



Numerical investigation of the formation of elevated pollution layers over the Los Angeles air basin

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ABSTRACT

Observations of the vertical distribution of pollutants over the Los Angeles basin show that maximum concentrations can occur within the stable layer above the base of the temperature inversion. This inversion-bound pollution may returned to the ground during the daytime by fumigation as the boundary layer deepens, owing to convective thermals generated by surface heating. Hence, surface pollutant concentrations may be enhanced by the fumigation of aged pollutants.

A three-dimensional mesoscale boundary layer model is used to study the formation of elevated pollution layers. Detailed spatial and temporal variations in the boundary layer structure and tracer transport are simulated. The land-sea thermal discontinuity and coastal mountains cause strong horizontal inhomogeneities and complex vertical circulation in the boundary layer and result in the formation of these pollution layers. Sea breeze inland intrusion can produce the elevated pollution layers over the western side of the air basin in the afternoon. The pollution layers over the eastern side of the air basin are generated by the sea breeze inland propagation and mixed layer stabilization processes. The daytime mountain up-slope flow and chimney effect can also vent pollutants above the base of temperature inversion.

INTRODUCTION

During the summer, the Southern California coastal region typically lies under the eastern edge of the Pacific High. A strong temperature inversion is formed between the cold moist air in a shallow marine layer near the surface and the warm dry air descending in the lower troposphere. The inversion limits vertical mixing of air pollutants formed in the Los Angeles air basin. Most of the pollutants are expected to be confined under the base of the temperature inversion. However, maximum pollutant concentrations have been found above the inversion base. Edinger [1] and Blumenthal et al.[2] detected



elevated pollution layers over the western Los Angeles basin in the late afternoon using light planes equipped to measure pollutants and meteorological parameters. Wakimoto and McElroy [3] also observed elevated pollution layers over the eastern part of the basin during the evening with a downward-looking lidar aboard an aircraft. Similar layered structures have been seen in the southern and central California coastal regions.

The formation of these elevated pollution layers is related to the daytime vertical convective turbulent mixing in the boundary, the sea breeze circulation generated by the land/sea thermal discontinuity, and the vertical circulations produced by mountain thermal and dynamical effects. Lu and Turco [4] simulated the formation of elevated pollution layers in a coastal environment with a strong elevated temperature inversion using a two-dimensional mesoscale model. Both the sea-breeze and mountain flows contribute to the generation of these pollution layers. The principal mechanisms include:

(1) Sea breeze inland intrusion in the afternoon. The well mixed pollution layer is undercut by clean air brought onshore by the sea breeze. The sea breeze circulation return flow can also inject pollutants into the stable layer above the base of the temperature inversion.

(2) Injection of pollutants into the stable layer by upslope flow over mountains. The upslope flow can vent pollutants into the free-atmosphere above the mountain (sometimes referred to as the mountain chimney effect). When the upslope flow is coupled with sea breeze, pollutants can be injected into the temperature inversion layer.

(3) Mixed layer stabilization in the vicinity of high mountains. As the daytime mixed layer stabilizes in late afternoon and evening, pollutants in the mixed layer, together with mixed layer air, move upslope and then are incorporated into the temperature inversion layer.

In this study, a three-dimensional mesoscale model with realistic topography is used to simulate the formation of elevated pollution layers over the Los Angeles Basin. The pollution layer formation processes in the three-dimensional simulations are complicated due to the presence of complex terrain in the coastal region. However, the mechanisms proposed by Lu and Turco [4] are dominant in the formation processes in the air basin.

