PERGAMON

AE International – North America

Atmospheric Environment 37 Supplement No. 2 (2003) S95–S117

**ATMOSPHERIC
ENVIRONMENT**

www.elsevier.com/locate/atmosenv

MM5 simulations of a SCOS97-NARSTO episode

D. Boucouvala^{a,b}, R. Bornstein^{a,*}, J. Wilkinson^c, D. Miller^d

^aDepartment of Meteorology, San Jose State University, San Jose, CA 95192, USA

^bDepartment of Applied Physics, University of Athens, Athens, Greece

^cSchool of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, USA

^dDepartment of Meteorology, Naval Postgraduate School, Monterey, CA, USA

Received 6 February 2002; accepted 31 March 2003

Abstract

MM5 simulations of the 4–7 August SCOS97-NARSTO ozone episode in the SoCAB showed that a relatively rare easterly upper-level background flow influenced surface wind flow directions at in-land sites. An inland-moving surface convergence zone resulted where the offshore background flow met an inland moving westerly (sea breeze plus thermal upslope) onshore flow. Maximum inland penetration of the zone was to the San Gabriel Mountains, where it produced peak observed ozone concentrations. MM5 reproduced the main qualitative features of the evolution of the diurnal sea breeze cycle, as it reproduced the opposing easterly flow, inland movement of the sea breeze front, and retreat of the land breeze front. The accuracy of predicted surface winds and temperatures were improved by modifications of MM5 and/or its input parameters, e.g., by use of the PSU MBLI scheme, analysis nudging with NCAR/NCEP model output, accurate specification of deep-soil temperature, observational nudging with SCOS97-NARSTO surface and upper level winds and temperatures, and use of updated urban land-use patterns.

© 2003 Elsevier Ltd. All rights reserved.

Keywords: SCOS97-NARSTO; SoCAB; MM5; Meteorological conditions

1. Introduction

South Coast Air Basin (SoCAB) ozone arises from a combination of complex precursor emissions, topography, meteorology, and photochemistry, as described in the companion observational study by Boucouvala and Bornstein (2003), hereafter referred to as BB03. The various observational studies mentioned in BB03 have provided a general understanding of the complex meteorological and chemical processes producing high ozone concentrations in the SoCAB. Additionally, 3-D mesoscale meteorological modeling studies using the various databases have provided additional details. Ulrickson and Mass (1990a) used the prognostic hydrostatic Colorado State University Mesoscale Model (CSUMM) to simulate summertime flows in SoCAB. Simulated daytime onshore, upslope winds were gen-

erally more accurately reproduced than were nighttime low speed, spatially variable wind patterns. Output from additional winter and summer simulations by Ulrickson and Mass (1990b) were input into a pollution trajectory model, which showed entrainment and upward motion producing planetary boundary layer (PBL) growth that mixed pollutants into the elevated subsidence inversion layer.

The mass-consistent wind model of Douglas and Kessler (1991) used SCCAMP data to analyze SoCAB mesoscale flow patterns associated with the Catalina Eddy, but such diagnostic models cannot reproduce its evolution. Better results were obtained with the CSUMM (Kessler and Douglas, 1991), but off shore area winds were sometimes overestimated, as the uniform initial wind fields did not include many large-scale details. Taha (1997) also used CSUMM to simulate effects from urban-induced albedo increases on SoCAB flow patterns, with results input into the photochemical Urban Airshed Model (UAM). Results showed that an increased albedo lowered; surface temperatures and

*Corresponding author. Tel.: +1-408-924-5205; fax: +1-408-9234-5191.

E-mail address: pblmodel@hotmail.com (R. Bornstein).

mixing depths; emission and reaction rates; and peak ozone concentrations. Mesometeorological output from the hydrostatic UCLA model was input into a passive tracer model by Lu and Turco (1995) to qualitatively reproduce many observed features of the polluted marine boundary layer (MBL) over the SoCAB. The San Fernando convergence zone was shown to lift pollutants into the elevated inversion, resulting in a residual elevated reservoir of daytime polluted air that survived throughout the night.

The non-hydrostatic fifth generation mesoscale meteorological model (MM5) has been used to investigate meteorological conditions over California during ozone episodes. Hegarty et al. (1998) used it to simulate South Coast air quality study (SCAQS) data with two-way nesting in three domains, initial conditions from ECMWF-TOGA analyses, and average US Navy sea surface temperatures (SSTs). Predictions after 48 h were not completely accurate, however, due to a lack of analysis nudging and four-dimensional data assimilation (FDDA).

Stauffer et al. (2000) simulated a six-day SCAQS ozone period using MM5 with analysis nudging and FDDA. Although general agreement existed with the observations, the model underestimated afternoon overland wind maxima by $1\text{--}2\text{ m s}^{-1}$. These MM5 options were also used by Tanrikulu et al. (2000) to design the SoCAB measurement program for the 1997 summer time Southern California ozone study (SCOS97-NARSTO). Results showed that MM5 with FDDA generally reproduced observed mixing depth and PBL wind, but that simulated mesoscale return flows that recirculate SoCAB air back over the sea were, however, too weak and intermittent.

