The Catalina Eddy and its Effect on Pollution over Southern California

ROGER M. WAKIMOTO

Department of Atmospheric Sciences, University of California, Los Angeles, 90024

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ABSTRACT

A case study of a Catalina Eddy during Project BASIN is presented. There appears to be a topographic influence in the generation of this eddy. Detailed surface and upper-air data over Los Angeles illustrate the effect of the eddy on the boundary layer and on the transport of ozone out of the basin. Isentropic analyses are consistent with visual satellite images of the phenomena. The Catalina Eddy was shown to extend throughout the entire depth of the strong temperature inversion that exists over Los Angeles, with maximum wind speeds within the inversion. Surface ozone levels downwind of the eddy are shown to vary depending on the local circulations.

1. Introduction

Mesoscale cyclonic and anticyclonic eddies are frequently observed with satellite imagery near coastal regions (e.g., Rosenthal, 1968; Brandli et al., 1977; Dorman, 1985). The best known of these eddies has been referred to by meteorologists as the “Catalina Eddy” — so called because it frequently appears centered near Catalina Island off southern California.

The importance of this eddy is its alteration of the coastal airflow patterns from Baja California to beyond Santa Barbara. The evolution of this circulation is accompanied by a deepening of the marine layer along the aforementioned coastal strip and the development of a persistent stratus deck that frequently appears as a spiral feature on a visual satellite image (e.g., see Rosenthal, 1968). Eichelberger (1971) has stated that strong eddies can deepen the marine layer from 100 to 1500 m in less than 24 hours.

The first detailed mesoscale study of a Catalina Eddy was presented by Bosart (1983), analyzing the 1968 case briefly discussed by Rosenthal. His conclusions were (refer to Fig. 1)

1) the incipient circulation forms on the coast near Santa Barbara, in ambient northwest flow at all levels downwind of the coastal mountains;

2) cyclonic shear vorticity appears offshore in response to lee troughing downstream of the coastal mountains between Vandenberg and Pt. Mugu, California;

3) mountain wave activity may be aiding incipient eddy formation in association with synoptic-scale subsidence and the generation of a stable layer near the crest of the coastal mountains;

4) a southeastward displacement and offshore expansion of the circulation occurs following the passage of the synoptic-scale ridge line;

5) dissipation of the eddy occurs with the onset of a broad onshore flow as the synoptic-scale ridge line moves further eastward.

Bosart’s second conclusion reinforced previous works (e.g., Rosenthal, 1968) suggesting that the eddy was a wake low forming downstream from the coastal mountains east of Pt. Conception and Pt. Arguello. In contrast, Dorman (1985) suggested that the Catalina Eddy was a result of an internal solitary Kelvin wave within the marine layer propagating northward along the coast. In light of Bosart’s statement that the air mass off the coast is typically very dry and cannot sustain cloudiness until the eddy convergence and ascent act for a long time, Dorman’s wave propagation speed of 5–8 m s⁻¹ may be considered suspect since it appears to be based entirely on satellite imagery.

Based on these past studies, it is apparent that the formation of the Catalina Eddy is still not completely understood; accordingly, the eddy is difficult to forecast by the National Weather Service (Lessard, personal communication, 1985).

This creates operational problems for the inhabitants of southern California for several reasons. With the unexpected appearance of a persistent stratus deck of clouds during an eddy, commercial and military shipping and air traffic may be adversely affected. Maximum air temperatures may drop as much as 7°C from the previous day (Eichelberger, 1971). The Catalina Eddy also impacts the air pollution forecasts in southern California. Air pollutants within the Los Angeles Basin are hypothesized to mix vertically and hence become diluted within the deeper marine layer with resulting north to northwest transport through mountain passes.

1 Meteorologist-in-Charge, Los Angeles Office.
In an attempt to resolve current concepts of the Catalina Eddy, this paper presents an analysis of an event using the high-resolution data set collected during Project BASIN (Wakimoto and Wurtele, 1984). In addition, surface and vertical profiles of ozone concentrations are examined to determine the transport of pollution with time. It has been hypothesized that once the Catalina Eddy forms, much of the pollution from Los Angeles is advected into the Santa Barbara/Ventura area producing a major smog episode.

