Analysis of transport patterns during an SCOS97-NARSTO episode

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Abstract

Objectives for the current study included use of SCOS97-NARSTO data to understand transport factors in the occurrence of high ozone concentrations during 4–7 August 1997. Meteorological data for the case study included observations at 110 SCOS97-NARSTO surface sites, and upper-air measurements from 12 rawinsonde and 26 profiler sites. Analysis showed that the peak ozone resulted from an infrequent combination of large-scale upper-level synoptic forcing associated with a weak local coastal 700 mb ridge. Its movements over the California South Coast Air Basin lowered and strengthened the coastal subsidence inversion and also rotated the upper-level synoptic background flow from its normal westerly onshore direction to a less common offshore easterly flow during the nighttime period preceding the peak-ozone hours. Resulting easterly upper-level background winds produced easterly surface flow directions at inland sites, so that a surface frontal convergence zone formed where this flow met the westerly onshore combined sea breeze and upslope flows. The maximum inland penetration of the convergence zone on the peak-ozone day was to the western side of the San Gabriel Mountains, the location of maximum ozone concentrations.

Keywords: SCOS97-NARSTO; Meteorological analysis; Ozone episode

1. Introduction

The California South Coast Air Basin (SoCAB) is one of the most severe summertime ozone problem areas in the US. Its peak concentrations arise from a combination of extensive precursor emissions, mountain ranges on three sides of the Basin, complex photochemical processes, and complex meteorological patterns that involve General Circulation (GC) and mesoscale factors. SoCAB lies in the coastal plain between the Pacific Ocean to the west and surrounding high terrain (peaks to 3000 m MSL) on its northern, eastern, and southern edges (Fig. 1).

The summertime GC Pacific High, located offshore north of the basin, deflects rain producing storms northward, producing a dry summer climate. Its subsidence produces warm dry air, which caps cool moist air near the surface, creating a marine boundary layer (MBL). High inland temperatures create a thermal low-pressure system, and resulting daytime horizontal pressure differences create a cool onshore mesoscale sea-breeze flow that augments the normally onshore flow from the GC Westerlies. This flow is further augmented by inland directed, thermally driven upslope flows associated with the inland mountain ranges. During nighttime hours, land surfaces cool more quickly than the sea, and the reversed temperature difference produces an offshore mesoscale land-breeze flow also augmented by a seaward directed, downslope flow from the inland mountains.

Field campaigns have increased understanding of mesoscale conditions critical for SoCAB ozone episodes. Airborne lidar data were collected over the SoCAB during summer 1982 by McElroy et al. (1982). Analysis
by McElroy and Smith (1986) showed distinct elevated aerosol layers that formed by: sea-breeze undercutting, roughness-induced convergence zones, upslope topographic flows, and/or nighttime land-breeze. Analysis of the August 1984 Project BASIN (Basic Studies on Airflow, Smog, and Inversions) upper-air data by Wakimoto (1987) found that an offshore (thermally and topographically induced) cyclonic Catalina Eddy reduced inland ozone concentrations and increased values northeast of Los Angeles.

Autumn 1985 SCCCAMP (South-Central Coast Cooperative Aerometric Monitoring Program) study obtained meteorological and ozone data were used in Santa Barbara Channel air quality modeling. These data were used by Baxter (1991) to show that doppler radars produce the most accurate mixing depths. McElroy and Smith (1991) showed that MBL boundary to resemble a cold front, with a depth that varied from about 150 m over water, sloped upward over the coastal plane, and was “blocked” by inland topographic features. Scire and Chang (1991) showed that high SCCCAMP ozone concentrations were related to the simultaneous occurrence of high 850 mb temperatures (reflecting subsidence) and pressure gradients consistent with easterly or southerly synoptic flows. This first effect had been noted in the SoCAB by Smith (1984) and Moore and Reynolds (1986), and the second by Smith and Lehrman (1987). Moore et al. (1991) used SCCCAMP trajectories to show ozone exceedances in Ventura and Santa Barbara Counties to result from upper-level (200–500 m) westward or northwestward transport from Los Angeles. Data collected by Lawson (1990) during the summer and fall 1987 Southern California Air Quality Study (SCAQS) generally showed mid-afternoon peak-ozone concentrations (Lu et al., 1997).