Among the objectives of the California air resources board (CARB) sponsored SCOS97-NARSTO (Fujita et al., 2000) were the following: produce an extensive upper air database (Wolfe and Weber, 1999; CARB, 2001); improve understanding of relationships between emissions, transport, and ozone exceedances; and develop plans for further emission reductions to attain the US air quality ozone standards. Objectives of the current effort include use of SCOS97-NARSTO data and MM5 simulations to understand meteorological factors in the formation of high SoCAB ozone concentrations. The period selected by CARB for the study was 4–7 August, during which maximum SCOS97-NARSTO surface ozone (187 ppb) concentrations occurred at 2200 UTC (1500 PDT, Pacific Daylight Time) on 5 August.

2. Methodology

A series of six MM5 simulations was carried out, and this section describes the formulation of the final one.

Results from this simulation are described in Sections 4.2 and 4.3, while the successive steps (and their impacts) are given in Section 4.1.

MM5 Version 2.12+ is used in the current simulation, where the plus indicates that several options used in the current simulation are not normally available in 2.12. MM5 is described by Grell et al. (1994) and Haagenson et al. (1994), and options currently selected include: Deardorff (1972) force-restore surface temperature, Dudhia (1989) simple ice, Kain and Fritsch (1993) cumulus parameterization in the outer three domains (none in inner), Gayno-Seaman (Gayno, 1994) 1.5 order turbulent kinetic energy (TKE) (only normally available in MM5 Version 3), and one-way continuous nesting. With this nesting option, only one MM5 simulation is required, information is fed to the inner domains at each time step, and no feedback exists from inner to outer domains (Lozej and Bornstein, 1999). With “normal” one way nesting, each domain is simulated in a separate run, outputs are kept at hourly intervals, and information is fed to inner domains. Two-way nesting is like continuous one-way nesting, but feedback exists from inner to outer domains. Note that the counter-gradient heat flux correction term in the Gayno-Seaman TKE scheme allowed for an unreasonable maximum diagnostic mixing depth of 5 km, but this resulted in a numerical instability; reduction to a value of 3 km corrected the problem.

Version 2.12+ also uses the Leidner et al. (2000) Penn State University (PSU) marine boundary layer initialization (MBLI) scheme (not yet in NCAR MM5 releases) during a 13 h spin-up period, which quickly establishes realistic MBLs in data-sparse marine regions. Establishment of such a simulated layer during summertime Pacific High conditions normally requires about 48 h, as cool marine surfaces produce only weak near-surface shear-induced turbulence mostly suppressed by subsidence-induced stability.

Quadruple nested grid domains were used in the current simulation (Fig. 1). Domain 1 (outermost) is centered at 34.5N, 118W, and has a large upwind fetch that includes the Pacific High, a horizontal resolution of 135 km, and 41×33 grid points in the E–W and N–S directions, respectively. Domain 2 has a grid resolution of 45 km and dimensions of 67×61 ; Domain 3 has a resolution of 15 km and dimensions of 91×85 ; and the inner domain (Domain 4) has a grid resolution of 5 km and dimensions of 121×85 . All domains have 32 vertical layers, with a minimum sigma level closest to the surface that corresponds to about 14 m, with wind and temperatures at half sigma levels.

The 25-category US Geological Survey (USGS) global land-use distribution in MM5 was used with 10 min latitude and longitude resolution in Domains 1 and 2, 5 min in Domain 3, and 30 s in Domain 4. Grid averaged topographic heights for the SoCAB were

Fig. 1. Four MM5 domains, with 135, 45, 15, and 5 km mesh sizes, respectively.

obtained from: PSU/NCAR for Domain 1, Geophysical Data Center for Domains 2 and 3, and Defense Mapping Agency for Domain 4. SST and NCEP/NCAR global gridded model analyses from were both obtained from the NCAR Mass Storage System at a resolution of $2.5 \times 2.5^\circ$. Both fields provided initial and boundary conditions, the latter at 12 or 6 h intervals, respectively, with linear interpolation for intermediate time steps. Low resolution Domain 1 input analysis fields were improved by assimilation of data (via the MM5 RAWINS preprocessor) from about 70 upper air and several hundred surface sites within Domain 1. Initial conditions for the inner three domains are obtained via sequential interpolation of values from each encompassing coarser domain.

The FDDA technique used in the current simulations is based on Newtonian relaxation (or nudging), as described by Stauffer and Seaman (1990), Seaman et al. (1995), and Shafran et al. (2000). Nudging is a continuous form of FDDA that “relaxes” model results toward the “correct solution” by artificial tendency terms in the prognostic equations. In the current application these terms depend on differences between MM5 values and linearly interpolated (in time and space) global analyses. As these are only available at 12 or 6 h intervals, smaller scale upper-level forcings may not be captured. The process was only carried out above

the PBL (assumed at 850 mb) in temperature and wind only in Domain 4.

The current observational nudging, similar to analysis nudging, used SCOS97-NARSTO observations within a preset radius of influence and a predetermined 2 h time window. Observational nudging for (surface and upper air) winds was done throughout the vertical model extent in Domain 4, while rawinsonde and radar atmospheric sounding system (RASS) temperature and moisture were again only nudged above the PBL. Based on an average distance of 20 km between SCOS97-NARSTO surface observational sites, Stauffer (2001) recommended a 75 km surface radius of influence. The value was doubled above the surface, as the number of SoCAB measurement sites decreases and gradients become smoother with increasing height. Data from almost all the 110 surface, 12 rawinsonde, and 26 profilers discussed in BB03 were included in the observational nudging. Point Loma (PLM) rawinsonde and El Centro (ECO) profiler data (see BB03) were, however, excluded due to their irregular winds. No data were held back, however, as the goal was production of the most accurate possible input meteorological fields for the photochemical air quality simulation model.