THE MODEL

The model is a three-dimensional hydrostatic primitive equation mesoscale model originally developed by Lu [5] for typhoon and mesoscale system studies. It has been operationally used in the Shanghai Meteorological Center to forecast rainfall rate over the Yangze River Delta region, China. The model has been modified to simulate the Los Angeles air basin airflow patterns and boundary layer variations for air pollution transport studies in the basin (Lu and Turco [6]). It is a finite difference model and the vertical coordinate is a terrain-following σ -coordinate defined as:

$$\sigma = \frac{p - p_{\text{top}}}{p_s - p_{\text{top}}},$$

where p is air pressure; p_s is the ground surface pressure and p_{top} is the pressure at the top of the model atmosphere. The model top (p_{top}) is at 200 mb in this study. The model equations include the momentum equations, thermodynamic equation, air mass continuity equation, hydrostatic equation and mass continuity equations for water vapor and passive tracers carried in the model.

The model includes major physical processes that play important roles in controlling the air flow patterns and pollutant transport over the Los Angeles basin. These processes are vertical turbulent diffusion, horizontal sub-grid diffusion, water vapor condensation and precipitation, solar and infrared radiation transfer and heating, soil heat and moisture transfer and ground surface energy balance, and complex topographic effects. Detailed descriptions of these processes in the model are given by Lu and Turco[4]. The boundary layer vertical turbulent fluxes are calculated by a hybrid boundary layer model in which three turbulent regimes are considered. Under strong stable conditions, turbulence is suppressed by the stable stratification. Turbulent fluxes under moderate unstable to weak stable conditions are calculated by a first order closure model. When the surface layer is strongly unstable, the boundary layer is driven primarily by buoyancy force. Under this condition, the boundary layer is considered within free-convection regime and a convective plume model is used for turbulent fluxes. The model uses realistic topographic elevation data in the southern California coastal region averaged over model grid boxes.

In this simulation, the computational domain covers the southern California coastal region. Horizontal 85x55 grids are used with grid spacing of 0.05 degree longitude (4.6km) and 0.045 degree latitude (5km). The model atmosphere has non-uniform 20 vertical layers with high resolution in the lower troposphere. The lowest layer is the model surface layer with a depth of about 20 meters. The model predicts horizontal and vertical winds, temperature, water vapor mixing ratio at each grid points and boundary layer height. Passive tracers are also carried in the model to study the characteristics of air pollutant diffusion and transport in the coastal environment. These simulated tracer distribution patterns are used to identify pollutant transport pathways and to interpret observed pollutant distributions.

INITIAL CONDITIONS

The simulation starts at 0500LST. The initial atmosphere is at rest and horizontal uniform with vertical temperature and water vapor structures given from a composition of temperature and dew-point temperature 0500 LST soundings over UCLA, California in July, 1991. The profiles show the typical summer-time vertical structure over the southern California coastal region that a strong low-level elevated temperature inversion separates the cold moist



marine layer air and the warm dry air above. Large scale forcing is neglected because synoptic pressure gradient force is small under the Pacific High and local forcing strongly influence the flow patterns near surface. The passive tracer is initially put in the surface layer of the model with column density $1/m^2$ in the western side of the Los Angeles air basin which is the major source region of most air pollutants emitted in the basin. The tracer emission processes have not considered because the purpose of this study is to simulate the formation of pollution layer by the secondary pollutants which are produced by chemical reactions in the atmosphere. After the tracer vertical mixing in the morning, the transport of the tracer in the atmosphere are similar to that of the secondary air pollutants.

THE SIMULATION RESULTS

In the southern California coastal region, the local thermal and dynamical forced flows are the major components of the flow patterns within the boundary layer. These flows include the sea and land breezes that blow onshore (offshore) during day (night), the thermal induced mountain-valley flows and the flow forced by the mountain dynamic channeling effect. In the morning, the ground surface is warmed by the solar radiation. The sea-breeze begins to blow perpendicular to the shore over most part of the coastline. Upslope flows are generated over mountain slopes. Both the sea-breeze and the mountain upslope flow are equally important in producing the local winds in the Los Angeles air basin. As the surface temperature rises, a general flow blows from coastline inland to eastern part of the basin. The simulated later afternoon surface layer flow pattern is shown in figure 1. This flow pattern has the same major features as that observed in a typical summer over the basin as documented by Keith et al.[7]. The onshore flow splits into two branches. One turns left into San Fernando valley and generates a convergence zone in the valley with a sea-breeze from the west. The major part of the flow goes inland into the eastern part of the basin. The inlandward flow has nearly fixed direction own to channeling of the terrain in the basin. The air blows out of the basin through mountain passes such as Cajon pass and Newhall pass.