Results from the above studies show that pollutant concentrations in the SoCAB vary significantly in time and space over typical diurnal cycles. A large fraction of primary pollutants (from traffic and industrial sources) is emitted in the western region of the Basin during morning rush hours. Peak surface ozone concentrations, however, are mostly found during afternoon hours on the upwind edge of the mountains east of the basin due to ongoing photochemical reactions during eastward advection by the onshore flow. The flow can then rise over the mountains, as convective heating over their slopes raises the inversion to produce a chimney effect that allows polluted air to exit the Basin (Wakimoto and McElroy, 1986).

Alternatively, a daytime recirculation can develop aloft, in which the flow is opposite in direction to the onshore sea-breeze flow below. Surface ozone thus carried aloft can produce elevated pollutant layers during late afternoon hours (Lu and Turco, 1996) which blanket the entire western Basin. By evening they extend over the eastern Basin as well (due to the return-flow aloft), albeit at lower concentrations (Wakimoto and McElroy, 1986). They then sequentially decouple from surface polluted layers during the evening transition period (when the turbulent boundary layer collapses), persist throughout the nighttime stable period, and are fumigated to the surface during the morning transition period.

Whereas previous analyses of SoCAB ozone episodes had access to only limited upper-air data, the current study uses the rich data set from the California Air
Resources Board (CARB) sponsored summertime 1997 Southern California Ozone Study (SCOS97-NARSTO). The vertical observations in SCOS97-NARSTO were the most complete ever obtained in the SoCAB. The data are thus used in detailed four-dimensional, multiscale analyses of meteorological factors determining the transport patterns leading to the 4–7 August peak-ozone period (highest SCOS97-NARSTO concentrations).

2. SCOS97-NARSTO data

SCOS97-NARSTO objectives included: an updated database; a new understanding of relationships between emissions, transport, and ozone exceedances; and plans for the further SoCAB emission reductions needed to attain the ozone National Ambient Air Quality Standards (NAAQS). The objective of the current study is use of SCOS97-NARSTO data and mesoscale simulations with the Fifth Generation Meteorological Model (MM5) (discussed in a companion paper by Boucouvala et al., 2003). The current paper details four-dimensional, multiscale analyses of meteorological factors determining the transport patterns during the 4–7 August surface ozone period. This period was selected by CARB, as maximum SCOS97-NARSTO surface ozone concentrations (187 ppb) occurred on 5 August at 2200 UTC (1500 PDT, Pacific Daylight Time) at a site at the southwest edge of the San Gabriel Mountains.

SCOS97-NARSTO meteorological data (Fujita et al., 2000) include hourly surface measurements of wind (7 m AGL, unit for all subsequent heights) and temperature (2 m AGL) from 259 sites, and after a CARB quality assurance (QA) analysis (CARB, 2001) the 110 most reliable sites were selected (Figs. 2a and b). SCOS97-NARSTO is also rich in upper-air meteorological measurements, including wind, temperature, and humidity profiles every 6 h (starting at 0500 PDT) from 12 rawinsonde sites (Fig. 2c). Hourly averaged (centered on half-hours) wind and temperature profiles from 26 Radar Wind Profiler/Radar Acoustic Sounding System (RWP/RASS) profilers (Fig. 2d) are also available. Wind speeds during the study period were generally <15 m s⁻¹, and thus are plotted in mesoscale code: half barb for 0.5, full barb for 1, and flag for 5 m s⁻¹.

Rawinsonde data underwent a QA analysis at CARB and San Jose State University, while profiler data were checked at the NOAA Environmental Research Laboratory (ERL) by Wolfe and Weber (1999). Note that few surface and upper-air sites are located at high-elevation inland sites, which leads to uncertainty in inland sea-breeze frontal positions. RASS and rawinsonde temperature observations only extended down to about 100 and 50 m AGL, respectively. It was not, however, possible to combine surface (2 m) network temperatures with these data, as the two were not always consistent. Inversion tops were thus easier to identify, and only bases about 100 m or higher were discernable from rawinsonde data.

The two data sets were combined to produce upper-level horizontal temperature distributions, with data linearly interpolated to key AGL heights (e.g., within sea breeze and synoptic flows). Temperatures from a given AGL level were then interpolated horizontally to a regular Lambert conformal grid (by use of an inverse distance-square weighting scheme), and results smoothed (by a four-point scheme) and contoured (Bornstein et al., 2001).