The input deep-soil temperature in the “force-restore” surface temperature prediction equation was reduced by 4 K to correct a systematic bias in domain-averaged

nighttime minimum temperatures, as this parameter is the “restore” that balances daytime solar heating (Bornstein et al., 1996). First half-sigma level (7 m) simulated temperatures were adjusted for statistical comparisons with 2 m observed values by use of a log law profile that used MM5 simulated friction potential-temperature values. The MAPS statistical package of McNally and Tesche (1994) were used for all statistical analyses.

The following modifications to MM5 input parameters were also made to produce accurate 7 m simulated winds: (1) extension of Los Angeles urbanized area according to updated land use maps, (2) increase of urban roughness value z_0 from 0.5 to 1.5 m, (3) increase of z_0 values for other land use classes by about a factor of two, and (4) replacement of sea-surface wind speed dependent z_0 formulation by a constant value.

The initial sea surface z_0 value in MM5 (0.01 cm) is normally internally increased as a function of increasing wind speed using the formulation of Charnock (1955). This formulation, however, is only valid under “complete equilibrium” conditions, which rarely “exist over lakes and oceans” (Arya, 1988). As the more general formulation of Kitaigorodski (1970), which relates sea surface z_0 values to wave height, yields values of up to 10 cm, a value of 1 cm was thus used in the current simulations. The 50 cm MM5 urban z_0 value is too low for a city the size of Los Angeles, as literature values range up to 4–5 m (Arya, 1988). A value of 1.5 m was thus selected, and given the generally rough topography of the SoCAB domain, several other z_0 values were likewise increased. Additional details are given in Bornstein et al. (2001).

All simulations started at 1200UTC on 2 August to include a 2-day spin-up period. Only results from inner domain (centered on the SoCAB) are presented.

3. Observational summary

For more complete synoptic and mesoscale observational summaries of this case than are given below (see Sterbis (2000) and BB03, respectively). For readability, SCOS97-NARSTO date-hour specifications generally will be abbreviated. Thus 0500UTC on 6 August 1997 will be noted as 06/05UTC, and its PDT equivalent of 2200PDT on 5 August 1997 will be given by 05/22PDT.

The first observed synoptic wind shift over the SoCAB (before the ozone peak) resulted from a northwesterly along-shore movement of a 700 mb synoptic ridge. The SoCAB was thus no longer on the eastern side of the ridge (in a generally northwesterly onshore flow), but was now on its southeastern side (with a generally northeasterly offshore flow). The second observed shift (after the ozone peak) resulted from an eastward onshore movement of the ridge. The SoCAB was thus

no longer on the southeastern side of the high, but on its southern side (with a generally southeasterly along-shore flow).

By 05/22UTC, the onshore (sea breeze plus upslope) flow reached its maximum intensity and had an inland penetration that generally extended to the west side of the San Bernardino Mountains (SBM). As winds on the eastern mountain slopes were from the north-northeast (opposite to onshore flow), a strong convergence zone formed. As the onshore flow developed, precursor pollutants were carried eastward (inland) to the mountains, and the low wind speeds within the convergence zone allowed ozone concentrations to increase by photochemical processes driven by oxides of nitrogen and non-methane hydrocarbon emissions. The mountains acted as a barrier, however, and thus five sites on the western slopes of the SGM reported ozone concentrations at 05/22UTC (or 05/15PDT) at 120–187 ppb. After the peak was reached southeast of SGM, pollution advected slowly eastward and values decreased, and by 06/03UTC the sea breeze had retreated back to the coast.

4. Results

4.1. Simulations

As accurate temperatures are required to produce realistic thermal mesoscale flows (Pielke, 1984), attention should first focus on the simulation of accurate surface temperature values (Bornstein et al., 1996). Changes were thus successively made (and applied to subsequent simulations) until accurate MM5 surface temperatures (Table 1).

The first simulation (Fig. 2) did not include either analysis or observational nudging, and thus observed versus first-level MM5 domain-averaged diurnal temperatures show a maximum under prediction of daytime temperatures of 5 K and a maximum over prediction of nighttime values by 2 K (Run 1 curve). The cyclic equilibrium in the predicted diurnal temperature waves is an expected result, given both the lack of cloud cover and small day-to-day variation in solar forcing during the short simulation period. The observations, however, show a warming on the 5 August (peak ozone day) due to the previously discussed intensification of the GC upper level high.

The addition in Run 2 of analysis nudging every 12 h from NCEP GDAS model fields in the three outer domains reproduced the observed warming on 5 August. The maximum daytime under prediction was reduced to 3 K, while the maximum nighttime over prediction was still about 2 K (Run 2a curve). While temperatures are observed at about 2 m AGL, MM5 first-level values were calculated at 23 m. A post-simulation log-law

Table 1
MM5 simulations; see text for description

Runs	Analysis nudging: domains	Log-law temp. correction	Lower deep soil temp.	Obs. FDDA domains	Updated urban zone	New Sfc roughness	First half-sigma level (m)
1	None	No	No	None	No	No	23
2	GDAS: 1–3	No/yes	No	None	No	No	23
3	GDAS: 1–3	Yes	Yes	None	No	No	23
4	GDAS: 1	Yes	Yes	3 + 4	No	No	23
5	GDAS: 1	Yes	Yes	3 + 4	Yes	Yes	23
6	NCAR: 1	Yes	Yes	4	Yes	Yes	7

Fig. 2. Domain averaged 2m AGL predicted (different symbols for each Run) and observed (*) temperatures ($^{\circ}\text{C}$), where 0 h is 0700UTC or 0000PDT.

height correction to 2 m was thus made by use of computed surface boundary layer (SBL) scaling friction potential temperatures to the simulated values. While the correction worked well for daytime values (it almost completely eliminated all differences), it had virtually no effect on nighttime values (Run 2b curve).

