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Long-range transport of ozone from the Los Angeles Basin: A case study

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[1] Airborne lidar measurements of ozone above the Los Angeles Basin on 17 July 2009 show orographic lifting of ozone from the surface to the free troposphere by the San Gabriel Mountains. Mixing ratios in excess of 100 parts-per-billion-by-volume (ppbv) were measured ~4 km above mean sea level (ASL). These observations are in excellent agreement with published model studies, confirming that topographic venting by the so called "mountain chimney effect" is a potentially important pathway for removal of pollutants from the Los Angeles Basin. The lofting of ozone and other pollutants into the free troposphere also greatly increases the potential for long-range transport from the Basin, and trajectory calculations suggest that some of this ozone may have been transported ~1000 km to eastern Utah and western Colorado. **Citation:** Langford, A. O., C. J. Senff, R. J. Alvarez II, R. M. Banta, and R. M. Hardesty (2010), Long-range transport of ozone from the Los Angeles Basin: A case study, *Geophys. Res. Lett.*, *37*, L06807, doi:10.1029/2010GL042507.

1. Introduction

[2] The Los Angeles Basin experiences some of the highest ozone mixing ratios in the United States. Photochemical production occurs throughout much of the year as clear skies and warm temperatures promote reactions of nitrogen oxides and non-methane hydrocarbons emitted from industrial activities, transportation, and other sources associated with a population of nearly 18 million people. A deep persistent temperature inversion created by warm subsiding air from the semi-permanent East Pacific High traps this ozone in a shallow layer near the surface as the sea breeze transports it inland to the eastern half of the Basin. Here the polluted air masses encounter the San Gabriel and San Bernardino Mountains to the north and east, respectively. Although the temperature inversion limits the depth of convective mixing over most of the Basin, thin layers with high ozone and aerosol concentrations within the inversion have been observed since the 1960s. These layers, which typically lie between 1 and 2 km ASL, are well documented by airborne lidar [*McElroy and Smith*, 1993], in-situ aircraft [*Anderson et al.*, 1989; *Blumenthal et al.*, 1978; *Edinger*, 1973; *Rosenthal et al.*, 2003], and ozonesondes [*Lea*, 1968; *Rosenthal et al.*, 2003]. They have been attributed to orographic [*Edinger*, 1973] and convective [*Wakimoto and McElroy*, 1986] lifting of polluted air by and near the mountains that surround the Basin.

[3] The chemistry and meteorology of the Los Angeles Basin has been examined in a number of major field campaigns, including the Southern California Air Quality Study (SCAQS) [*Lawson*, 1990] in 1987, and the Southern California Ozone Study (SCOS97-NARSTO) in 1997 [*Croes and Fujita*, 2003]. The complex interaction between the sea-land breeze and mountain-valley circulations within the Los Angeles Basin was also investigated by *Lu and Turco* [1994, 1995] using 2-D and 3-D transport models, respectively. They later used [*Lu and Turco*, 1996; *Lu et al.*, 1997] a fully integrated air pollution modeling system, the Surface Meteorology and Ozone Generation (SMOG) model, to simulate ozone formation and transport over a three-day period (26–28 August 1987) from the SCAQS intensive. These models reproduced the layers seen during SCAQS and other studies, and showed that much of the ozone formed in the Basin is transported out over low ridges and through mountain passes.

[4] The model simulations of *Lu and Turco* [1996] also showed that the heated mountain slopes lift some ozone well above the highest peaks (~3 km ASL) and into the free troposphere. This phenomenon, which they dubbed the "mountain chimney effect", not only ventilates the boundary layer, but also greatly increases the potential for long-range transport. However, since the layers formed by the mountain chimney effect lie above the maximum altitudes (~1600 to 3000 m ASL) of previously published aircraft measurements [*Edinger*, 1973; *Blumenthal et al.*, 1978; *Collins et al.*, 2000], this phenomenon has not been directly observed in the Los Angeles area to our knowledge.