3. Results

For readability, SCOS97-NARSTO date–hour specifications will be abbreviated. Thus 0500 UTC on 6 August is noted as 06/05 UTC, and its PDT equivalent of 2200 PDT on 5 August becomes 05/22 PDT. The remaining sections of this paper seek to explain the transport patterns that resulted in the following observed surface peak-day ozone distributions at 05/22 UTC.

While urban nitric oxide emissions produced a morning coastal ozone minimum (due to titration) on the peak-ozone day of 20 ppb at 05/17 UTC or 05/10 PDT (Fig. 3a), 3 h later a high more inland ozone area (maximum of 121 ppb) had formed (Fig. 3b). By 05/22 UTC, its center of mass had achieved a maximum inland penetration to the western slopes of the San Gabriel Mountains with a peak value of 187 ppb (Fig. 3c). After two additional hours, it had started to retreat coastalward and its maximum ozone had been reduced to about 90 ppb (Fig. 3d).

3.1. Synoptic summary

Weak, slightly changing anticyclonic synoptic forcing existed over the SoCAB throughout the test period. NWS 300 mb charts (not shown) showed that the GC Pacific High over the western US kept the GC long-wave trough and Polar Front jet far north of the SoCAB. The center of a 700 mb GC high was not clearly defined, had low wind speeds, and changed in intensity only slightly during the period. It reached a maximum intensity at 06/00 UTC (time of peak ozone), when it was centered over the southern California coast (Sterbis, 2000). At that time, temperatures had increased as its subsidence inversion base lowered.

Both the surface offshore GC high and (inverted) thermal low-pressure trough (which extended up beyond the 850 mb level) also produced low wind speeds, changed only slightly during the period, and were strongest at 06/00 UTC (Fig. 4). At that time, the
Fig. 2. SCOS97-NARSTO: (a, b) surface, (c) rawinsonde, and (d) profiler sites, with topographic heights (dashed lines, at 500 m interval).
surface high was closest to the coast and its central pressure was increased by about 2 mb (from that 24 h previous), producing a maximum onshore pressure gradient.

3.2. SCOS97-NARSTO winds

The offshore San Clemente Island (SCE) profiler site provides insight into the changing upper-level synoptic
flow; its low-level flows are dominated by local mesoscale flows and may not be representative of those at coastal sites. Its southerly synoptic flow above 1500 m AGL shifted to southwesterly and then to westerly between 04/12 and 04/18 UTC (not shown). Sometime during the upper-level data gap from 05/00 to 05/04 UTC (Fig. 5a), it turned to a northeasterly flow, and by 05/11 UTC it became easterly above 2200 m AGL.

Fig. 3. Surface ozone concentrations (solid lines, ppb) and topographic heights (dashed lines, 500 m interval) on 5 August at (a) 1700, (b) 2000, (c) 2200, and 2400 UTC, with relative high (H) and low (L) concentrations shown.
The near-surface westerly flow of the daytime period was replaced at 05/08 UTC (05/01 PDT) by nocturnal weak chaotic flow of about 1000 m in depth. On 6 August (Fig. 5b), the westerly near-surface layer deepened to about 1800 m due to the now stronger large-scale onshore pressure gradient, while the still easterly upper-level synoptic flow increased in speed. By 06/10 UTC the near-surface flow became southerly...
through a layer that increased up to 900 m by 06/22 UTC due to development of a surface based Catalina eddy (Rosenthal et al., 2003).

The coastal Los Angeles (LAX) profiler site on 4 August (not shown) also initially had southerly upper-level synoptic flow, but only above 2000 m AGL (vs. 1500 m AGL at SCE) due to deeper over-land mesoscale influences. It turned northwesterly sometime between 04/11 and 04/16 UTC, and then northerly at about 04/20 UTC (4–8 h earlier than at SCE). The near-surface onshore westerly sea-breeze flow lasted until about 04/04 UTC (03/21 PDT), but persisted aloft (up to 1400 m) for eight additional hours. A 600 m deep AGL nocturnal downslope offshore (drainage and land breeze) flow started about 04/05 UTC (03/22 PDT). The sea breeze that replaced the nocturnal flow on the next morning at about 04/18 UTC (04/11 PDT) was similar (in start time, intensity, depth, and duration) as 24 h previously.