In Run 3, the input constant deep soil temperature (discussed in Section 2) was reduced by 4 K. While this change produced excellent nighttime results, daytime maximum values on the peak-ozone day were reduced to a level slightly below observed values. Run 4 (for the first time) also included observational nudging in Domains 3 and 4 by the SCOS97-NARSTO measurements. As surface and PBL temperatures were not nudged, domain-average predicted temperatures for Run 4 did not change much from the good results of Run 3.

An overestimation of domain-averaged surface nighttime winds by about 1 m s^{-1} existed in Run 1 (not shown), with the analysis nudging of Run 2 producing

an even larger error (about 1.5 m s^{-1}). Even inclusion of observational nudging in Run 4 in the two outer domains did not improve the results. Runs 5 and 6 thus focused on improved surface wind values and thus did not significantly alter the accurate Run 4 first half-sigma level temperatures. As most SCOS97-NARSTO observations were within the innermost domain, observational nudging was thus performed only for this domain in this final simulation. The Los Angeles urban area was also updated (extended), z_0 values were updated for several land-use classes (Table 2), and the new sea-surface z_0 formulation was introduced. These changes generally decreased nighttime speeds, with the new sea surface formulation in particular reducing the excessive speeds on both sides of the Ventura coast (at the SoCAB northern edge).

To increase near-surface wind accuracy, the number of vertical grid levels was increased by two (to total of 32) in Run 6 (final case), with the first half-sigma level thus reduced from 23 to 7 m. This eliminated the need

Table 2
MM5 roughness lengths

MM5 land use class	Land use description	Roughness length (cm)	
		Old	New
1	Urban	50	150
7	Grassland*	12	10
8	Shrubland	10	20
9	Shrubland and grass mix	11	30
10	Savanna	15	40
11	Deciduous broadleaf	50	100
14	Evergreen	50	100
16	Water bodies	0.01	1

* Erroneously in Haagensohn et al. (1994) as 0.12.

for a wind-speed height correction. In addition, to obtain more frequent global analysis data, 6 h NCEP-NCAR analysis-nudging fields were used in this simulation.

4.2. Final-run temperatures

MM5 2 m temperatures at the 05/09UTC (05/02PDT) nighttime period prior to the daytime peak ozone (Fig. 3a) generally reproduced average observed features. These include an onshore gradient, with a cool (onshore side of) coastline (18°C), warm coastal plain (24°C), warmest inland southeast desert (30°C), and cool mountains (few observations available) (18°C). Concurrent observed 2 m values (Fig. 13a in BB03) are about 20°C, 22°C, 30°C, and 20°C, respectively, although accurate assessment of observed coastal values is difficult due to the lack of over-water observations. Similar problems exist with mountain top observations, and a more complete statistical evaluation for the entire simulation follows.

Daytime 2 m MM5 temperatures (Fig. 3b) 12 h later at 05/21UTC (05/14PDT) (hour before peak ozone) also generally reproduce the concurrent observations, with an onshore coastal gradient larger than 12 h before. Values have increased during the previous 12 h (as expected near the surface) to an average of about 33°C at the (onshore side of) coast, 36°C on the coastal plane, 40°C at inland southeast desert, and 24°C on the mountains. Concurrent observed values (Fig. 13b in BB03) are about 33°C, 38°C, 43°C, and 35°C, respectively, with the above mentioned mountaintop data-gap again rendering a comparison useless.

MM5 800 m temperatures (a level generally close to the coastal subsidence inversion top) at 04/12UTC (04/05PDT), two nights before the ozone peak, also generally reproduced average observed features

(Fig. 4a). This field is displaced by 3 h from that in the above surface comparison to utilize the denser upper-level observations at this time. A weaker (compared to surface) horizontal temperature gradient exists, as nighttime cooling over land areas generally decreases with height. The gradient is also reversed from that at the surface, with a warm coast (30°C), cool coastal plain (27°C), cooler inland southeast desert area (25°C), and cold mountains (12°C). Observed values (Fig. 15a in BB03) also show a weaker and reversed gradient (relative to surface), with values of about 30°C along the coast and 28°C on the coastal plain; no data are available in inland desert and mountain areas. As discussed in BB03, the observed (and now also the simulated) reversed gradient at 800 m AGL is due to the existence of the subsidence inversion at coastal (but not inland) sites.

Daytime 800 m MM5 temperatures 12 h later (day before ozone peak) at 05/00UTC (Fig. 4b) do not show the (strong) onshore coastal gradient seen at the surface, as inland surface heating decreases with height. Temperature values have also not greatly changed from the previous 12 h (as expected aloft, where diurnal variations are reduced), and thus the weak reversed gradient simulated 12 h before still exists. Concurrent observations (Fig. 15b in BB03), however, do show a weak (non-reversed) onshore gradient, with coastal temperatures about 2 K cooler than coastal plain values. Given the sparse offshore observations, it is difficult to say which is correct, but in either case, 800 m AGL coastal gradients are weak.