The tracer transport in the basin is controlled by the local winds. Within the mixed layer, the tracer in the western part of the basin is transported slowly northward in the morning. Then, most of the tracer is moved rapidly eastward into the eastern basin. These transport characters in the mixed layer are consistent with results of tetroon (constant volume balloon) trajectory studies in the basin. The tracer can be transported out of the basin into high desert through mountain passes. Figure 2 shows the simulated total vertical column concentration distribution at 1900LST in the Los Angeles basin. The north-eastward transport of tracer near the surface can be clearly seen from surface distribution (not shown). However, the vertical column concentration distribution shows that a large portion of the tracer remains over the basin. This portion of tracer forms elevated layers as the pollution layers observed in the basin. The pollution layers cover nearly all the basin. The formation of these layers denotes that vertical circulation plays important role in air

pollution transport in the coastal environment with complex topography as pointed out by Lu and Turco[4].

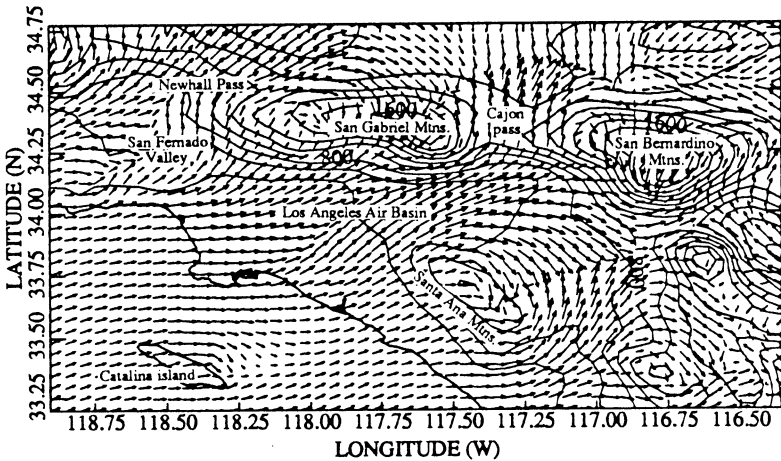


Figure 1. Model simulated 1700LST surface layer flow pattern in the Los Angeles basin. Solid contours are topographic elevation (meters)

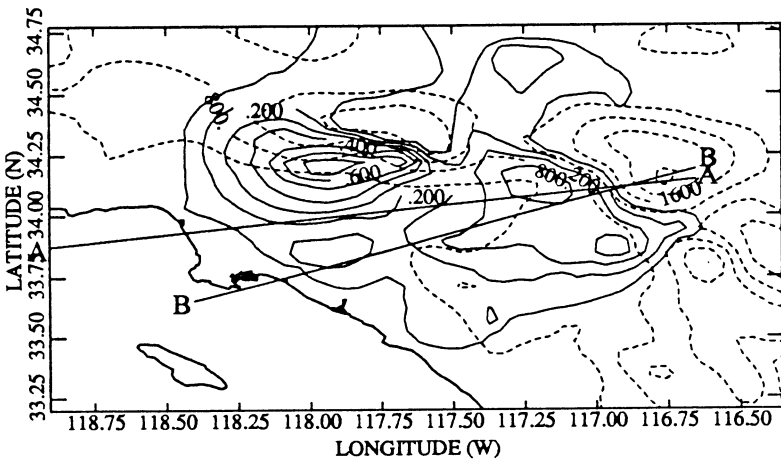


Figure 2. 1900LST tracer column concentration (m^{-2} , solid contours) over the basin. Dashed contours are topographic elevation.