The generally northerly upper-level synoptic flow on 5 August (Fig. 6a) weakens at 05/01 UTC. Its base at 3500 m AGL at LAX is again higher (by about 1300 m) than at offshore SCE. The flow then turns easterly at about 05/09 UTC, ≈2 h earlier than at SCE. The near-surface sea breeze (to about 1700 m AGL) on this day was capped by a chaotic layer to about 2200 m AGL, an easterly return-flow layer (i.e., upper branch of sea-breeze circulation cell) to about 3000 m AGL, and the then prevailing northerly synoptic flow. The low-speed local (as discussed below) nocturnal offshore flow again started about 05/06 UTC, was again about only 700 m deep, and was capped by both a low-speed downslope (from local inland mountains) northerly flow up to about 2000 m AGL and the now easterly synoptic flow.

The easterly synoptic flow persists above LAX (as at SCE) throughout the 6th (Fig. 6b). The onshore westerly sea-breeze flow, which began at 05/18 UTC (05/11 PDT) on this the peak-ozone day, lasted until about 06/05 UTC (05/22 PDT). While this approximated the sea-breeze period of the previous day, it was deeper (at 2100 m AGL at 06/01 UTC vs. 1400 m AGL) and faster.
Fig. 5. Profiler horizontal-winds (flag is 5 m s\(^{-1}\)) at SCE on: (a) 5 August and (b) 6 August, with key flow areas indicated by arrows and bounded by solid lines.
than on the two previous days. The strengthening is associated with the above-discussed intensification of the GC Pacific high, which increased both onshore pressure gradients and coastal land temperatures. The sea-breeze layer was capped by a chaotic layer (shallower than on previous days) and an (7 vs. 5 m s\(^{-1}\)) than on the two previous days. The strengthening is associated with the above-discussed intensification of the GC Pacific high, which increased both onshore pressure gradients and coastal land temperatures. The sea-breeze layer was capped by a chaotic layer (shallower than on previous days) and an
easterly return-flow layer until 06/02 UTC (05/19 PDT), after which (next 3 h) it apparently blended with an unexplained westerly flow.

The nocturnal offshore flow again started about 06/06 UTC, but grew to about 1300 m AGL (vs. the 700 m of the previous 2 days). In addition, it was faster, better organized, and lasted 4 h longer at the 100 m AGL level than during the previous two nights (until 2100 UTC or 1400 PDT). It was again capped by downslope topographic flows up to roughly 2500 m AGL. The easterly synoptic flow, still present above 3000 m AGL, perhaps somehow (even with intrusion of the intervening non-easterly flow layer) caused the stronger near-surface easterly flow. The expected sea-breeze flow did not form on the next morning, but the easterly flow near the surface turned southerly at 06/22 UTC due to formation of the Catalina eddy mentioned above.

The inland Hesperia (HPA) profiler site is in a mountain pass (surface elevation near 1 km MSL) surrounded by peaks that block marine air intrusions. Its flow patterns (thus not affected by MBLs) only showed mesoscale influence from near-surface up- and downslope flows. Its lack of data gaps (as at SCE and LAX) allows for accurate estimates of times changes in the upper-level synoptic forcing. Its initially southerly synoptic flow turned westerly at 04/01 UTC (not shown), 10–16 h earlier than at the more westerly SCE and LAX. It then became northerly at about 04/23 UTC (about 3 h later than at LAX) and then easterly at about 05/05 UTC (Fig. 7a), about 4 and 6 h before the shift at LAX and SCE, respectively. Without marine influences, the base of its synoptic layer is generally about 1300 m AGL over the entire period (Figs. 7a and b), similar (in MSL) to that at coastal LAX.

Nocturnal downslope flows at complex-topography sites like HPA are dependent on synoptic wind direction, which determines upwind topographic features. Before the peak-ozone hours, a northwesterly nocturnal near-surface drainage flow existed until 1800 UTC (05/11 PDT). This was superceded by 5 h of northeasterly (combined easterly synoptic forcing, topographic channeling, and upslope) flow starting at 05/19 UTC, which prevented further inland penetration of the combined sea breeze and valley breeze.

Resulting low speeds within such convergence zones allow pollutants to concentrate, resulting in upward ejection (McNider et al., 1998). As the sea-breeze front on the peak-ozone day moved westward past the Norton (NTN) profiler site (not shown, but upwind of HPA), ozone levels at nearby sites peaked. On the days preceding and following the peak-ozone day, however, late afternoon HPA surface winds remained generally westerly, with ozone thus advecting away.

