2004

MM5 simulations of transport from SFBA to Sacramento and SJV during CCOS

Tesfamichael Berhane Ghidey
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Ghidey, Tesfamichael Berhane, "MM5 simulations of transport from SFBA to Sacramento and SJV during CCOS" (2004). *Master's Theses*. 2658.

DOI: <https://doi.org/10.31979/etd.jdg2-y7xt>

https://scholarworks.sjsu.edu/etd_theses/2658

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

NOTE TO USERS

This reproduction is the best copy available.

UMI[®]

MM5 SIMULATIONS OF TRANSPORT FROM SFBA
TO SACRAMENTO AND SJV DURING CCOS

A Thesis Presented to
The Faculty of the Department of Meteorology
San Jose State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Tesfamichael Berhane Ghidey

December 2004

UMI Number: 1425460

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI Microform 1425460

Copyright 2005 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

© 2004

Tesfamichael Berhane Ghidey

ALL RIGHTS RESERVED

APPROVED FOR THE DEPARTMENT OF METEOROLOGY

Prof. Robert D. Bornstein

Dr. Robert Van Buskirk

Prof. Eugene Cordero

APPROVED FOR THE UNIVERSITY

ABSTRACT

MM5 SIMULATIONS OF TRANSPORT FROM SFBA TO SACRAMENTO AND SJV DURING CCOS

by Tesfamichael Berhane Ghidey

MM5 was run with three one-way nested domains (horizontal grid lengths of 36, 12, and 4 km), 32 expanding vertical-levels up to 100 hPa (first sigma level at 20 m), 1.5 higher order TKE closure, and either GDAS or ETA large-scale NCEP forcing and analyzing nudging. Analyses showed that the 700 hPa synoptic-forcing was better reproduced by GDAS, as its surface-pressure lower boundary-condition better captured central-California topographic effects than did the mean sea-level pressure boundary-condition of ETA. MM5 results for the 30 July to 02 August 2000 Central California Ozone Study (CCOS) episode showed that a strengthening coastal high at 700 hPa settled over the San Francisco Bay Area (SFBA) and then moved inland to create evolving upper-level background flows. The related movements of two surface Central Valley thermal-lows, i.e., the Fresno and Sacramento eddies, sequentially produced flows from the SFBA into Livermore, Sacramento, and San Joaquin Valley. MM5 reproduced these flows, as well as the resulting surface mesoscale sea/land and mountain/valley breezes, as well as the associated confluence zones that sequentially produced the ozone exceedances in the three areas listed above.

Acknowledgements

I would like to thank my advisor, Professor Robert Bornstein, for the assistance and insights he provided me. I would also like to thank my supervisor at Lawrence Berkeley National Laboratory (LBNL) and my sponsor, Dr. Robert Van Buskirk, for granting me this opportunity and for his assistance and guidance. He has been every thing to me since my undergraduate studies at the Asmara University (until 1997) in Eritrea, and during my study in the US. I would also like to thank Professor Eugene Cordero for his willingness to be on my thesis committee, and for his insights and encouragement.

My gratitude is also extended to my friends and colleagues in the Meteorology Department at San Jose State University (SJSU), especially to Dimitra Boucouvala for her tireless help and advice with my MM5 modeling problems and to Bereket Habtezion for his computer program assistance. I also appreciate the NCAR Mesouser group, who provided me with online assistance whenever I asked. Thanks also to “the family” of the Meteorology Department at SJSU for their warm treatment and to my Eritrean friends for always being at my side and for sharing my agonies, homesickness, and glories of life, and with whom I spent countless hours in class and in the graduate-student room. I also appreciate my grand family back home for their endless material and moral help and for their encouragement since I separated from them.

This research was funded by LBNL under Account No. 3660-73.