[5] In preparation for a major new study, CalNex (www.esrl.noaa.gov/csd/calnex/) in 2010, the Atmospheric Remote Sensing Group flew the NOAA Twin Otter with the downward-looking Tunable Optical Profiler for Aerosols and oZone (TOPAZ) differential absorption lidar (DIAL) [*Alvarez et al.*, 2008] over the Los Angeles Basin between 15 and 20 July 2009. In this paper, we describe measurements from 17 July 2009 made under meteorological conditions similar to 27–28 August 1987, the period modeled by *Lu and Turco* [1996] (hereafter *LT96*). These measurements show an example of the mountain chimney effect seen in the model studies, with ozone mixing ratios in excess of 100 ppbv lofted to ~4 km ASL above the San Gabriel Mountains and into the free troposphere. We use trajectory calculations to show that some of this ozone may have been transported to the surface nearly 1000 km to the east.

2. Meteorological Background

[6] Figure 1a shows the 1000 hPa geopotential height and winds at 0000 UT on 18 July 2009 (1600 Pacific Standard

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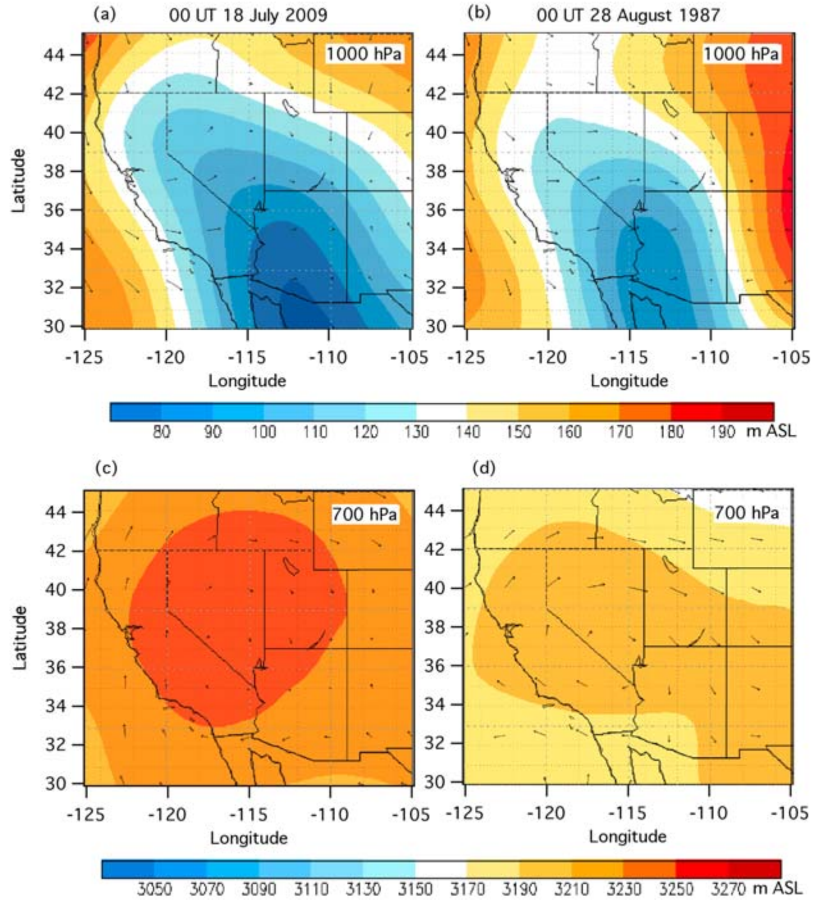

Figure 1. 1000 hPa geopotential surface and winds over the southwestern U.S. at (a) 0000 UT 18 July 2009 and (b) 0000 UT 28 August 1987. (c) 700 hPa geopotential surface and winds at (c) 0000 UT 18 July 2009 and (d) 0000 UT 28 August 1987.