MM5 800 m temperatures (Fig. 4c) during the night before the ozone peak (05/09UTC or 05/02PDT) are concurrent with the 2 m values in Fig. 3a, but are 4 h after the 800 m observed values of Fig. 15b of BB03. They show virtual elimination of the reversed horizontal gradient of the previous night, consistent with the large-scale upper-level warming discussed above and in BB03. While coastline temperatures have remained at about 30°C, coastal plain values increased (by about 1°C) to 30°C. Values did not significantly change over the next 3 h (not shown), and thus the 4 h time difference mentioned above is not a problem.

Daytime 800 m MM5 temperatures 12 h later (1 h before ozone peak) at 05/21UTC (05/14PDT) (Fig. 4d) have not generally changed from the previous 12 h. The exception is a 3°C warming along the coast, which produces a well-defined maximum. This maximum is consistent with the concurrent observations BB03, which showed that an eastward movement of the upper level ridge produced offshore flow that advected warm subsiding air over the coastline during this period.

MM5 has thus captured the most important features of the observed temperature fields during the peak ozone period. Both analysis and observational nudging positively influenced both the 7 and 800 m AGL results.

Fig. 3. MM5 terrain heights (dashed lines, 500 m increment) and 7 m AGL temperatures (solid lines, 3°C interval) on 5 August at: (a) 0900 and (b) 2100 UTC, with relatively warm (W) and cold (C) areas indicated.

Fig. 4. MM5 terrain heights (dashed lines, 500 m increment) and 800 m AGL temperatures (solid lines, 3°C interval) at: (a) 1200UTC 4 August; (b) 0000UTC 5 August; (c) 0900UTC 5 August; and (d) 2100UTC 5 August, with relatively warm (W) and cold (C) areas indicated.

(c)

(d)

Fig. 4 (continued).

4.3. Final-run winds

MM5 winds at the sigma level closest to 3800 m AGL ($\sigma = 0.575$) shows patterns that reflect the changing position of the upper-level ridge discussed above. At 04/18UTC (Fig. 5a) the high is located offshore of the northern SoCAB (with a smaller that will move out of the domain one to the north) and thus produces onshore (generally westerly) flow over the northern SoCAB, along shore flow (northwesterly) over the central SoCAB coast, and offshore (generally easterly) flow over the southern SoCAB. Concurrent observations (Fig. 8a in BB03) also imply that the high is offshore of the northern SoCAB, but the lack of offshore observations makes it impossible to determine its exact location. The observations do, however, show onshore (generally westerly) flow over the northern SoCAB and along shore flow (northwesterly) over the central SoCAB coast. The observed onshore flow over the southern SoCAB coast, which disagrees with the offshore MM5 results in that area, is based only on one site.

Twelve hours later at 05/06UTC (Fig. 5b), the MM5 high is now further northwest (west of the SoCAB, and south of the Santa Monica Mountains; SMM) in association with (offshore) northerly to easterly flow over the Basin. This pattern is consistent with the concurrent observations (Fig. 8b in BB03). By the peak ozone time of 05/20UTC (Fig. 5c), the MM5 high is more northward (along coast), and thus the flow is mostly easterly offshore over most of the SoCAB, except for a narrow zone of northerly flow along the coast in the northwest part of the domain. This pattern is again consistent with the concurrent observations (Fig. 8c in BB03), which shows northeasterly flow over the entire Basin. The lack of an observed coastal high is due to a lack of observations.

By 06/12UTC (Fig. 5d), the high has moved even further eastward and inland, maintaining offshore flow in the southern SoCAB, but producing southeasterly along-shore flow over the northern SoCAB and a small area of onshore southerly flow north of the SoCAB. This pattern is again consistent with the concurrent observations (Fig. 8d in BB03), which show offshore flow in the southern SoCAB and southeasterly along shore flow over the northern SoCAB. The lack of any observed onshore southerly flow north of the SoCAB is again due to a lack of observations.

The changing upper-level synoptic flows also impacted MM5 flows nearer the surface. While the MM5 7 m flow at 04/12UTC (04/05PDT) (Fig. 6a) (two nights before ozone peak) shows strong onshore flow in offshore areas, a complex combination of low-speed flows exists over the SoCAB. Although inland areas show organized down-slope flows towards the coast, no clearly defined coastal-plain land breeze is seen. A coastal zone of near-calm flow between the westerly flow

over the sea and the down slope flow off of the mountain peaks narrows into a convergence line along the coast in the northern part of the domain. The concurrent observed flow (Fig. 9a in BB03) also shows a complex combination of low-speed coastal-plain chaotic flows, a coastal convergence zone, and no clearly defined coastal land breeze. Inland down-slope flows, however, are not as strong as those from MM5 (about 2.5 versus 4 m s^{-1}).

By 04/15UTC or 04/08PDT (Fig. 6b), the coastal convergence zone and coastal plain near-calm area are still present, but the latter is decreased in size. The down-slope flows, however, have weakened, as this time is within the “transition to upslope flow” period. The concurrent observations (Fig. 9b in BB03) show generally lower coastal plain speeds and thus a more extensive chaotic flow area, but about the same amount of thermally driven mountain flows as the MM5 results.

Three hours later at 04/18UTC (Fig. 6c), a sea breeze flow (in the same direction as the large-scale westerly flow) and a thermal upslope flow have formed. Between the two resulting westerly flow areas, easterly flow still exists. Two distinct thermal forcings (i.e., land–sea and topographic) have thus each produced separate westerly flow areas (e.g., coastal and on the westward facing slopes). The observations (an hour before) also show similar developing sea breeze and opposing easterly upslope flows (Fig. 9c in BB03), but instead of an area easterly flow between the two westerly flow regions, only a narrow poorly documented calm (or along-coast) flow region exists.