In summary, the large-scale forcing consisted of a weak and slowing changing offshore high-pressure system. SCOS97-NARSTO time–height sections showed changing (from onshore westerly to northerly and then to offshore easterly) upper-level (> 3 km) winds. The second change occurred during the evening hours preceding the ozone peak, first at inland SoCAB sites and then a few hours later at western coastal sites. The onshore (sea breeze plus upslope) flow on the day before the peak-ozone period had an average depth at coastal LAX of about 1700 m AGL, and was capped by a 500 m chaotic layer, an 800 m easterly return-flow layer (i.e., upper branch of sea-breeze circulation cell), and the synoptic flow. The top of the return-flow region was thus about 1.5 times the average topographic height, in agreement with the simulations of Lu and Turco (1996). The strongest and deepest sea breeze occurred on the peak-ozone day, due to the above-discussed effects from the strengthening of the GC high.

The spatial extent of the above-discussed wind-shifts resulted from changes in the position of a small-scale upper-level ridge. The 3800 m AGL level winds (seen above as unaffected by mesoscale influences) at 04/18 UTC (Fig. 8a) show this ridge just offshore of the northern SoCAB. This produces onshore or along-shore (northwesterly) flows over the entire SoCAB. By 05/00 UTC (not shown), it produced offshore flow in the southern Basin, consistent with a more northerly position. Six hours later (Fig. 8b) the ridge is now further northwest (offshore of the Santa Monica Mountains, just north of the SoCAB), producing offshore northeasterly flow over the entire Basin. After another 6 h (at 05/12 UTC) (not shown), it started to move back eastward (inland) over the coastal plain, producing a transitional along the coast flow. By the peak-ozone time of 05/20 UTC (Fig. 8c), it is more inland (northward and eastward), and thus the flow is mostly easterly offshore over the entire SoCAB. By 06/12 UTC (Fig. 8d) the ridge moved southward, maintaining offshore flow in the southern SoCAB and producing southeasterly along-shore flow over its northern half.

The above is consistent with conditions identified by Ulrickson and Mass (1990a, b) that produce infrequent (one or two) summer ozone episodes per year over the SoCAB. First, the GC high strengthens, tilts eastward with height, and produces an inland ridge at the 500 mb level. The surface inverted thermal trough then also strengthens, deepens (to 850 mb), and moves northward. When the upper-level ridge thus also moves northward, offshore easterly flow develops over the SoCAB, adiabatic downslope warming results over the Basin, the elevated subsidence inversion lowers, and a surface ozone episode results a day before a marine air surge develops due to the high inland temperatures. As will be shown below, inversion lowering also played a key role in the timing and location of the observed peak ozone.

Changes in the upper-level synoptic forcing thus impact near-surface flows, as does near-surface
land-sea and topographic mesoscale forcing. The nighttime 7 m flow at 04/12 UTC (Fig. 9a) is complex and low speed, and although inland areas show downslope flows, no clearly defined coastal land breeze is seen. Land breezes are generally weaker than sea breezes, and can be suppressed with an onshore opposing flow (as is normal on the West Coast). In addition, the normally cold California coastal SSTs also can prevent formation of the nocturnal offshore pressure gradients necessary for land-breeze formation.
By 04/15 UTC (Fig. 9b), onshore westerly sea-breeze flows (nearly perpendicular to the shoreline) formed, as have easterly upslope flows on the eastern slopes. Sites between these two flow areas show either calm or along coast flows (in either direction). Two hours later (Fig. 9c), a second separate westerly flow region has formed (from thermal heating) on the western slopes of the inland mountains, producing a weak surface convergence zone where it meets the easterly upslope flows. A narrow low-speed zone (with few observational sites) also exists between the two westerly flows. By 04/23 UTC (Fig. 9d), sea-breeze speeds reached maximum intensity, and both westerly flows have merged into a single strong inland-directed breeze. The low SCOS97-NARSTO inland station density (relative to coast sites) implies that mesoscale modeling (as in Boucouvala et al., 2003) could better determine the inland-moving boundary between the two surface westerly flows.