BASIN, a mesoscale meteorological project over Los Angeles, which was the main data source for this research paper is discussed in section 2. The synoptic and mesoscale conditions during the analysis periods are described in sections 3 and 4, respectively. Surface and upper-air ozone concentrations at selected stations during a Catalina Eddy are shown in section 5. Discussion and conclusions drawn from the analyses are presented in section 6.

2. Project BASIN

In the summer of 1984, the most comprehensive collection of air quality and meteorological data ever attempted over Los Angeles was directed by the University of California at Los Angeles (UCLA), with the aid of several organizations listed in Wakimoto and Wurtele (1984). Although Project BASIN (Basic studies on Airflow, Smog, and the INversion) had no official connection with the Olympic Games, the spirit of cooperation associated with this event played an important part in the success of the project. An overall and enlarged base map of the BASIN network are shown in Figs. 1 and 2, respectively. A dense network of surface stations recording windspeed and direction, temperature, and dew-point temperature was used during the project. In addition to these parameters, the South Coast Air Quality Management District (SCAQMD), Ventura County Air Pollution Control District, and Santa Barbara County Air Pollution Control District stations recorded gaseous air pollutant concentrations (e.g., ozone) on a continuous basis. During the field phase of BASIN, radiosondes and airsondes were launched every 4 h around the clock at 11 upper-air stations (Table 1 and Fig. 2); there were three complete days of monitoring which consisted of the following periods:

1) 05 PST 8 August–04 PST 10 August
2) 16 PST 17 August–15 PST 18 August.

2 Not all stations recorded all of these variables.
3 UTC = 8 h + PST. Hours are given by two-digit numerals herein.
Fig. 2. An enlarged map of the BASIN network. The 11 upper-air sites are listed in Table 1. The 1000 ft contour equals 305 m.
TABLE 1. BASIN upper-air sites.

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Location</th>
<th>Elevation (m MSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSU</td>
<td>California State University,</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>Northridge</td>
<td></td>
</tr>
<tr>
<td>CWA</td>
<td>Cowan Ave</td>
<td>47</td>
</tr>
<tr>
<td>ELM</td>
<td>El Monte</td>
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<tr>
<td>ETW</td>
<td>Eaton Wash Dam</td>
<td>280</td>
</tr>
<tr>
<td>GRV</td>
<td>Green River Golf Course</td>
<td>146</td>
</tr>
<tr>
<td>LGB</td>
<td>Long Beach Airport</td>
<td>16</td>
</tr>
<tr>
<td>MTW</td>
<td>Mount Wilson</td>
<td>1725</td>
</tr>
<tr>
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</tr>
<tr>
<td>FVR</td>
<td>Palos Verdes</td>
<td>105</td>
</tr>
<tr>
<td>RIV</td>
<td>Riverside Airport</td>
<td>244</td>
</tr>
<tr>
<td>TUS</td>
<td>Tustin</td>
<td>17</td>
</tr>
</tbody>
</table>

Only the first operational period for BASIN will be examined in this paper.

Upper-air soundings were also available from the Pacific Missile Test Center at Pt. Mugu and San Nicolas Island, and the National Weather Service upper-air sites at San Diego and Vandenberg Air Force Base.

3. Synoptic analysis

A series of subjectively drawn 700 and 500 mb maps at 24-h intervals for 8, 9 and 10 August is shown in Fig. 3. A strong ridge had built over California on 7 August at the 500 mb level (not shown), drifted eastward in response to a short-wave trough approaching the Pacific Northwest, and was centered over northwestern Colorado, northeastern Utah, and southwestern Wyoming by 10 August. The 700 mb pattern exhibits the same basic features as the 500 mb level with one exception; a well-defined cyclonic circulation is apparent in extreme southeastern New Mexico in Fig. 3d. In subsequent analysis times this low center moved westward in the easterlies south of the subtropical anticyclone. As this trough approaches southern California the winds at 700 mb shift, changing from south-

![Fig. 3. The 500 and 700 mb analyses for 04 PST on (a) and (d) 8, (b) and (e) 9 and (c) and (f) 10 August. Black lines are contours and dashed lines are isotherms.](image-url)
easterly at 04 PST 8 August to northeasterly at 04 PST 9 August. As will be discussed in section 4, the Catalina Eddy formed just offshore in the afternoon on 8 August. This observation is in slight disagreement with Bosart (1983) who states that the eddy forms under northwesterly flow at all levels and expands with the passage of the synoptic ridge axis.