By 04/23UTC (04/16PDT) (Fig. 6d), 1 day before the ozone peak, MM5 has produced local northeasterly upslope thermal flows on the eastern side of the SBM. Simulated sea breeze speeds reached maximum intensity, and both westerly flows have merged into one strong inland-directed breeze that reaches to the peaks of the SBM. Concurrent observations (Fig. 9d in BB03) also show the merging of the two westerly flows at about the same location. By 05/04UTC (not shown), MM5 and observed coastal winds both have started to become offshore. Two hours later (not shown), the sea breeze flow has been replaced by a chaotic flow over most of the coastal plane, and upslope flows have become down-slope, as on the previous night.

The 05/12UTC MM5 surface flow field (Fig. 7a) is again complex, similar to that on the 4th, except that the flow along the southern SoCAB has shifted from westerly to northerly. In addition, a somewhat faster (more organized) easterly flow is now seen in the northeastern part of the domain. The latter change, related to the observed shift in the upper level flow (Fig. 9c in BB03), is not yet apparent in the one surface site in that region (Fig. 10a of BB03). By 05/15UTC (Fig. 7b), neither organized sea breeze nor westerly upslope thermal flows on the western side of the inland mountains have begun. A stronger and more organized

Fig. 5. MM5 terrain heights (solid lines, 500 m increment) and 3800 m AGL winds (barb is 1 m s⁻¹) at: (a) 1800 UTC 4 August; (b) 0600 UTC 5 August; (c) 2000 UTC 5 August; and (d) 1200 UTC 6 August, with anticyclone center(s) (H) based on general flow directions (large subjective arrows).

Fig. 5 (continued).

Fig. 6. MM5 terrain heights (light solid lines, 500 m increment) and 7 m AGL winds (barb is 1 m s^{-1}) on 4 August at: (a) 1200, (b) 1500, (c) 1800, and (d) 2300UTC, with subjective general flow directions (large arrows), near-calm chaotic areas (outlined areas), and convergence-zones (dark solid lines).

Fig. 6 (continued).

Fig. 7. Same as Fig. 6, but for 5 August and with convergence-zone zoom-in area (box).

Fig. 7 (continued).

Fig. 8. MM5 terrain heights (light solid lines, 500 m increment) and 7 m AGL winds (barb is 1 m s^{-1}) within zoom-in area for Run 6 for: (a) 2100UTC 4 August; (b) 0100UTC 5 August; (c) 2100UTC 5 August; (d) 0100UTC 6 August; and for (e) Run 1 at 2100UTC 5 August, with subjective general flow directions (large arrows) and convergence-zones (dark solid lines).

Fig. 8 (continued).

Fig. 8 (continued).

easterly flow has formed on the eastern site of SGM and SBM due to the now easterly flow from the new position of the upper-level high. Concurrent observations (Fig. 10b in BB03) show somewhat more onshore sea breeze flow, but also (as in the MM5 results) no westerly upslope thermal flows.

By three hours later at 05/18UTC (Fig. 7c), the sea breeze and thermal upslope flows have begun, and the boundary between the two westerly flow areas is again easy to discern. Because of the influence of the now easterly upper level background flow, the sea breeze is less developed than 24 h before (Fig. 6c). This agrees well with the observations (Fig. 10c in BB03), but they are not dense enough to discern the calm region between two MM5 westerly flow regions (just inland and at SGM-SBM).

By 05/23UTC (time of ozone peak), the MM5 westerly flow again reaches maximum intensity and the convergence zone is again between SGM and SBM (Fig. 7d). Convergence zone movement on the peak ozone day relative to that of the previous day is significant for ozone transport determination, and thus the winds in key SGM-SBM convergence zone area are discussed in greater detail. While Figs. 8a and c show

only slight differences in inland penetration at 2100UTC (1400PDT) between the 4th and 5th, the opposing background in the Cajon Pass between SGM and SBM on the peak ozone day (5th) is more organized. While 4 h later (Figs. 8b and d), the inland directed flow had penetrated through the Pass on the 4th, it could not do so on the 5th, as the flow north of the Pass on the 4th was then westerly, as opposed to northerly on the 5th. The northerly flow on the 5th resulted from the changes in the upper level flow discussed above, and the lack of penetration through the pass on the 5th allowed ozone peak formation in that area. The higher peak ozone on the 5th (relative to the 4th) at 2100UTC probably in part resulted from the increased subsidence warming on the 5th. Organized opposing flow was only correctly simulated with analysis nudging, as the Run 1 (no analysis nudging) 05/21UTC results (Fig. 8e) indicate only weak opposing flow and hence the convergence zone pasted SGM-SBM.

MM5 surface winds in this critical area at this time compared well to the observations over most of the domain (Fig 10d in BB03). The maximum westerly flow penetration in the gap region on the 5th was thus less than on the previous day, and by 06/03UTC (05/20PDT)

Fig. 9. MM5 terrain heights (light solid lines, 500 m increment) and 800 m AGL winds (barb is 1 m s^{-1}) on 4 August at (a) 1200 and (b) 2300 UTC and on 5 August at (c) 0500 and (d) 2200 UTC, with subjective general flow directions (large arrows) and convergence zones (dark solid lines).

Fig. 9 (continued).