By 05/02 UTC (not shown), the onshore flow weakened and the surface westerly flow showed maximum inland penetration as gravity-current effects kept its leading edge moving inland, even as coastal winds became offshore (Ueda et al., 1988). By 05/06 UTC (not shown), offshore flow existed over most of the coastal plane, as the sea breeze become a land breeze and upslope flows became downslope. The 05/12 UTC surface flow (Fig. 10a) is as complex as on the 4th, but by 05/15 UTC (Fig. 10b) coastal sea breeze and inland upslope easterly flows have again formed; they are also again separated by calm or near-calm areas (as on the 4th).

Two hours later (Fig. 10c), the two separate westerly flows of the previous day may or may not be present (a near lack of observations in the area that would show calm or along coast flows prevents a definitive determination). Inland frontal penetration is reduced (relative to the 4th) due to the now stronger offshore opposing northeasterly flow on the eastern facing slopes of inland mountains. By 05/22 UTC (time of ozone peak), the westerly flow again reaches maximum intensity (Fig. 10d) with winds somewhat faster than on the previous day. Its inland penetration, however, was still
somewhat less than on the 4th. The opposing flow is a combination of the surface projection of the upper-level easterly large-scale flow discussed above and of the north-northeasterly upslope flow (more variable on the previous day). The resulting convergence zone (on this, the peak-ozone day) is stronger and further upwind (west) of the inland ridges than on the 4th. Its exact location is again difficult to determine, given the low data density in inland mountain areas.

The maximum westerly flow penetration several hours later on the 5th was thus less than on the previous day, and by 06/03 UTC or 05/20 PDT (not shown) the sea breeze again (as on the previous day) had retreated back to the coast. On 06/23 UTC (not shown), the afternoon after the peak-ozone event, the sea breeze was more southerly and its penetration thus further inland to the San Bernardino Mountains (compared to the previous days). This increased surface penetration resulted from the turning of the opposing synoptic flow aloft from offshore (northeasterly) on the 5th to along-shore (southeasterly) on the 6th, which encouraged formation of the surface Catalina Eddy.

The nighttime 800 m AGL flow (middle of inland directed sea-breeze layer in Figs. 5–7) at 04/12 UTC (Fig. 11a) shows a somewhat less complex combination and faster speeds (than in the concurrent surface chart) because of reduced surface mesoscale influences. While inland downslope flows are seen, no land breeze exists again (same as at the surface), as coastal sites generally show along-coast flows. While speeds increased (same as at the surface) by 04/16 UTC (not shown), they were not yet organized into an onshore flow, and the offshore opposing synoptic flow at inland sites was likewise unorganized. By 04/23 UTC (Fig. 11b), the onshore flow reached maximum intensity, but flow directions at inland mountain regions cannot be determined, due to the lack of operational observational sites.

Nighttime 800 m AGL flow speeds at 05/12 UTC (not shown) were faster, more organized, and more offshore (northerly) (due to the changing synoptic flow) than on the 4th (when it was along-shore from the northwest). At 05/16 UTC (Fig. 11c) an onshore breeze was again (as on the 4th) not yet present, even though it had already started to form (and grow upward) at coastal

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Fig. 9. Winds at 7 m AGL (flag is 5 m s⁻¹) on 4 August at: (a) 1200, (b) 1500, (c) 1700, and (d) 2300 UTC, with topographic heights (500 m interval), general flow directions (large subjective arrows), near-calm chaotic areas (outlines), and convergence zones (solid lines).
surface sites (Fig. 6a). By 05/22 UTC, the onshore flow reached its maximum intensity (Fig. 11d).

It then turned along-shore (from northwest) over most of the Basin, but remained offshore (from north) at its northern edge until 06/06 UTC (not shown). That flow then turned northeasterly and expanded southward into the Basin. By 06/15 UTC (not shown), directions over the entire basin were southeasterly (i.e., along coast), influenced by the Catalina Eddy formation mentioned above.

In summary, the initial (northwestward) movement of the upper-level coastal ridge at 3800 m AGL during the evening of the 4th projected the resulting upper-level offshore flow down to the surface at high-elevation inland sites. The surface offshore flow in conjunction with the onshore (combined sea and valley) flow produced a stronger inland-moving convergence zone (in which the peak-ozone values formed) that did not pass the San Bernardino Mountains, as it did on the preceding and following days. The daytime onshore (sea plus valley breeze) coastal flow within the PBL (800 m AGL) on the peak-ozone day started somewhat later, lasted longer, and was stronger than that at 7 m. The opposing 800 m AGL daytime offshore flow at inland sites was also stronger, better organized, and more directed to the coast than on the previous and following day (when the upper-level ridge moved back southward and produced along-shore flow aloft). Low observational site-density made precise determination of upper-level locations of the resulting inland-moving convergence zone more difficult than at the surface.