The surface maps (Fig. 4) are characterized by the combined influence of the semipermanent Pacific High and the thermally induced low pressure over the desert regions in the extreme southwestern United States and northern Mexico. This thermal low is not related to the cyclonic circulation noted at the 700 mb level; however, once the trough of this upper-level low affects California at ~16 PST 8 August, it appears to deepen the thermal low to its lowest surface pressure value during the entire analysis period. In response to the increasing pressure gradient, the offshore wind speeds increase substantially and remain approximately parallel to the coast. At the same time, the ocean buoys off the coast of Los Angeles report a turning of the wind to a westerly direction. The diurnal nature of the thermal low is clearly shown as it fills and the coastal winds weaken in the morning of 9 August (Fig. 4c) and re-intensifies in the afternoon (Fig. 4d). The surface frontal feature in the Pacific Northwest is associated with the short-wave trough at upper levels. In contrast to Dorman (1985), no wind direction shift progressing northward up the coast was detected in Fig. 4, which might indicate a Kelvin wave progression in the marine layer. It should be noted that surface maps were analyzed every 3 h, although only the maps at 12 h intervals are shown in Fig. 4.

4. Mesoscale analysis

a. Surface analysis

Detailed 12-h surface analyses on the meso-α scale (200–2000 km) over the coastal areas of southern California are shown in Fig. 5. Initially, California is under a northwesterly flow regime (Fig. 5a) that is altered by the afternoon sea breeze at coastal areas (Fig. 5b). The first suggestion of a coastal trough near Catalina Island

![Fig. 4. Surface analyses for 04 and 16 PST on (a) and (b) 8 and (c) and (d) 9 August, and (e) 04 PST on 10 August. Black lines are isobars.](http://journals.ametsoc.org/doi/pdf/10.1175/1520-0493(1987)115<0837:TCEAIE>2.0.CO;2)
FIG. 5. Meso-α scale surface analyses over southern California for (a) 0500 and (b) 1600 PST on 8 August, (c) 0400 and (d) 1600 PST on 9 August, and (e) 0400 PST on 10 August. Black lines are isolars. The dashed boxed-in area is enlarged in Fig. 6 except for Fig. 5e.
in the lee of the coastal mountains near Pt. Conception occurs at 1600 PST 8 August. Recall that the coastal winds are strongest at this time. By 0400 PST 9 August (Fig. 5c) this trough becomes a closed circulation. The winds at San Diego that were northwesterly 12 hours earlier are now shifting to southwesterly as the Catalina Eddy expands. A curious feature at this time is the relatively high pressure over the Los Angeles Basin. The apparent diurnal nature of this phenomenon leads to the conclusion that it is thermally induced; however, a mechanism for its formation has not been formulated. The areal growth of the eddy continues at 1600 PST 9 August (Fig. 5d) as the winds at San Diego become more southerly. Interestingly, a small-scale trough that was first noted in Fig. 5c near Santa Barbara is still evident at 1600 PST 9 August. It appears to be a wake trough since its location is immediately in the lee of the coastal mountains. The eddy does not change significantly by 0400 PST 10 August (Fig. 5e). Unfortunately the field phase of BASIN terminated at this time; however, an examination of the surface synoptic maps (not shown) suggests that the eddy continued until the afternoon of 12 August.

In contrast to the results of Bosart (1983), there are no indications of downslope flow near Santa Barbara, hypothesized as being an indication of mountain wave activity. Bosart states that the downslope flow resulting from northwesterly flow may be important for eddy development; however, the results in this paper do not support this conclusion.

