Vertical Distribution of Ozone at Four Sites in the United States

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We report ozonesonde observations from the following four locations across the United States: Trinidad Head, CA; Boulder, CO; Huntsville, AL; and Wallops Island, VA. The data used in this study represents ozonesondes launched between 13:00 and 23:00 GMT covering the period between April 1995 and March 2002.

Figure 1 shows time-height cross-sections of all the data used in this study. The upper-tropospheric variability results from STE and/or larger scale meteorological/photochemical processes, and the boundary layer variability, especially in the summertime, results from local pollution modulated by the local weather. The profiles of Figure 2 are averaged at 50 hPa increments between 1000-100 hPa, and at 10 hPa increments between 100-10 hPa. The same average profiles were used to produce the annual cycle of the mean monthly ozone between 1000-100 hPa of Figure 3.

The annual cycle of the monthly mean ozone mixing ratios (ppbv) and the coefficient of variation for the troposphere and lower stratosphere appear in the time-height cross-sections of Figure 3. The three heavy solid lines represent the monthly averaged tropopause and tropopause +/- one standard deviation calculated from the individual soundings at each of the four stations.

The seasonal cycle of ozone in the upper and middle troposphere peaks in the spring and early summer (Figure 3). In the summer, upper and middle-tropospheric ozone mixing ratios over Trinidad Head actually decrease from their springtime high, while at the other three stations they increase toward the east. Seventy plus (ppbv) mixing ratios extend as far down as 400 hPa over Boulder and 500-550 hPa over Huntsville and Wallops Island.

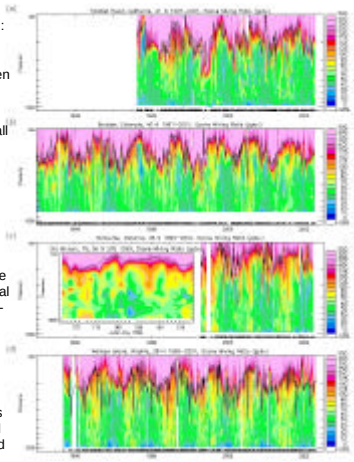

Figure 1. Time-height cross-sections of ozone mixing ratios (ppbv) from ozonesondes at (a) Trinidad Head, CA; (b) Boulder, CO; (c) Huntsville, AL (inset – daily ozonesondes launched at Old Hickory, TN during SOS99, June 15 – July 15, 1999); and (d) Wallops Island, VA. The solid black line represents the thermal tropopause. The triangles at the base of the cross-sections indicate the time of each sounding.

Although they decrease substantially during the summer, the ozone coefficients of variation in the upper troposphere remain notable (40-70%). The summer coefficient of variation maximum is located almost entirely below the average tropopause, with a large gradient at the tropopause, highlighting the substantial week-to-week variability in the upper troposphere, as well as completely decoupling this variability from local stratospheric influences. Possible sources of this variability include transport of ozone previously exchanged into the upper troposphere at higher latitudes and/or en-route photochemical production of ozone.

Little variation in the ozone cycle occurs in the lower troposphere over Trinidad Head; however, the seasonal signature is very strong over Huntsville and Wallops Island and is moderate over Boulder. From the magnitude and vertical extent of the coefficient of variation peaks, a west-to-east gradient is evident in the frequency and/or relative magnitude of these STE events and upper free-tropospheric ozone mixing ratios.

Figure 4 (a & b) represent the extremes in temperature profiles observed in this study where the height of the thermal tropopause is ambiguous by most definitions (Figure 4a) and clearly defined (Figure 4b). Figure 4c shows a spaghetti plot of the Trinidad Head ozonesonde profiles for the month of May. The average profile in red is the same as the average May profile shown in Figure 2, but in full resolution. This profile is strongly influenced by the four soundings in May of 1998 (shown in black) in which a high number of STE events occurred. Further evidence of this appears in the TOMS monthly mean total ozone for May 1998, Figure 4d. The average total ozone for May 1998 is over 45 DU (>13%) higher than the average total ozone for May 1997-2002 Figure 5 (a, b, & d). By virtue of its location in the Northwestern United States, a region of strong frontogenesis in the spring months, Trinidad Head is expected to observe higher upper-tropospheric and lower-stratospheric ozone, as well as higher total ozone than the other three stations. However, May 1998 appears to be an especially active month and perhaps warrants further investigation.

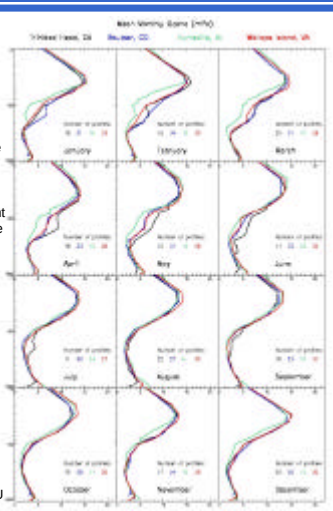

Figure 2. Monthly averaged vertical ozone profiles (partial pressure in mPa) for Trinidad Head, CA (black); Boulder, CO (blue); Huntsville, AL (green); and Wallops Island, VA (red). The number of launches at each site for each month are indicated on the charts.