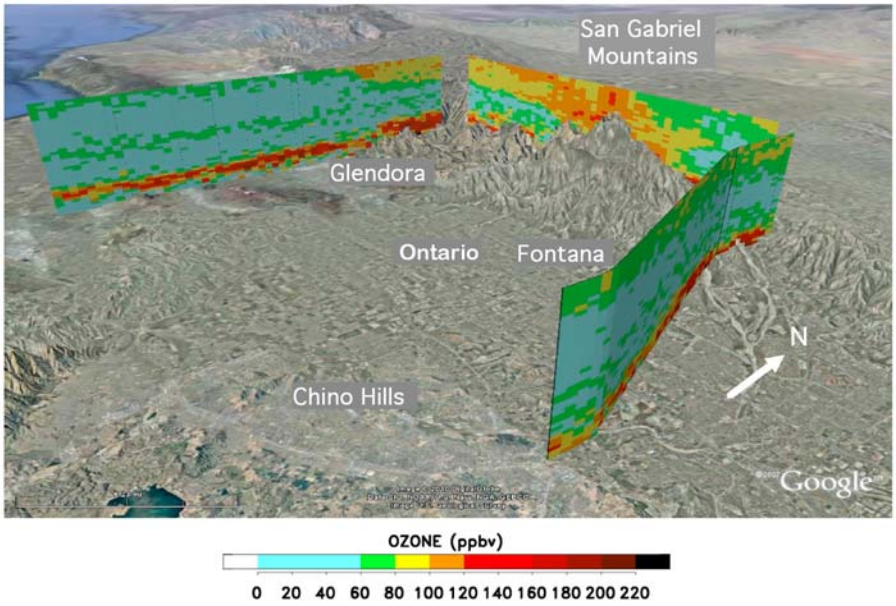

Figure 2. Vertical distribution of ozone measured by TOPAZ above the San Gabriel Mountains and Los Angeles Basin between 2337–0005 UT (1537–1605 PST) on 17–18 July 2009. The curtain plot extends from ~300 m AGL to 4000 m ASL. The profiles are superimposed on a surface terrain map from Google Earth.

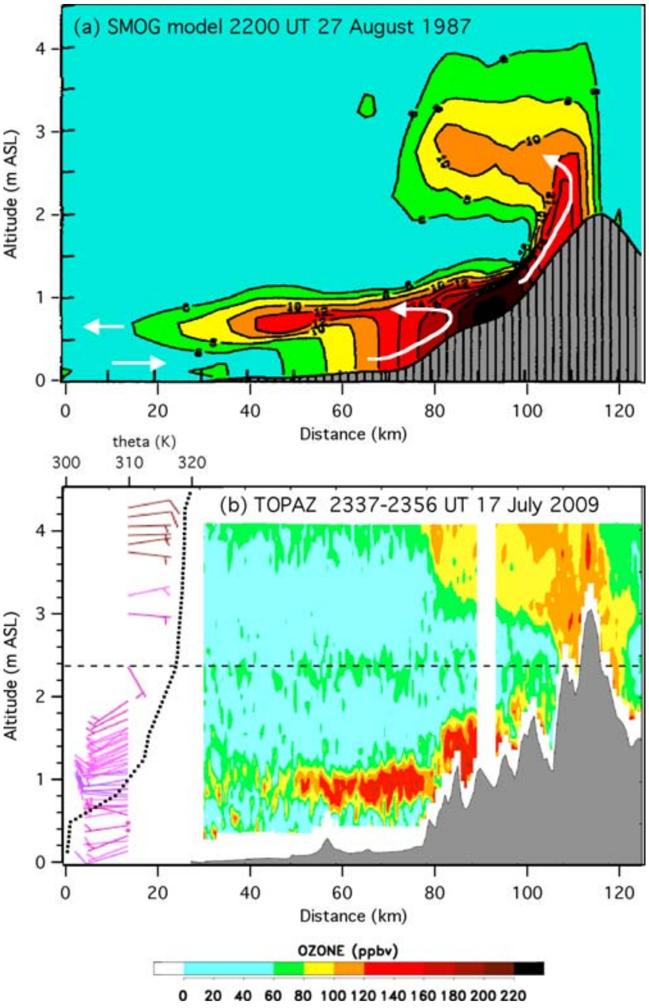

Figure 3. (a) SMOG model cross-section of ozone mixing ratios at 2200 UT on 27 August 1987 along transect from Santa Monica Bay to the San Gabriel Mountains. The plot is based on Figure 4b from *Lu and Turco* [1996]. The contours are labeled in parts-per-hundred-million (pphm). (b) TOPAZ measurements from the leftmost two panels in Figure 2 collapsed from three to two-dimensions. The color scale is the same as in Figure 3a. The barbs show the 0000 UT 18 July winds from the Ontario Airport radar profiler; the dotted line the potential temperature from the 0000 UT 18 July San Diego sounding.