(not shown) the sea breeze again (as on the previous day) had retreated back to the coast. On 06/23UTC (afternoon after peak ozone, not shown), the sea breeze was more from the south and penetrated further inland near SBM (as compared to previous days). Increased penetration of the modeled and observed sea-breeze front resulted from the turning of the synoptic flow aloft from an opposing northeasterly flow on the 5th to a southeasterly flow on the 6th in association with the formation of a surface Catalina Eddy (Rosenthal et al., 2003).

Nighttime 800 m AGL MM5 winds at 04/12UTC (Fig. 9a) show a somewhat less complex combination of faster speeds than the concurrent 7 m MM5 results due to reduced surface influences aloft. Simulated down slope MM5 flows at inland sites agree with the observations in Fig. 11a in BB03. In addition, no clearly defined land breeze has been simulated, as MM5 coastal winds correctly show generally along-coast flows. One area of disagreement, however, is that the observed southeasterly along-coast flow in the northern SOCAB has not been simulated. By 04/23UTC (Fig. 9b), the onshore sea breeze flow reached maximum intensity, with speeds faster than the corresponding 7 m MM5 speeds (Fig. 6d). The offshore flow at inland sites is likewise faster and more organized than at 7 m. MM5 results in the coastal plane agree with the concurrent observed flow field (Fig. 11b in BB03), but inland flow directions cannot be determined due to a dearth of observational sites.

By 05/05UTC or 04/22PDT, offshore flow exists over the northern half of the SoCAB coastline, while along shore flow exists over its southern half (Fig. 9c). The concurrent observations (Fig. 11c in BB03) do not show such a well defined along shore flow, but few observations are available right on the coast. By 05/22UTC (Fig. 9d), the onshore MM5 flow had reached maximum intensity and penetration, as with the concurrent observations of Fig. 11d in BB03. The MM5 coastal flow over the SoCAB was, however, more onshore than the observations. Its inland penetration was reduced over that simulated on the previous day (Fig. 9b) due to the now stronger opposing easterly flow at inland sites.

5. Conclusion

Simulations of the 4–7 August SCOS97-NARSTO ozone episode in the SoCAB with MM5 showed that a relatively rare easterly upper-level synoptic background flow influenced surface wind flow directions at inland sites. An inland-moving surface convergence zone resulted where the offshore background flow at inland sites met an inland moving westerly (sea breeze plus thermal upslope) onshore flow. Maximum inland penetration of the zone was to the SGM, where it

produced peak observed ozone concentrations. MM5 reproduced the main qualitative features of the evolution of the diurnal sea breeze cycle with reasonable accuracy, as it first simulated the diurnal variation of coastal temperature gradients that produce the spatial wind velocity distributions associated with the diurnal sea breeze cycle. It also reproduced the opposing easterly flow, inland movement of the sea breeze front, and the retreat of the land breeze front.

The accuracy of predicted surface winds and temperatures were improved by the following sequential modifications of MM5 and/or its input parameters: analysis nudging, accurate specification of deep-soil temperature, observational nudging with SCOS97-NARSTO surface and upper level coarse RWP and rawinsonde winds and RASS temperatures, use of updated urban land-use patterns, use of corrected input ocean and urban surface roughness parameter values, and proper limitation of MM5 diagnosed mixing-depth values.

Quantitative aspects of the diurnal evolution of the observed sea breeze cycle less accurately simulated include too low MM5 nighttime wind speeds (1.5 vs. 2.5 m s^{-1}), which could result from: errors in the early version of the observational data set (version MET-0), high threshold anemometer wind speed values, errors in global-model winds, over-nudging in the vertical of (profiler and rawinsonde) winds, an inner-domain lateral-boundary too close to the Ventura coast, and/or a too large inner-domain horizontal grid spacing. Although comparisons between the SCOS97-NARSTO observations and MM5 model results are mostly positive, complete understanding of the meteorology of the 4–7 August peak ozone event requires additional data analysis and model simulations.

Acknowledgements

This research was sponsored under contract No. 97–310 from the California Air Resources Board (CARB). Thanks to Jonas Haile and Ruri Imamura for help with the graphics.

References

- Arya, P., 1988. Introduction to Micrometeorology. Academic Press, New York, 307pp.
- Bornstein, R., Thunis, P., Grossi, P., Schayes, G., 1996. Development of the topographic vorticity-mode mesoscale (TVM) model. *Journal of the Applied Meteorology* 35, 1824–1834.
- Bornstein, R., Boucouvala, D., Wilkinson, J., Yadav, A., Seaman, N., Stauffer, D., Hunter, G., Miller, D., 2001. Improvement and evaluation of the mesoscale