Figures 3 and 4 suggest the presence of different mechanisms controlling ozone concentrations at different levels of the atmosphere, and especially in the troposphere, across the United States. A particular mechanism that couples latitudinal structure with longitudinal structure in the stratosphere is the presence of planetary waves with preferred seasonal phase. For example, Figure 5 (c, d, and e) shows the monthly average planetary wave structure in February, May, and August. This structure changes significantly during these months. As a result, the apparent longitudinal structure in February is actually a latitudinal difference between Huntsville and the other three stations in a zonal atmosphere. In August, however, because of the standing wave, the measurements show that Boulder has lower column ozone amounts compared to the other three stations, but this difference can be explained by the wave pattern.

As a result of several years of ozonesonde measurements at four locations in the United States, a climatology of the vertical profile of continental U.S. ozone is beginning to emerge. This vertical distribution of ozone displays significant variation on time scales ranging from days to interannual in both intra- and inter-station observations. The records show strong evidence of stratosphere-troposphere exchange, especially in the winter and spring, and more so at the Pacific coast station, Trinidad Head. All stations show variability in the boundary layer pollution sources. The middle troposphere is the least variable region. The variability throughout the troposphere and lower stratosphere is quantified by coefficients of variation of the monthly means showing strong vertical and seasonal structure. Even with this strong variability, comparison to MOZAIC aircraft measurements (not shown) shows good agreement, except at 300 hPa, which may be attributed to strong interannual variability between the data sets.

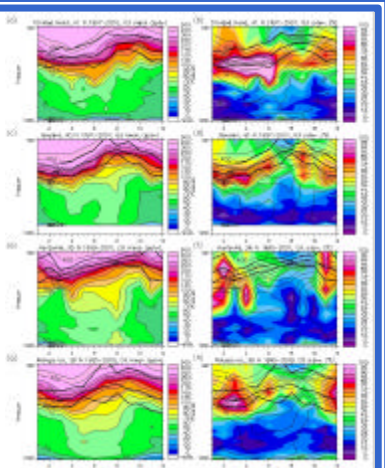

Figure 3. Vertical profiles of the annual cycle of monthly mean ozone mixing ratios (ppbv, left panels) and coefficient of variation (right panels) for (a,b) Trinidad Head, CA; (c,d) Boulder, CO; (e,f) Huntsville, AL; and (g,h) Wallops Island, VA.

In the lower troposphere, the two eastern stations –– Huntsville, AL, and Wallops Island, VA – measure the highest ozone amounts compared to the two western stations – Trinidad Head, CA, and Boulder, CO. The lower-stratospheric ozone at Huntsville, AL is noticeably lower on average than at the other three stations in the winter and springtime. All stations show very strong variability in this altitude region, especially in winter and springtime. During extreme events, stratospheric peak ozone partial pressures pervade the troposphere down to 500 hPa.

Throughout the stratosphere, the Huntsville profiles display more tropical character than the other three stations, a distinction most noticeable during winter and spring.

In comparing the seasonal signature of ozone across the United States, eastern stations exhibit higher tropospheric ozone concentrations as a result of local pollution effects. The seasonal cycle maximizes in the summer months at all stations except at Trinidad Head, which has the opposite phase. Huntsville experiences the highest ozone mixing ratios in the summertime convective boundary layer, reaching 75 ppbv on average in August. The other three sites experience significant vertical gradients in volume mixing ratio in the lowest ~1km with surface minima.

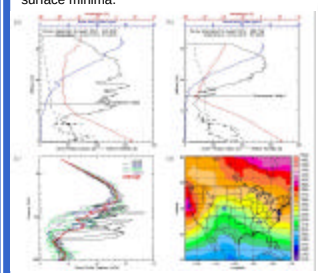

Figure 4. Individual soundings (a & b) from Wallops Island that demonstrate the extremes in lapse rate structure used to determine the height of the tropopause given the definition in the text and its effect on the computed tropospheric ozone. (c) Spaghetti plot of the nine Trinidad Head soundings in the month of May for the study period. The black profiles (4) are in 1998, the blue (1) is in 1999, the green (4) are in 2000, the magenta (3) are in 2001, and the red is the average profile. (d) Monthly mean total ozone from TOMS for May 1998. The blue diamonds mark the locations of the four ozonesonde stations.

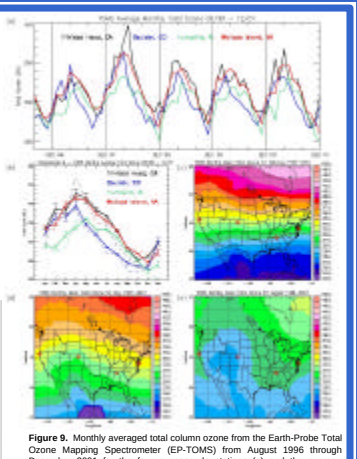

Figure 9. Monthly averaged total column ozone from the Earth-Probe Total Ozone Mapping Spectrometer (EP-TOMS) from August 1996 through December 2001 for the four ozonesonde stations (a) and the average monthly total ozone for that period from ozonesondes and TOMS ± one standard deviation (b). Monthly mean total ozone from TOMS (c, d, & e) for February, May, and August, respectively, over the study period. The red diamonds mark the locations of the four ozonesonde stations.

Adapted from:

Newchurch, M.J., Ayoub, M.A., Oltmans, S., Johnson, B., and Schmidlin, F.J., Vertical distribution of ozone at four sites in the United States, *J. Geophys. Res., in press* 2002.

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