Table of Contents

	Page
List of Tables.....	vii
List of Figures.....	viii
1. Introduction.....	1
<i>A. Central California meteorology.....</i>	<i>1</i>
<i>B. Central California modeling studies.....</i>	<i>5</i>
2. Methodology.....	8
3. Results.....	14
<i>A. Synoptic patterns.....</i>	<i>15</i>
<i>B. Domain 1.....</i>	<i>23</i>
<i>C. Domain 3.....</i>	<i>27</i>
1) SURFACE TEMPERATURES.....	28
2) UPPER LEVEL FLOW.....	30
3) SURFACE FLOW.....	32
4. Conclusion.....	36
References.....	40
Appendix A: Acronyms.....	46
B: Tables.....	49
C: Figures.....	51

List of Tables

	Page
1. Domain boundaries for: MM5 (coarsest domain), ETA, and GDAS.....	49
2. NWS and MM5 locations of 700 hPa synoptic high pressure-system at 1200 UTC.....	50

List of Figures

	Page
1. MM5 Domain-3 (4 km grid) with terrain heights (interval of 500 m).....	51
2. Three MM5 nested domains (36, 12, and 4 km grids).....	52
3. Domain-3 surface met-sites and terrain heights (interval of 300 m).....	53
4. Domain-3 sub-areas (boxes) and terrain heights (interval of 300 m).....	54
5. Livermore-section of Domain-3, with terrain heights (m).....	55
6. SFBA- and Sacramento-section of Domain 3, with terrain height (m).....	56
7. Central Valley-section of Domain 3, with terrain heights (m).....	57
8. NWS 700 hPa analysis at 1200 UTC on 29 July.....	58
9. 700 hPa GDAS velocities (flag is 5 m s ⁻¹) for every 4th value at 1200 UTC on 29 July, with terrain heights (dotted lines, at 500 m interval).....	59
10. 700 hPa ETA velocities (flag is 5 m s ⁻¹) for every 4th value at 1200 UTC on 29 July, with terrain heights (dotted lines, at 500 m interval).....	60
11. NWS 700 hPa analysis at 1200 UTC on 30 July.....	61
12. 700 hPa GDAS velocities (flag is 5 m s ⁻¹) for every 4th value at 1200 UTC on 30 July, with terrain heights (dotted lines, at 500 m interval).....	62
13. 700 hPa ETA velocities (flag is 5 m s ⁻¹) for every 4th value at 1200 UTC on 30 July, with terrain heights (dotted lines, at 500 m interval).....	63
14. NWS 700 hPa analysis at 1200 UTC on 31 July.....	64
15. NWS 700 hPa analysis at 1200 UTC on 1 August.....	65

16.	700 hPa GDAS velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 31 July, with terrain heights (dotted lines, at 500 m interval).....	66
17.	700 hPa GDAS velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 1 August, with terrain heights (dotted lines, at 500 m interval).....	67
18.	700 hPa ETA velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 31 July, with terrain heights (dotted lines, at 500 m interval).....	68
19.	700 hPa ETA velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 1 August, with terrain heights (dotted lines, at 500 m interval).....	69
20.	NWS 700 hPa analysis at 1200 UTC for 2 August.....	70
21.	700 hPa GDAS velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 500 m interval).....	71
22.	700 hPa ETA velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 500 m interval).....	72
23.	NWS surface weather analysis at 1200 UTC on 29 July.....	73
24.	First half-sigma ($\sim 10 \text{ m}$) GDAS velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 29 July, with terrain heights (dotted lines, at 500 m interval).....	74
25.	First half-sigma ($\sim 10 \text{ m}$) ETA velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 29 July, with terrain heights (dotted lines, at 500 m interval).....	75
26.	NWS surface weather analysis at 1200 UTC on 31 July.....	76

27.	First half-sigma (~ 10 m) GDAS velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 31 July, with terrain heights (dotted lines, at 500 m interval).....	77
28.	First half-sigma (~ 10 m) ETA velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 31 July, with terrain heights (dotted lines, at 500 m interval).....	78
29.	NWS surface weather analysis at 1200 UTC on 1 August.....	79
30.	First half-sigma (~ 10 m) GDAS velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 1 August, with terrain heights (dotted lines, at 500 m interval).....	80
31.	First half-sigma (~ 10 m) ETA velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 1 August, with terrain heights (dotted lines, at 500 m interval).....	81
32.	NWS surface weather analysis at 1200 UTC on 2 August.....	82
33.	First half-sigma (~ 10 m) GDAS velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 500 m interval).....	83
34.	First half-sigma (~ 10 m) ETA velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 500 m interval).....	84