One of the objectives of this paper is to examine the eddy’s alteration of the boundary-layer features and hence the pollution patterns over Los Angeles. The surface analyses on the meso-β scale (20–200 km) is shown in Fig. 6. In Fig. 6a, the synoptically forced northwesterly flow is evident in the western part of the basin. In the east basin, a nocturnal drainage flow exists. By 1000 PST 8 August (Fig. 6b), the sea breeze regime is firmly established with winds as far inland as San Bernardino and Riverside showing a westerly direction. Maximum ozone concentrations at this time are ~10 parts per hundred million (pphm). Note the wake eddy (~10 km in diameter) in the lee of the Palos Verdes Hills. At 1600 PST 8 August (Fig. 6c), vast quantities of ozone are advected into the east Basin as the sea breeze intensifies. This is a common scenario over Los Angeles in the summer; ozone is produced in the heavy traffic and industry areas near central and western Los Angeles and is advected eastward by the sea breeze while the photochemical reactions continue bringing very high ozone concentrations into the east basin. Two hours earlier at 1400 PST 8 August, the ozone level reached 31 ppbh at Glendora. In Fig. 6d the remnants of the sea breeze are apparent; however, the first indication of southerly flow associated with the Catalina Eddy has developed in the southern part of the network near Costa Mesa. By 0400 PST 9 August (Fig. 6e), the southeasterly flow of the eddy has expanded over the entire west Basin. Interestingly, the northerly flow over the east Basin appears to be drainage winds off the San Gabriel Mountains with the Chino Hills and the Santa Ana Mountains acting as a barrier to separate these two regimes. The eddy flow is dominating the entire Los Angeles Basin in Fig. 6f, except near Santa Monica.
Fig. 6. Meso-β scale surface analyses over Los Angeles for (a) 0500, (b) 1000, (c) 1600, and (d) 2200 PST on 8 August and (e) 0400, (f) 1000, (g) 1600, and (h) 2200 PST on 9 August. Black lines are streamlines and dashed lines are surface ozone concentrations in parts per hundred million (pphm).
Fig. 6. (Continued)
and the Los Angeles International Airport (LAX) where the sea breeze forces the winds toward a westerly direction. As the eddy winds intensify by 1600 PST 9 August (Fig. 6g), the sea breeze also strengthens and reaches as far inland as possible against these winds. There is a dramatic drop in ozone concentrations at this time compared to 24 hours earlier (Fig. 6c). When the sea breeze weakens at night (Fig. 6h), the south-easterly flow prevails over most of the Los Angeles area.

Two lines of convergence are seen in the analyses presented in Fig. 6. The first line is near Perris (see Fig. 2) toward the east end of the BASIN network illustrated in Figs. 6d, f and h. Upon examination of Fig. 5 it becomes apparent that this convergence line is orographically induced as the southeasterly flow associated with the eddy diverges around the Santa Ana Mountains. The western branch flows into the east basin through the GRV site and subsequently turns toward a northerly direction and collides with the flow from the eastern branch. This phenomenon is similar to the Elsinore convergence zone discussed by Edinger and Helvey (1961).

The second convergence line is located near the Newhall and Simi Valley sites (Fig. 1) and is evident in the northwest corner of Fig. 6c and also Figs. 5b and d. Figures 5b and 6c show the early stage of the San Fernando convergence zone as discussed by Edinger and Helvey (1961) caused by the collisions of the two sea breezes originating from the Ventura coast and the Los Angeles coast as they wind through the various mountain passes. The convergence line in Fig. 5d is slightly different since it results from the collision of the sea breeze front from the Ventura area and the combined southerly flow of the Catalina Eddy and the sea breeze originating from Los Angeles. This convergence zone plays an important role in preventing pollution from reaching the Ventura area as will be discussed in section 5.

b. Isentropic analysis

In an attempt to understand the trajectories of the winds during the evolution of a Catalina Eddy a series of maps of pressure and Montgomery stream function on the \( \theta = 310 \) K surface for 1300 PST 8 August, and 0500 PST and 1300 PST 9 August are shown in Fig. 7. Owing to its low elevation, this surface does not extend past the coastal mountains.