Time, PST on 17 July) above the southwestern U.S. from the NOAA/NCEP/CDAS (Climate Data Assimilation System) Reanalysis [*Kalnay et al.*, 1996]. The edge of the east Pacific High lies off the coast of California, and a low pressure cell induced by surface heating extends northward from Mexico. This pressure gradient produces an onshore background flow component across the Los Angeles Basin. Figure 1b shows a similar plot for 0000 UT on 28 August 1987, the second day of the three-day simulation described in *LT96*. The surface meteorology patterns are similar, but with a somewhat weaker pressure gradient across the southern California coastline during the SCAQS period. The 700 hPa surfaces on both days (Figures 1c and 1d) show a high-pressure dome centered over Nevada. Near the coast, warm subsiding air creates a strong temperature inversion above a thin layer of cooler air that was recently over the ocean. The afternoon San Diego sounding for 0000 UT on 18 July 2009 (see below) indicates a well-mixed boundary layer ~500 m deep capped by a temperature inversion extending up to ~2400 m ASL. Similar profiles were measured on 28 August 1987. The 18 July 2009 sounding also showed northwesterly flow extending from the surface up to ~2000 m ASL, rotating to easterly flow above ~2600 m ASL. The latter reflects the anticyclonic flow around the upper level high-pressure cell.

3. Ozone Measurements

[7] The study period coincided with three of the four highest 8-h ozone days during 2009 within the South Coast Air Basin (SCAB), which includes Los Angeles County (www.arb.ca.gov). On 17–19 July, peak 8-h mixing ratios ranged from 110 to 128 ppbv, well in excess of the current standards. The corresponding 1-h maximum mixing ratios ranged from 142 to 149 ppbv. The highest surface ozone was measured at Fontana and Glendora near the San Gabriel Mountains (cf. Figure 2), and at Crestline, in the foothills of the San Bernardino Mountains. In contrast, the peak 8-h mixing ratios near the coast at Costa Mesa ranged from 38 to 44 ppbv. Even higher surface mixing ratios were measured on 27 August 1987, with 1-h and 8-h maximum mixing ratios of 330 and 210 ppbv, respectively, at Glendora. These were the highest mixing ratios measured in SCAB during 1987.

[8] Figure 2 also shows the vertical distribution of ozone from 300 m above ground level (AGL) to 4 km ASL measured by TOPAZ over the San Gabriel Mountains between 1537 and 1605 PST (2337-0005 UT) on 17–18 July 2009. The profiles were calculated with 90-m vertical range resolution and 600-m horizontal resolution (10-s integration) and smoothed with a 450-m running filter. They are superimposed on a surface terrain map from Google Earth. The plot shows only a small segment from a 4-h flight that covered ~70 × 150 km^2 from the Pacific Ocean beyond the San Bernardino Mountains to Palm Springs. A thin layer of high ozone (>120 ppbv) spreads to the south and west of the mountains ~1 km above the Basin within the temperature inversion, similar to previous observations. The TOPAZ measurements also show a striking plume of high ozone lifted above the mountain peaks and advected westward by the upper level flow. The plume did not extend upwind of the San Gabriel Mountains and was still present during a second pass (not shown) over the mountains near 1800 PST (0200 UT on 18 July). It does coincide with a less distinct layer lifted over the Basin by the San Bernardino Mountains to the east.

4. Comparison to Model Simulation

[9] The model simulation of *LT96* used an 85 × 55 grid cell meteorological domain enclosing a 51 × 31 grid cell domain for the tracer chemistry model that covered the entire Los Angeles Basin and adjacent areas. The horizontal spatial resolution was ~0.05° (~5 km). Twenty non-uniform vertical layers were used for both models. Figure 3a shows a curtain plot of the calculated ozone mixing ratios at 2200 UT on 27 August 1987 along a cross-section from