35.	700 hPa Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 29 July, with terrain heights (dotted lines, at 500 m interval).....	85
36.	First half-sigma ($\sim 10 \text{ m}$) Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 29 July, with terrain heights (dotted lines, at 500 m interval).....	86
37.	700 hPa Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 30 July, with terrain heights (dotted lines, at 500 m interval).....	87
38.	First half-sigma ($\sim 10 \text{ m}$) Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 30 July, with terrain heights (dotted lines, at 500 m interval).....	88
39.	700 hPa Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 31 July, with terrain heights (dotted lines, at 500 m interval).....	89
40.	First half-sigma ($\sim 10 \text{ m}$) Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 31 July, with terrain heights (dotted lines, at 500 m interval).....	90
41.	700 hPa Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 1 August, with terrain heights (dotted lines, at 500 m interval).....	91

42.	First half-sigma (~ 10 m) Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 1 August, with terrain heights (dotted lines, at 500 m interval).....	92
43.	700 hPa Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 500 m interval).....	93
44.	First half-sigma (~ 10 m) Run 4 Domain 1 velocities (flag is 5 m s^{-1}) for every 4th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 500 m interval).....	94
45.	Domain-average MM5 (for each of four simulations) and observed (all observational sites) 10 m temperatures.....	95
46.	Domain-average 10 m temperature-bias (MM5 minus observed) between all observations and the GDAS+GN and ETA+GN result.....	96
47.	Domain-average temperatures at the 52 sites with observations at at 10 m and from the closest GDAS+GN grid point.....	97
48.	Domain-average bias (MM5 minus observed) between the 52 sites with temperatures at 10 m and the closest GDAS+GN grid-point.....	98
49.	Domain-average height-uncorrected (10 m) and corrected (to 2 m) GDAS+GN temperature values at the closest grid-point to each 71 NWS sites (2 m observations).....	99

50.	Domain-average bias (MM5 minus observed) between the height-corrected and uncorrected GDAS+GN temperatures and the 71 NWS values (2 m); gaps indicate too few data points.....	100
51.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 1000 UTC on 30 July, with terrain heights (dotted lines, at 300 m interval).....	101
52.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 0700 UTC on 31 July, with terrain heights (dotted lines, at 300 m interval).....	102
53.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 2100 UTC on 31 July, with terrain heights (dotted lines, at 300 m interval).....	103
54.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 0600 UTC on 1 August, with terrain heights (dotted lines, at 300 m interval).....	104
55.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 1300 UTC on 1 August, with terrain heights (dotted lines, at 300 m interval).....	105
56.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 2100UTC on 1 August, with terrain heights (dotted lines, at 300 m interval).....	106

57.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 0200 UTC on 2 August, with terrain heights (dotted lines, at 300 m interval).....	107
58.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 0600 UTC on 2 August, with terrain heights (dotted lines, at 300 m interval).....	108
59.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 300 m interval).....	109
60.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 2100 UTC on 2 August, with terrain heights (dotted lines, at 300 m interval).....	110
61.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 0600 UTC on 3 August, with terrain heights (dotted lines, at 300 m interval).....	111
62.	700 hPa Run 4 Domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 2100 UTC on 3 August, with terrain heights (dotted lines, at 300 m interval).....	112
63.	First half-sigma (10 m) Run 4 SFBA Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 2nd value at 2100 UTC on 30 July, with terrain heights (dotted lines, at 100 m interval).....	113