3.3. SCOS97-NARSTO temperatures

The rawinsonde temperature time–height cross-section at the offshore San Nicolas Island (SNIC) site (Fig. 12a) showed a persistent (throughout study period) daytime and nighttime strong (10 K) subsidence inversion with tops at about 600–800 m AGL, with its most intense segment, from 200 to 400 m AGL. As mentioned in Section 2, accurate inversion base determination is difficult below 100 m AGL. While the base on the both the days preceding and following the peak ozone appears just about at that level, no determination can be made for its elevation during the period from 05/18 to 06/12 UTC (which brackets the peak-ozone day).
Warming occurred throughout the inversion from 05/00 to 06/06 UTC, with cooling thereafter. The upper-level warming thus strengthened (and lowered) the inversion base towards the surface on the peak-ozone day (but not on preceding and following days) and also favored higher ozone levels due to the resulting increased photolysis rates. The warming coincided with the above-discussed northward movement of the upper-level ridge to the northern SoCAB edge, with SNIC thus further south of the ridge center. As inversion layer elevation decreases and subsidence intensity increases with distance from a ridge center, the inversion over the SoCAB thus lowered and warmed during this northward movement period. The ridge movement to the north also produced an easterly offshore flow (as discussed above) in association with downslope adiabatic warming that also contributed to the observed temperature rise over the SoCAB during this period. The southward movement of the ridge after the peak-ozone day resulted in the observed return to normal (offshore) upper-level flow and higher-elevation inversion conditions.

Rawinsonde temperature cross-section patterns are similar at coastal UCLA (not shown), except that inversion intensity peaked one launch earlier at 06/00 UTC as subsiding air moved outward (southward from UCLA to SNIC) from the inland upper-level ridge. Temperatures at the 29 Palms (29PA) inland site (east of San Bernardino Mountains) show no influence from the upper-level ridge (Fig. 12b), as they lack an elevated inversion and have near-isothermal and/or weak nocturnal surface-inversion layers.

In summary, maximum subsidence warming from the upper-level ridge was confined to a narrow coastal-zone during the 24h encompassing the surface ozone peak. As the ridge moved northward during this period, its subsidence inversion intensified and descended, while the resulting offshore upper-level offshore flow produced downslope adiabatic warming that was intensified over the inland mountains of the eastern SOCAB. These conditions enhanced photochemical formation of ozone, which peaked in the moving surface convergence zone discussed above.
The 2 m SCOS97-NARSTO observed temperatures at 04/12 UTC (04/05 PDT) (not shown) revealed an expected maximum in the low desert area north of the Mexican border and a secondary maximum in the inland plateau east of the San Gabriel Mountains. Minimum temperatures occurred (as expected) on mountain peaks,

Fig. 12. Rawinsonde temperature (2°C interval) time section (diamonds indicate soundings) at: (a) SNIC and (b) 29PA, with inversion top and bottom (dotted lines) and with relative warm (W) and cold (C) areas.
when such observations were available. The average nighttime coastal–inland temperature difference of about 8°C (18°C vs. 26°C) increased to a mid-day value of about 10°C at 04/18 UTC (36°C vs. 26°C), and to a late afternoon difference of about 13°C at 05/00 UTC (39°C vs. 26°C). Throughout the peak-ozone day of 5 August, most SoCAB land areas warmed by 2–3°C (consistent with the subsidence warming in Fig. 12a), but spatial patterns remained similar to those during the previous day, e.g., see Fig. 13a for 05/09 UTC. Coastal–inland gradients on 05/21 UTC (Fig. 13b) were thus about 2–3°C stronger than on the 4th, which produced a

Fig. 13. Temperatures (solid lines, at 2°C interval) at 2 m AGL at: (a) 0900 UTC 5 August and (b) 2100 UTC 5 August, with topographic heights (500 m interval) and with relative warm (W) and cold (C) areas.
stronger onshore sea-breeze flow on this day (discussed above). Throughout the daytime hours of the 6th (not shown), temperatures over the entire basin cooled to almost those of the 4th.