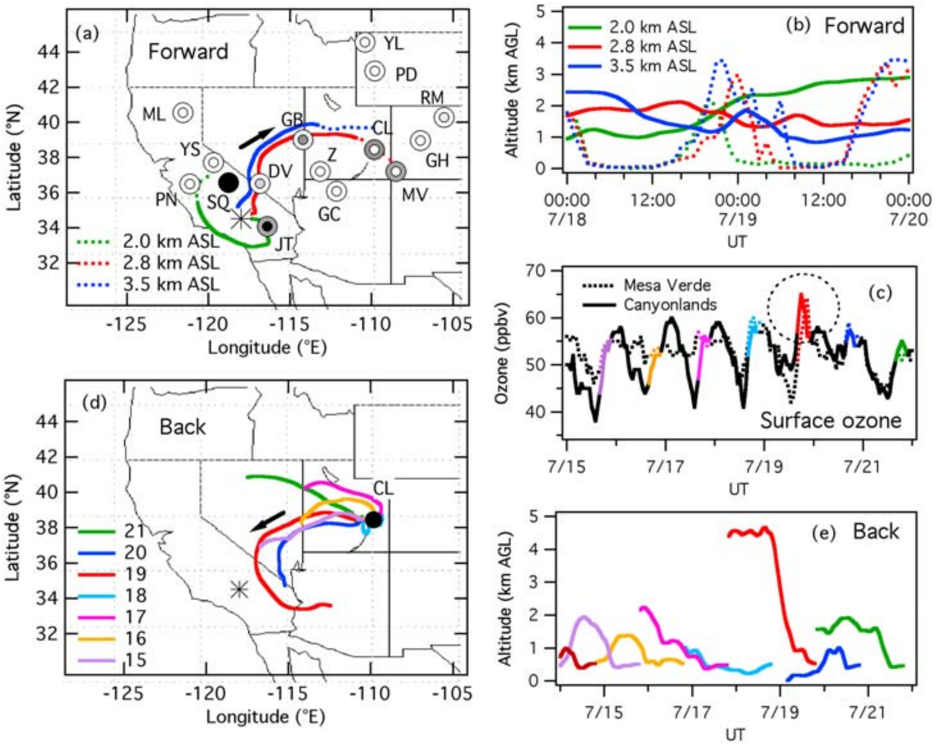

Figure 4. (a) HYSPLIT 48-h forward trajectories originating at 0000 UT on 18 July from 2000, 2750, and 3500 m ASL near the San Gabriel Mountains (solid lines). These trajectories lie below, at, and above the top of model mixed layer. The dotted lines show 60-h trajectories. The circles show the locations of CASTNET surface ozone monitors; the inner and outer circles represent the daily 1-h maximum ozone measured on 18 and 19 July, respectively, scaled from 60 ppbv (white) to 70 ppbv (black). (b) Altitudes (solid lines) and mixed layer depths (dotted lines) for the trajectories plotted in Figure 4a. (c) Time series of ozone at Canyonlands (CL) and Mesa Verde (MV). The colors highlight the data from 1600–2200 UT on each day. The dotted circle shows the spike attributed to long-range transport on 19 July. (d) Back trajectories originating from Canyonlands at 1900 UT, the colors are the same as in Figure 4c. (e) Altitudes of the back trajectories plotted in Figure 4d.

Santa Monica Bay to the San Gabriel Mountains. The plot is based on Figure 4b from *LT96*. The TOPAZ measurements in the leftmost two panels from Figure 2 are collapsed from three to two dimensions and plotted in Figure 3b. The colored barbs show the 0000 UT winds from the Ontario Airport radar profiler operated by the South Coast Air Quality Management District. The winds rotate from SW to WNW in a narrow region near 1 km ASL coinciding with the lower ozone layer as the sea breeze is perturbed by the return flow from the mountains. The winds become easterly above 2 km ASL as shown in Figure 1c. The dashed line shows the top of the inversion layer from the 0000 UT San Diego sounding (dotted line).

[10] Strong similarities in the O_3 distributions are evident between the two cross sections. The simulation also shows the thin layer of high ozone extending westward from the mountain flanks within the temperature inversion at ~800 m ASL. The second dramatic plume of high O_3 extending above 4 km ASL in the DIAL measurements is also reproduced by the model. That the modeled plume does not reach the heights of the observed plume is not surprising, since these cross-sections represent different days in different years, but the possibility of deep lofting of pollutants over the mountain ridge predicted by the model is confirmed by the observed cross-section. The occurrence of deep vertical lofting on both occasions suggests that this may be a regular feature of certain high-pollution days.