At 1300 PST 8 August (Fig. 7a) there is evidence of a coastal trough developing as shown by the west wind at San Nicolas Island and the northwest winds at Vanden-berg and San Diego. The local observation of a deepening marine layer once the eddy forms is confirmed by the lifting of the 920–900 mb layer along the coastal water from Los Angeles to San Diego. Interestingly, by 0500 PST 9 August (Fig. 7b), there has been an \( \approx 180^\circ \) shift in wind direction over the Los Angeles Basin as the Montgomery Stream function values fall over the ocean. Several of the upper-air sites did not report a wind speed and direction for this surface owing to the loss of the balloon (teledolite-tracking) in the stratus deck of clouds; however, the thermodynamic information was still being recorded. Deepening of the boundary layer is continuing along the coastal waters; however, to the north, subsidence of the 910–880 mb level has developed over the Santa Barbara and Ventura area. Recall that it has been hypothesized that air pollutants (in particular, ozone) are advected from Los Angeles to the Santa Barbara/Ven-utura area during a Catalina Eddy event. Figure 7b supports this idea and suggests subsidence over the same area may contribute to a smog episode. In Fig. 7c (1300 PST 9 August), the eddy circulation is still vigorous. Note that the pressure analysis at this time suggests that the eddy is a warm-core low.

Kinematic computations of vertical motion were made for selected triangles, shown in Fig. 7c using the computational method described by Bosart and Sanders (1981). The input winds consisted of values at the surface and thereafter at every 50 mb to the highest level of the sounding. Unfortunately, except for the Vanden-berg and San Diego sounding, no data were collected at levels higher than 500 mb; thus, a correction factor could not be applied to the vertically inte-grated divergence in order to allow the upper boundary condition of \( \omega \) equal to zero at 100 mb.

The results presented in Fig. 8 must be considered suspect owing to the limitation just discussed. In addition, the diurnal effect of the sea breeze and the effect of flow in the boundary layer channeling through the complex topography may contaminate the vertical motion calculations.

The Pt. Mugu–Vanden-berg–San Nicolas triangle (Fig. 8a) exhibits weak subsidence below 870 mb with strong ascent above at 1300 PST 8 August. The rising motions are apparently an indication of the ridge at upper levels moving eastward and the approach of the short-wave trough toward the Pacific Northwest. This same pattern is also apparent for the Pt. Mugu–San Nicolas–San Diego triangle (Fig. 8c). Strong ascent, however, is apparent at all levels in the Pt. Mugu–San Diego–Riverside triangle (Fig. 8b) consistent with the isentropic analysis in Fig. 7a.

Once the Catalina Eddy has developed by 0500 PST 9 August, there is pronounced descent shown in the Pt. Mugu–Vanden-berg–San Nicolas triangle (Fig. 8a) of \( \approx 5-6 \times 10^{-3} \) mb s\(^{-1}\) in agreement with Fig. 7b. Figure 8b shows a change from ascent shown earlier to descent at levels below \( \approx 750 \) mb with ascent above. This figure suggests that the effect of the eddy extends to this level. This will be examined in more detail in section 4c. Surprisingly, Fig. 8c indicates subsidence at all levels when lifting would be expected in Fig. 7b. It is believed that the vertical motion calculations at this time are in error.
Fig. 7. Isentropic analyses for the 310 K surface at (a) 1300 PST on 8 August, (b) 0500 and (c) 1300 PST on 9 August. Black lines are Montgomery Stream Function values and the dashed lines are isobars. The approximate intersection of this surface with the mountains is shown by the dash-dot line. Actual launches at Vandenberg and San Diego occurred at ~0300 and 1500 PST. In Fig. 7c, the black triangles bound areas where kinematic analyses were performed.
By 1300 PST 9 August, strong subsidence is still apparent over the Pt. Mugu–Vandenber–San Nicolas triangle (Fig. 8a). The initial descent when the eddy winds first developed over the Pt. Mugu–San Diego–Riverside triangle at 0500 PST 9 August has switched to rising motions below 810 mb with descent aloft at 1300 PST 9 August (Fig. 8b). This vertical profile of $\omega$ is also apparent over the Pt. Mugu–San Nicolas–San Diego triangle (Fig. 8c). These observations are in reasonable agreement with the analysis presented in Fig. 7c.

The strong subsidence shown in Fig. 8a at 0500 and 1300 PST 9 August apparently contributed to the formation of the warm core low in Fig. 7c. Some of this descending motion probably extends into the Pt. Mugu–San Nicolas–San Diego triangle; however, the rising motion in the southeast corner of this triangle dominates at 1300 PST 9 August.