Many mechanisms may be included in the generation of these elevated pollution layers. The most important factors in the pollution layer formation in the Los Angeles basin are the vertical turbulent mixing in the mixed layer, sea-breeze vertical circulation and the vertical circulation due to terrain effects. In the morning the mixed layer depth over land grows and horizontal winds are usually small. The tracer is well mixed in the mixed layer at noontime except over the coastline where a weak sea-breeze circulation produces an elevated pollution layer above the marine boundary layer. In the afternoon the sea-breeze increases in its strength and intrudes inland. Figure 3 is the winds and

tracer distribution along a vertical cross-section. Although the sea-breeze front structure is not easy to find near the surface due to the coupling of sea-breeze with mountain thermal flow in the basin, a vertical sea-breeze circulation can be seen in the cross-section. The sea-breeze front can be identified through the sharp gradient in tracer concentration across the front. The boundary layer behind the front is shallowed by both the cold marine air inland advection and the adiabatic heating related to the sea-breeze circulation return flow. As the sea-breeze intrudes inland, the clean air brought onshore undercuts the polluted mixed layer and the sea-breeze return flow also injects the tracer into the stable layer behind the front. The observations made by Edinger[1] shows that the formation of the elevated pollution layer in the western side of the basin is coincident with the decrease of boundary layer height in the afternoon. It can be explained by the sea-breeze inland intrusion process as simulated here.

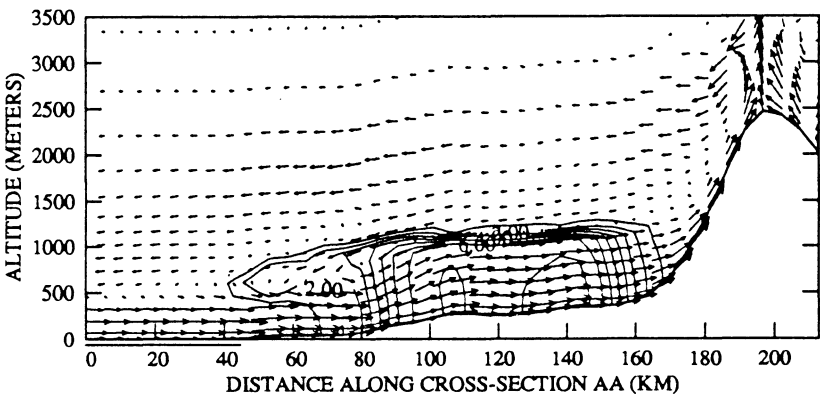


Figure 3. 1500LST tracer concentration (10^{-4}m^{-3} , solid contours) and wind component along the vertical cross section AA (in Figure 2).

In daytime mountains have the thermal effect of elevated heat islands. The air near the surface is warmed through turbulent sensible heat transfer from surface into the atmosphere. The warmed air goes upslope and rises above the mountain top. This effect is sometimes referred to as mountain chimney effect. For mountains which are higher than the elevated temperature inversion layer, the chimney effect pushes pollutants upslope and vents them into the free atmosphere above the inversion layer. Larger scale winds in the lower troposphere and the divergence of the rising air above the mountain top can generate pollution layers above the inversion layer. The chimney effect of the San Gabriel Mountains and the San Bernardino Mountains can be important air pollutant sinks for the Los Angeles air basin.

In the mid-afternoon, the sea breeze reaches the San Gabriel mountains and couples with the mountain upslope flow. The diabatic heating from the surface over the mountain slope is balanced by both the cold advection of marine air and the adiabatic cooling of the upslope motion. The mixed layer depth is reduced. A return flow is generated in the temperature inversion layer



above the mixed layer. The tracer in the mixed layer, as well as the mixed layer air, can be detrained into the inversion layer and then transported back over the basin by the return flow to form a pollution layer in the inversion layer. In this sense, the San Gabriel mountains act as coastal mountains as discussed by Lu and Turco[4]. In the western part of the Los Angeles air basin, the simulated elevated tracer layer in the temperature inversion layer in the afternoon has the same characteristics as observed by Edinger [1] and Blumenthal et al.[2]. The formation of the tracer layer suggests that these observed pollution layers are generated by the sea breeze inland intrusion. Both the purely sea-breeze circulation and the coupled circulation of sea breeze and mountain upslope flow plays important roles in the formation processes.