5. Long-Range Transport of Ozone

[11] Lofting of ozone and other pollutants into the free troposphere greatly increases the possibility of long-range transport from the Basin. The solid lines in Figure 4a represent 48-h forward trajectories originating from (34.5°N, −118°E) above the San Gabriel Mountains at 0000 UT on 18 July 2009. The dotted lines show the 60-h trajectories. These trajectories were calculated using the NOAA Air Resources Laboratory HYSPLIT model (available at http://www.arl.noaa.gov/HYSPLIT.php) with the NCEP EDAS (Eta Data Assimilation System), which has a 40 km grid resolution over North America. Trajectories starting below (2000 m ASL), just above (2750 m ASL), and well above (3500 m ASL) the top of the inversion are shown. Figure 4b plots the trajectory altitudes (solid lines) and model mixed layer depth (dotted lines) AGL. The lowest trajectory remains over southern California, rising above the mixed layer over the San Joaquin Valley on the second day. The two higher trajectories, however, are carried inland by the anticyclonic flow around the high-pressure cell (cf. Figure 1c), reaching eastern Utah by the afternoon of 19 July, and SW Colorado several hours later. Both trajectories lie within the

local daytime mixed layer on both 18 and 19 July. Although the EDAS model cannot resolve details within the Los Angeles Basin, the performance in the free troposphere should be reasonable.

[12] The concentric circles in Figure 4a show the locations of 15 monitoring stations operated by the U.S. National Parks Service and Environmental Protection Agency as part of the Clean Air Status and Trends Network (CASTNET) (http://www.epa.gov/castnet/index.html). The circles are shaded from white (60 ppbv) to black (70 ppbv) to show the daily maximum 1-h ozone measured on the 18th (inner circle) and 19th (outer ring). Mixing ratios of up to 62 and 65 ppbv were measured at Death Valley National Monument (NM) and Great Basin National Park (NP) on 18 July as the trajectories passed over Nevada, and 65 ppbv was measured at both Canyonlands NP and Mesa Verde NP on 19 July. The 1-h maxima remained below 60 ppbv at all of the other CASTNET sites on both days, except for Sequoia NP and Joshua Tree NP, which are subject to more localized transport as shown by the lowest trajectory. Figure 4c plots times series of the 1-h ozone at Canyonlands and Mesa Verde from 15 to 21 July. The interval from 1600 to 2200 UT on each day is marked by a different color. Both records exhibit sharp peaks near local noon (~1900 UT) on the 19th (red) that clearly stand out from the broader late afternoon photochemical maxima during the rest of the week. The timing between the spikes and the trajectories does not exactly match, but the spike at Mesa Verde lags that at Canyonlands by 3 hours, consistent with transport from the northwest. While more localized sources cannot be ruled out, the correspondence between these peaks and the trajectories is suggestive.

[13] Figure 4d plots 48-h back trajectories originating 500 m above Canyonlands NP at 1900 UT on each of the days plotted in Figure 4c; the trajectories are color coded to match. Figure 4e plots the corresponding trajectory altitudes (AGL). Although most of the back trajectories remain near the surface in Utah and Nevada, the (red) trajectory corresponding to the ozone spikes at 19 UT on 19 July in Figure 4c passes within 100 km of the San Gabriel Mountains two days earlier at ~4 km AGL. The trajectory does not exactly coincide with the forward trajectory in Figure 4a since it originated from a point near, but not on, that trajectory.

6. Summary and Conclusions

[14] The TOPAZ measurements on 17 July 2009 confirm the lofting of ozone and other pollutants from the Los Angeles Basin into the free troposphere over the San Gabriel and San Bernardino Mountains by the mountain chimney effect shown in the model simulations of *LT96*. Trajectory calculations, together with the lidar observations, suggest that transport of this elevated plume from the Los Angeles Basin could have been responsible for the 5-10 ppbv spikes in ozone observed at Canyonlands and Mesa Verde nearly 1000 km to the east ~48 hours later. Although the evidence presented here is circumstantial, it seems plausible that such transport may often take place since meteorological conditions similar to those described here occur frequently in the Los Angeles Basin during summer, and the upper level winds are often westerly. Additional measurements and model studies during the 2010 CalNex campaign should improve our understanding of this phenomenon and its importance to boundary layer venting and ozone export.

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