Although this case study has excellent data resolution for a complete analysis, it is unfortunate that visual satellite imagery was not typical of a Catalina Eddy, such as presented by Rosenthal (1968). The satellite images during the eddy formation (not shown) show a continuous deck of stratus extending from the southern California coastline out toward the ocean. The only indication of a small-scale circulation was the shadow or “wake effect” in the lee of several islands as discussed by Chopra (1973). Accordingly, a search was initiated through recent case studies of the eddy and an example on 24 April 1984 was found to be in near perfect agreement with the isentropic analysis shown in Fig. 7. In Fig. 9, the area of strong onshore flow and a deepening marine layer is covered with stratus clouds, while a clear slot occurs in the area where the isentropic analysis and vertical motions suggest subsidence. This is in contrast to Rosenthal (personal communication, 1985).
who suggested the advection of dry air as the primary mechanism for this clear slot. Finally, note an “eye” is visible in the center of this particular eddy. Although this is not a common observation with all Catalina Eddies, it is consistent with the warm core observed in Fig. 7. Apparently, the warm temperatures are a result of subsidence in the center of the eddy as shown in Fig. 8.

The lifting of the marine layer with time is shown with the serial radiosonde ascents at Long Beach (LGB) in Fig. 10. In ~30 hours, the base of the temperature inversion lifts ~30 mb. This increase would contribute to a reduction in pollutant concentration at the surface.

c. Serial radiosonde ascents

Radiosonde ascents over Vandenberg, Pt. Mugu, San Nicolas Island and San Diego are shown in Fig. 11.
Note that the upper-level winds on 8 August do not indicate northwesterly flow at all levels as shown in Bosart (1983; see his Fig. 10 at 0000 UTC 26 May) when the eddy has formed. The strong northwesterly winds at 1600 PST 8 August over Vandenberg are an indication of the increase in the low-level horizontal pressure gradient owing to the thermal trough and, as suggested by Bosart (1983), a possible orographic effect as the air flows around the coastal mountains near Pt. Conception and Pt. Arguello. The average summit of these peaks is 750–900 m (~920 mb). The shift in the low-level wind direction over Pt. Mugu and San Diego once the eddy forms in the early morning hours on 9 August is shown in the figure. At San Nicolas Island, the winds shift slightly toward the west, and the speeds increase at low levels. There are two other observations that are noted in Fig. 11:

1. Except for Vandenberg, the 316 K isentrope appears to be close to the maximum vertical extent of the Catalina Eddy;

2. The eddy flow is not confined to below the base of the temperature inversion but extends throughout the entire depth and apparently terminates near the top of the inversion.

These general features are examined in detail with the serial ascents over two BASIN upper-air sites. Recall that during a 48-hr period, balloons were launched at least once every 4 h over Los Angeles.

The upper-air data recorded at Cowan Ave. (CWA) is shown in Fig. 12. Balloons were launched every 2 h during the morning on both operational days; unfortunately, owing to the stratus clouds near the coast, several of the launches are not accompanied by wind data since tracking was by theodolite. In agreement with the sparse observations in Fig. 11, the Catalina Eddy winds extend throughout the depth of the temperature inversion (Figs. 12a and b) with the 316 K isentrope apparently acting as a cap to the eddy flow. Even with the persistent easterly flow associated with the eddy, the westerly winds of the sea breeze (confined below the base of the inversion) are apparent on 9 August and are undercutting the flow. In addition, the wind profiles in Fig. 12 suggest undercutting of the ambient air mass ahead of the eddy as the depth of the westerly winds moves aloft, from the surface to 830 mb at 1300 PST 8 August to 860 to 750 mb at 0100 PST 9 August. The wind speed maximum also moves toward higher levels from 920 mb to 840 mb for the same periods. The increase in the depth of the marine layer with time is shown in both the potential temperature (Fig. 12b) and the mixing ratio analyses (Fig. 12c). Values of 10–12 g kg⁻¹ within the marine layer are rather typical for this area (Edinger, 1963). The reason for the appearance of a dry slot at ~930 mb from 1300 PST 8 August–0100 PST 9 August is not clearly understood at this time although it may be related to the aforementioned jet of maximum horizontal wind speeds. It is also possible that it may be a result of subsidence accompanying a thermally direct frontogenetic circulation at the leading edge of the eddy front.