In the evening, the mixed layer stabilizes in the mountainous coastal region as the surface heating vanishes. The stabilization process plays a major role in eastern part of the basin where the sea breeze has not reached in the later afternoon. The warm mixed layer air moves adiabatically upward along the mountain slope and then is inserted into the layer around the height of the temperature inversion layer. At the same time, the cooler marine air moves into the eastern basin near the surface. The mixed layer is converted into the nighttime stable boundary layer. Along with the mixed layer air, the tracer is injected into the inversion layer and forms an elevated tracer layer. Figure 4 is the tracer distribution and wind pattern along a vertical cross section at 1800 LST. A tracer layer is generated at the height of about 800 meters in the eastern basin. The vertical circulation inside and below the tracer layer is produced by the mixed layer stabilization and cold marine air inland propagation processes. Elevated pollution layers, which are similar to that simulated here, has been observed by Wakimoto and McElroy[3] over the eastern basin in the evening. Their observations of aerosol distribution and winds also show that the westerly winds within the mixed layer are advecting pollutants eastward up the slope of the San Bernardino mountains and these pollutants are subsequently advected by the easterly winds at about 1 km level back over the basin. The sea-breeze inland propagation and the mixed layer stabilization processes are important mechanisms that lead to the formation of the pollution layer over the eastern Los Angeles Basin.

CONCLUSIONS

A three-dimensional mesoscale model is used to study the formation of elevated pollution layers over the Los Angeles air basin. A passive tracer is assumed as a surrogate for secondary air pollutants to simulate their transport characteristics. The simulation generates elevated layers over western basin in the afternoon and over the eastern basin in the evening, as observed in the basin. The elevated tracer layers cover most of the air basin, so that they are basin scale phenomena. At night, most of the tracer remains in the basin trapped in the elevated layers. The tracer may return to the surface in the next day as the mixed layer deepens. As a result, the elevated pollution layers are important phenomena in the air pollution transport problems in the Los Angeles air basin.



The pollution layer formation processes are complicated due to the complex terrain over the Los Angeles basin. However, the dominant mechanisms are similar to those discussed by Lu and Turco[4]. The pollution layers in the temperature inversion layer in the western basin are produced by the sea-breeze inland intrusion processes. Both the sea-breeze circulation and the coupled sea-breeze and upslope flow circulation are significant in the processes. In the evening, the pollution layers over the eastern basin are generated by the marine air inland propagation and the mixed layer stabilization processes. The mountain chimney effect in the daytime can also create pollution layers in the lower troposphere.

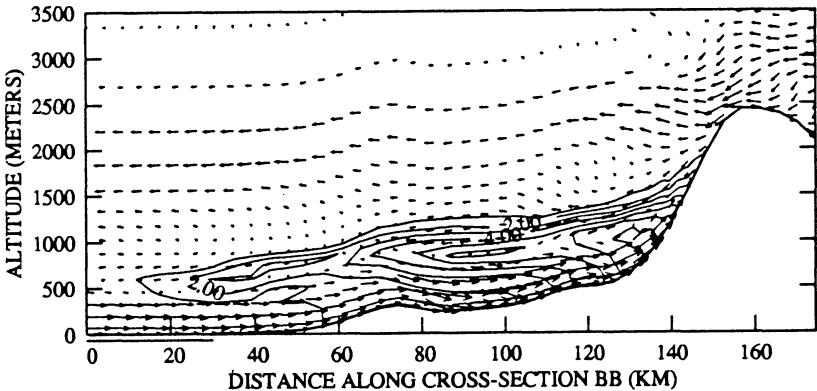


Figure 4. 1800LST tracer concentration (10^{-4}m^{-3} , solid contours) and wind component along the vertical cross section BB (in Figure 2).

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