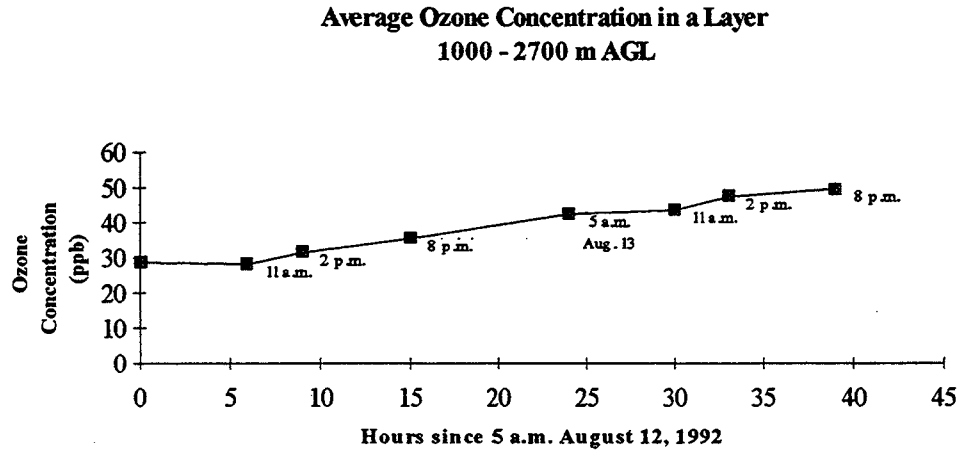


Figure 5. Average ozone concentrations in the layer from 1000 - 2700 m AGL at Clearbrook, B.C. from 5 a.m. PDT August 12 to 8 p.m. PDT August 13, 1992.

Summary

The data clearly shows the diurnal variations of ozone concentration in the boundary layer and the steady increase in ozone above the boundary layer At the surface during the night ozone concentration drops to near zero. A profile in the early morning indicates that just off the surface ozone concentrations gradually increase vertically upward to the base of the nocturnal inversion. During the morning and early afternoon ozone production and advection cause concentrations to rise rapidly at the surface and within the airmass under the weakened, elevated inversion. Surface ozone values peak in the late afternoon with ozone concentration being nearly homogenous in the airmass beneath the remnants of the weak inversion now based near 650 m AGL. Ozone concentration again slowly decreases through the evening at the surface and aloft as it is destroyed by chemical reactions. This classic pattern occurred both days despite the demise of a true sea breeze on the second day.

Above the boundary layer to a height of 4000 m AGL ozone values steadily increase over the two day period even when a capping inversion was not present on the second day. However, when the atmosphere is capped the vertical ozone concentrations appears more homogenous than when a cap does not exist. This steady increase in concentration indicates some ozone is being transported through the weak, elevated inversion and/or is being advected over the area.

The use of balloon borne sondes in the Fraser Valley to provide vertical profiles of ozone and meteorology in the lower troposphere proved to be very successful. The choice of launch times aided the understanding of the diurnal and episode long variations that occurred with the winds, temperature, relative humidity and ozone concentration during two days in August 1992. The ozonesonde program remained relatively unchanged for the Pacific 93 project with the exception that a new site was choosen. This site, east of Langley (15km northwest of Clearbrook), remained within the area of historically high ozone concentration yet was far enough away from the Abbotsford Airport to avoid balloon launch restrictions around Abbotsford Airshow time. The site was closer to the ocean, possibly a more favourable location for seeing the sea breeze return flow. It was also co-located with a full complement of meteorological sensors and air quality monitors operated by the GVRD.

The project in the summer of 1992 has given us a greater understanding of the depth and variability of ozone concentration near the surface in the Fraser Valley. The complete dataset of atmospheric chemistry and physics from the Pacific 93 project, including from the ozone and meteorological sondes is expected to processed by January 1994 and be presented at a data workshop in early April. It will provide comprehensive information on the photochemistry and meteorology associated with high concentrations of ground level ozone. Data from both these projects will be invaluable to researchers who try to better understand ozone formation and distribution to ultimately reduce ground level concentrations in the Lower Mainland and the Fraser Valley.

End Notes

[1]National Research Council "Rethinking the Ozone Problem in Urban and Regional Air Pollution" National Academy Press, Washington, 1991, pp 23.

[2]CCME-EPC "Management Plan for Nitrogen Oxides (NO_x) and Volatile Organic Compounds (VOCs) Phase 1, November 1990", 1990, pp xv.

[3]National Ambient Air Quality Objectives for Sulphur Dioxide, Carbon Monoxide, Ozone and Nitrogen Dioxide (Maximum Tolerable Levels) 1987.

[4]Martin, J. B.; Froude, F.A.; Thomson, B.; Evans, C. "Lower Fraser Valley Field Study" Air Quality Processes Research Division, A.E.S., 1992, pp 3.

[5]Kohmyr, W. D. "Operations Handbook -- Ozone Measurements to 40 km Altitude with Model 4A Electochemical Concentration Cell (ECC) Ozonesondes (Used with 1680 MHZ Radiosondes)" N.O.A.A. Technical Memorandum ERL-ARL-149, 1986, pp 5-10.

[6]Steyn, D. G.; Roberge, A C.; Jackson, C. "Anatomy of an Extended Air Pollution Episode in British Columbia's Lower Fraser Valley" Prepared for Waste Management Branch, British Columbia Ministry of Environment, 1990, pp 4.

[7]Faulkner, D. A. "Sea Breeze Statistics for Greater Vancouver" Scientific Services Division, A.E.S., Unpublished manuscript, Report No. 86-3, 1986.

[8]National Research Council "Rethinking the Ozone Problem in Urban and Regional Air Pollution" National Academy Press, Washington, 1991, pp 105.

[9]Ching, J. K. S.; Shipley, S. T.; Borwell, E. V. "Evidence for Cloud Venting of Mixed Layer Ozone and Aerosols" Atmospheric Environment 22-2, pp 225-241.