Early morning temperatures at 300 m AGL (generally just within lowest section of subsidence inversion and still influenced by surface heat fluxes) at 04/12 UTC (Fig. 14a) shows a coherent, consistent pattern, with cool air in coastal regions and warm air at inland locations (as at the surface); note the lack of upper-air mountain-top observations. Mid-afternoon temperatures at 05/00 UTC (Fig. 14b) show a similar pattern, but with somewhat warmer values (as expected from typical diurnal cycles). The distribution during the night before ozone peak at 05/12 UTC (not shown) is again similar to that of the previous day, but with higher values from the north and eastward movements of the upper-level ridge (as discussed above). Early morning values at 06/12 UTC (not shown) show cooling (relative to the 5th), but values are still warmer than on the 4th.

Fig. 14. Profiler and rawinsonde temperatures (K) at 300 m AGL at: (a) 1200 UTC 4 August and (b) 0000 UTC 5 August, with topographic heights (500 m interval) and with relative warm (W) and cold (C) areas.
Early morning 04/12 UTC (or 04/05 PDT) 800 m AGL coastal temperatures (Fig. 15a) are warmer than those at 300 m AGL by about 2°C, consistent with the elevated inversion in Fig. 12a. Inland temperatures, however, are cooler at 800 m than at 300 m, as no (surface or elevated) inversion exists at inland sites (Fig. 12b). The inversion (and thus the lack of surface heat flux influences) also explains the reversed 800 m AGL horizontal temperature gradient (relative to 2 and 300 m AGL patterns), i.e., warmer air in coastal regions and cooler air at inland locations. Mid-afternoon values at 05/00 UTC (Fig. 15b) are somewhat warmer than 12 h before (as expected), but still show the reversed gradient (except near to the coast due to onshore advection of cool marine air). The expected large-scale warming continued during the next 30 h, i.e., to a time 8 h past the 05/21 UTC ozone peak. Early morning values at 06/12 UTC (not shown) showed a combination of the large-scale and diurnal cooling.

In summary, warming patterns at 2 and 300 m AGL were dominated by diurnal surface forcing, while those at 800 m AGL were consistent with the changes in subsidence-inversion layer structure seen in vertical time sections. Coastal–inland temperature gradients on the peak-ozone day were stronger than on the other days, which produced the faster sea-breeze winds on this day.

Fig. 15. Same as Fig. 8, but for 800 m AGL.
4. Conclusion

Analysis showed that the SCOS97-NARSTO 4–7 August peak surface ozone resulted from a relatively infrequent large-scale upper-level synoptic forcing, in which a weak local coastal 700 mb ridge first moved from center of the SoCAB coast to a more westerly position at the northern SoCAB coast, then inland over the eastern SoCAB, and then back to the south. The first movement resulted in a rotation of the upper-level (>3000 m MSL) synoptic background flow from its normal westerly onshore direction to a less common offshore northeasterly flow during the nighttime period preceding the peak-ozone day. The last movement resulted in a further rotation of the upper-level synoptic background flow to an along-shore southeasterly flow during the nighttime period after the peak-ozone day. Onshore movement of the ridge also produced warming both aloft and at the surface at inland sites during morning hours of the peak-ozone day, as well as a concurrent sinking and strengthening of the associated elevated subsidence inversion over the SoCAB coast. The onshore (sea breeze plus upslope) flow on the day before the peak-ozone period had an average depth along the coast of about 1700 m AGL, and was capped by a 500 m chaotic layer, an 800 m easterly return-flow layer (i.e., upper branch of sea-breeze circulation cell), and the synoptic flow. The top of the return-flow region was thus about 1.5 times the average topographic height.

The strongest and deepest sea breeze occurred on the peak-ozone day, due to the effects from the strengthening GC high. Resulting easterly upper-level synoptic background winds influenced surface wind flow directions in high-elevation inland areas, so that a surface frontal convergence zone resulted where the easterly flow met the inland-moving combined westerly onshore (sea and valley breeze) flows. Maximum inland convergence zone penetration on the high ozone day was to a position west of the San Gabriel Mountain peaks, the location of peak-ozone concentrations.

A companion paper in this volume (Boucouvala et al., 2003) reports on MM5 simulations of the meteorological conditions discussed in this paper. Analyses reported here were used to evaluate results from those simulations, which could provide more precise locations for the sea-breeze convergence zone in the data sparse high-elevation areas.

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