Figure 13 shows the serial ascents for the upper-air site located at Green River (GRV). Again, the easterly flow associated with the Catalina Eddy extends throughout the inversion and terminates near the 316 K isentrope. Perhaps more clearly indicated than Fig. 12, the undercutting of the air ahead of the eddy is apparent as the depth of the westerly winds is displaced to higher levels and a jet axis is noted. An examination of Figs. 6f, g, and h explains why the easterly flow within the eddy does not extend to the surface in Fig. 13; the orography of the Los Angeles Basin forces the low-level flow from the eddy (below ~950 mb) toward a westerly direction through GRV. In advance of the leading edge of the eddy, moisture is being advected aloft from 1300–2100 PST 8 August (note the 10 g km⁻¹ isopleth) and at the same time a dry pocket is noted at ~970 mb in Fig. 13c. It is possible that a horizontal, anticyclonic rotor circulation has developed at the leading edge of this flow (looking into the figure) resulting in the observed displacement of moisture. This rotor could be a result of the vertical shear vorticity of the horizontal wind. These same general features of the vertical structure of the Catalina Eddy at GRV are also evident at RIV (not shown). It is interesting to note that the maximum wind speeds accompanying the eddy are within the temperature inversion in Figs. 12 and 13, consistent with the observations in Fig. 11.

5. Ozone concentrations

Although it has been stated that the Catalina Eddy is an effective "pollution remover" over the Los Angeles Basin, analyses in Figs. 5, 6, and 7 suggest that the eddy subsequently transports this pollution to the Santa Barbara/Ventura area. In order to quantitatively examine this hypothesis, surface ozone concentrations were examined at various sites located throughout the area and plotted in Fig. 14. (Refer to Figs. 1 and 2 for site locations.)

The ozone levels reached 31 ppbm at Glendora before the eddy formed, a value considered "unhealthful for everyone" by the South Coast Air Quality Management District (1985). After the eddy develops there is a dramatic drop in ozone concentrations on the succeeding 2 days. At Lennox, a coastal station close to the Cowan Avenue upper-air site, the ozone concentrations are relatively unaffected by the eddy. Both the wind direction shifts accompanying the eddy and the sea breeze are marked below the ozone trace. At Banning and Newhall, located at the east end and toward the north of the basin, respectively, significant drops in ozone levels are noted on 9 and 10 August.

The five other surface stations in Fig. 14 were selected to examine the effect the Catalina Eddy has on the
transport of ozone into the Santa Barbara/Ventura area. There is a large rise in ozone levels to 19 ppb, the highest value recorded during the entire month of August, at Simi Valley on the day the eddy developed. A dramatic shift in wind direction accompanying the sea breeze originating from the Ventura coast is seen on 9 August at 1400 PST. Recall that Fig. 5d shows this sea breeze/eddy convergence line. Once the sea breeze front passes the station, ozone levels drop as the relatively clean marine air moves eastward. This sea breeze/eddy front moves westward back through this site at 2000 PST on 9 August.

An increase in surface ozone concentrations on 9 August to 10 ppb was noted at Ojai, the second highest value recorded at this station in the month of August. In contrast, there was no significant ozone increase

**Fig. 12.** Time cross sections of (a) wind speed (m s⁻¹), (b) potential temperature (K) and (c) mixing ratio (g kg⁻¹), for Cowan Ave. Thick gray lines denote the estimated boundaries of the Catalina Eddy and the sea breeze. One full barb and half barb denote 5 and 2.5 m s⁻¹, respectively.
FIG. 13. As in Fig. 12, except for Green River. The thick gray line denotes the estimated boundary of the Catalina Eddy and the dashed gray line denotes a jet axis.

at El Rio on 9 August. The maximum value of 6 ppbm was equalled or exceeded on 12 days in August. Apparently, the sea breeze was persistent and strong enough to prevent ozone from reaching this location. However, it is believed that substantial quantities of pollutants must be advected aloft and toward the northwest above the sea breeze front. Lea (1968) has noted maximum ozone concentrations above the base of the temperature inversion on numerous days at Pt. Mugu. At Thousand Oaks, a station further inland from El Rio, a value of 10 ppbm was attained on 9 August. Although this ozone level is higher than 8 or 10 August, it was equalled or exceeded on 5 days during the month of August. Even in the absence of surface
Fig. 14. Surface ozone concentrations (pphm) for nine stations located in southern California. Surface wind speed and direction are plotted below each trace. One full barb and half barb denote 5 and 2.5 m s$^{-1}$, respectively.
wind data, it is clear that if the sea breeze can easily reach the Simi Valley site, that its influence must also be felt at this station.