- meteorological model MM5 for air quality applications in Southern California and the San Joaquin Valley. SJSU report to CARB for Contract No. 97-310, 237pp.
- Boucouvala, D., Bornstein, R., 2003. Analysis of transport patterns during a SCOS97-NARSTO episode. *Atmospheric Environment*, this issue [doi:10.1016/S1352-2310(03)00383-2].
- CARB, 2001. Proceedings of the SCOS97-NARSTO Data Analysis Conference, Abstract volume for 13–15 February Workshop, Diamond Bar, CA, 21pp.
- Charnock, H., 1955. Wind stress on a water surface. *Quarterly Journal of Royal Meteorological Society* 81, 639–640.
- Deardorff, J., 1972. Parameterization of the PBL for use in general circulation models. *Monthly Weather Review* 100, 93–106.
- Douglas, S.G., Kessler, R., 1991. Analysis of mesoscale airflow patterns in the south-central coast air basin during the SCCAMP 1985 intensive measurement periods. *Journal of Applied Meteorology* 30, 607–631.
- Dudhia, J., 1989. Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *Journal of Atmospheric Science* 46, 3077–3107.
- Fujita, E., Moosmuller, H., Green, M., Bowen, J., Rogers, F., 2000. SCOS97-NARSTO 1997 Southern California ozone study and aerosol study. Final Report to CARB, Contract No. 93-326, DRI, Reno, NV, 225pp.
- Gayno, G., 1994. Development of a higher-order, fog-producing boundary layer model suitable for use in numerical weather prediction. M.S. Thesis, Pennsylvania State University, 104pp.
- Grell, G. A., Dudhia, J., Stauffer, D., 1994. A description of the fifth generation Penn State/NCAR mesoscale model (MM5). NCAR Technical Note, NCAR TN-398-STR, 138pp.
- Haagenson, P.L., Dudhia, J., Grell, G., Stauffer, D., 1994. The Penn State/NCAR Mesoscale Model (MM5) Source Code Documentation. NCAR Technical Note NCAR/TN-392, 172pp.
- Hegarty, J., Leidner, M., Iakono, M., 1998. Modeling air pollution in the Los Angeles basin using the MM5-SAQM modeling system. Proceedings of the 10th Joint Conference on Applications of air Pollution meteorology with A&WMA, Phoenix, AZ. American Meteorological Society, Boston, Mass., J345–J348, preprints.
- Kain, J., Fritsch, J., 1993. Convective parameterization for mesoscale models: The Kain–Fritsch scheme. In: Emanuel, K., Raymond, D. (Eds.), *The Representation of Cumulus Convection in Numerical Models*. American Meteorological Society, Boston, Mass., pp. 678–684.
- Kessler, R.C., Douglas, S., 1991. A numerical study of mesoscale eddy development over the Santa Barbara channel. *Journal of Applied Meteorology* 30, 633–651.
- Kitaigorodski, S., 1970. *The physics of air–sea interaction*. Gidromet. Izdatel'stvo, Leningrad, 225pp. (Translated from Russian, Israel Program of Scientific Translations, Jerusalem.)
- Leidner, S., Stauffer, D., Seaman, N., 2000. Improving short-term numerical weather pre-diction in the California coastal zone by dynamic initialization of the marine boundary layer. *Monthly Weather Review* 128, 275–294.
- Lozej, C., Bornstein, R., 1999. Comparison of nesting techniques within a meteorological model. *Air Pollution VII*, Southampton, UK, pp. 1009–1021.
- Lu, R., Turco, R., 1995. Air pollutant transport in a coastal environment—II: three-dimensional simulations over the Los Angeles basin. *Atmospheric Environment* 29, 1499–1518.
- McNally, D., Tesche, T., 1994. MAPS2.3 User's Guide. Alpine Geophysics, LLC, Arvada, CA, 132pp.
- Pielke, R.A., 1984. *Mesoscale Meteorological Modeling*. Academic Press, New York, 267pp.
- Rosenthal, J., Helvey, R., Battalino, T., Fisk, C., Greiman, P., 2003. Ozone transport by mesoscale and diurnal wind circulations across Southern California. *Atmospheric Environment*, this issue [doi:10.1016/S1352-2310(03)00382-0].
- Seaman, N.L., Stauffer, D., Lario, A., 1995. A multiscale four-dimensional data assimilation system applied in the San Joaquin Valley during SARMAP. Part I: modeling design and basic performance characteristics. *Journal of Applied Meteorology* 34, 1739–1761.
- Shafraan, P., Seaman, N., Gayno, G., 2000. Evaluation of numerical predictions of boundary-layer structure during the lake Michigan ozone study. *Journal of Applied Meteorology* 39, 412–426.
- Stauffer, D., 2001. Personnel communication.
- Stauffer, D., Seaman, N., 1990. Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: experiments with synoptic data. *Monthly Weather Review* 118, 1250–1277.
- Stauffer, D., Seaman, N., Hunter, G., Leidner, S., Lario-Gibbs, A., Tanrikulu, S., 2000. A field-coherence technique for meteorological field-program design for air quality studies. Part I: description and interpretation. *Journal of Applied Meteorology* 39, 297–316.
- Sterbis, C., 2000. An analysis of short-term mesoscale forecasts in the Los Angeles basin using SCOS97 data. M.S. Thesis, Department of Meteorology, NPGS, Monterey, CA, 101pp.
- Taha, H., 1997. Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air basin. *Atmospheric Environment* 31, 1667–1676.
- Tanrikulu, S., Stauffer, D., Seaman, N., Ranzieri, A., 2000. A field-coherence technique for meteorological field-program design for air quality studies. Part II: evaluation in the San Joaquin Valley. *Journal of Applied Meteorology* 39, 317–334.
- Ulrickson, B.L., Mass, C., 1990a. Numerical investigation of mesoscale circulations over the Los Angeles basin. Part I: a verification study. *Monthly Weather Review* 118, 2138–2161.
- Ulrickson, B.L., Mass, C., 1990b. Numerical investigation of mesoscale circulations over the Los Angeles basin. Part II: synoptic influences and pollutant transport. *Monthly Weather Review* 118, 2162–2184.
- Wolfe, D., Weber, B., 1999. Data management—upper-air meteorological network. Draft Final Report to CARB on Contract 96-323, NOAA ERL, Boulder, CO, 122pp.