A value of 10 ppb of ozone was recorded on 9 August at Goleta, a station just outside of Santa Barbara. Interestingly, this value was the highest recorded for the entire month of August. Apparently, the orientation of the coast at Santa Barbara does not allow the sea breeze to protect the area. The preferred southerly direction of the sea breeze is not significantly different than the winds accompanying the eddy. In addition, upon a close examination of the surface wind directions on 9 August (Fig. 14) and recalling the analyses in Fig. 5, it appears that near the Pt. Conception area, a small-scale lee or wake eddy has formed off the coast from Santa Barbara. Perhaps this small eddy, through some mechanism that is not understood at this time, is forcing pollution closer to the ground.

Fortunately, a vertical profile of ozone was available for 12 PST on 8 and 9 August over El Monte (ELM). These data and the vertical sounding information for the closest time are shown in Fig. 15. The increase in height of the base of the temperature inversion is indicated. The maximum concentrations in ozone are attained at the base, consistent with previous studies (e.g. Blumenthal et al., 1978).

This increase in the mixed layer will dilute surface concentrations of ozone; however, the profile shown in Fig. 15 illustrates that this mechanism alone cannot account for the dramatic decreases. Two other mechanisms are likely to play an important role in the redistribution of ozone. First, as shown in Fig. 14, vast quantities of ozone are advected into the Santa Barbara/Ventura area. Second, it is apparent from Fig. 15 that ozone is also transported above the base of the inversion during a Catalina Eddy event. This redistribution may be a result of frontal uplift such as shown in Figs. 12 and 13 and turbulent mixing in the wake of the front simulated to laboratory experiments of density currents (Simpson, 1969).

6. Discussion and conclusions

A detailed case study of a Catalina Eddy was presented using data available from Project BASIN and other sources. The key synoptic features were the passage of an upper-level ridge (as discussed by Bosart (1983)) and a sudden increase in the intensity of the thermal low in conjunction with the northwesterly winds from the Pacific High. In contrast to Dorman (1985), there appears to be a strong topographic influence in the generation of the eddy. The effect of the Pt. Conception/Pt. Arguello peninsula may be similar to vortices produced by plates accelerated in a fluid at rest in laboratory experiments (Pierce, 1961). Certainly, the strengthening of the horizontal pressure gradient by the thermal low producing an acceleration of the surface northwesterly flow around this geographic obstacle may be considered an atmospheric equivalent situation.

For the first time, detailed surface and upper-air data were presented over the Los Angeles Basin to illustrate the effect of the Catalina Eddy on the boundary layer. Significant drops in ozone concentrations were noted as the marine layer deepened, the atmospheric pollutants were being advected out of the basin through various mountain passes, and ozone was mixed aloft into the temperature inversion. Isentropic analyses over southern California aided the interpretation of visual satellite imagery such as shown by Rosenthal (1968). The eddy was shown to extend throughout the entire depth of the very strong temperature inversion that exists over Los Angeles. In fact, the highest vertical extent of the eddy appeared to be near the top of the inversion.

Once the eddy develops, large quantities of ozone are advected toward the Santa Barbara/Ventura area, however, owing to the local effects of the sea breeze and a small-scale wake eddy near Santa Barbara, ozone concentrations measured at the surface may be quite varied. Figure 16 summarizes some of the key surface features of the Catalina Eddy.

A very important issue that still has not been resolved completely is the forecast criteria for the eddy. During potential hazardous ozone episodes over Los Angeles, strict emission controls are enforced on industry. Such drastic measures as oil refineries and utilities switching fuel from oil to gas or curtailing daily operations of the facilities can be implemented by the South Coast Air Quality Management District. If an eddy did not develop on 9 August in the present case study, chances are excellent that a major pollution episode would have continued over Los Angeles.
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