64.	First half-sigma (10 m) Run 4 SFBA Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 2nd value at 0100 UTC on 31 July, with terrain heights (dotted lines, at 100 m interval).....	114
65.	First half-sigma (10 m) Run 4 SFBA Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 2nd value at 2100 UTC on 31 July, with terrain heights (dotted lines, at 100 m interval).....	115
66.	First half-sigma (10 m) Run 4 SFBA Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 2nd value at 0100 UTC on 1 August, with terrain heights (dotted lines, at 100 m interval).....	116
67.	First half-sigma (10 m) Run 4 SFBA Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 2nd value at 2100 UTC on 1 August, with terrain heights (dotted lines, at 100 m interval).....	117
68.	First half-sigma (10 m) Run 4 SFBA Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 2nd value at 0100 UTC on 2 August, with terrain heights (dotted lines, at 100 m interval).....	118
69.	First half-sigma (10 m) Run 4 Sacramento Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 4th value at 0100 UTC on 1 August, with terrain heights (dotted lines, at 150 m interval).....	119
70.	First half-sigma (10 m) Run 4 Sacramento Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 4th value at 0100 UTC on 2 August, with terrain heights (dotted lines, at 150 m interval).....	120

71.	First half-sigma (10 m) Run 4 Sacramento Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 4th value at 2100 UTC on 2 August, with terrain heights (dotted lines, at 150 m interval).....	121
72.	First half-sigma (10 m) Run 4 Central-Valley Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 1200 UTC on 31 July, with terrain heights (dotted lines, at 300 m interval).....	122
73.	First half-sigma (10 m) Run 4 Central-Valley Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 1200 UTC on 1 August, with terrain heights (dotted lines, at 300 m interval).....	123
74.	First half-sigma (10 m) Run 4 Central-Valley Sub-domain 3 velocities (flag is 5 m s^{-1}) for every 10th value at 1200 UTC on 2 August, with terrain heights (dotted lines, at 300 m interval).....	124
75.	Domain-averaged observed surface wind-speeds at both all and only the 10 m stations, as well at the closest GDAS+GN grid point.....	125
76.	Domain-average biases between the observations at all the stations and only the 10 m wind-speed sites and MM5 values at the closest GDAS+GN grid-point.....	126
77.	Domain-average observed above-threshold ($>1.5 \text{ m s}^{-1}$) wind speeds from the 10 m stations and closest GDAS+GN grid point.....	127
78.	Domain-average biases between the above-threshold observed wind speeds ($>1.5 \text{ m s}^{-1}$) from the 10 m stations and the closest GDAS+GN grid-point.....	128

79.	Domain-average all and above-threshold ($>1.5 \text{ m s}^{-1}$) NWS wind speeds and the closest GDAS+GN grid-point values.....	129
80.	Domain-average biases between the all NWS wind speeds and only those above the threshold ($>1.5 \text{ m s}^{-1}$) and the closest GDAS+GN grid-point values.....	130
81.	Domain-averaged wind-directions from all stations and 10 m sites and the closest GDAS+GN grid-points.....	131
82.	Domain-average wind-direction biases between observations at all and only the 10 m sites and the closest GDAS+GN grid-points.....	132
83.	Domain-average wind directions from above threshold ($>1.5 \text{ m s}^{-1}$) 10 m stations and the closest GDAS+GN grid-point.....	133
84.	Domain-average wind-direction biases between observations above the threshold value ($>1.5 \text{ m s}^{-1}$) at the 10 m stations and the closest GDAS+GN grid-point.....	134
85.	Domain-average all and above-threshold ($>1.5 \text{ m s}^{-1}$) NWS wind directions and the closest GDAS+GN grid-point values.....	135
86.	Domain-average biases between observations wind directions at all the NWS stations and those above the threshold ($>1.5 \text{ m s}^{-1}$) and the closest GDAS+GN grid-point values.....	136

1. Introduction

A. Central California meteorology

Regional summer ozone levels in central California often exceed the 120 ppb hourly federal limit mandated by the Clean Air Act (McNerny and Ranzieri 1991). Central California air quality is governed by interactions on various scales between topography and meteorology, as well as by the distribution and composition of regional pollutant emissions (Quint *et al.* 1993, Seaman *et al.* 1995). Terrain features produce pollutant transport and mixing patterns over on the Orlanski (1975)-defined meso- β (20-200 km) and meso- α (200-2000 km) scales. Note that Thunis and Bornstein (1996) re-classified his meso- α to meso- γ .

The summertime General Circulation (GC, see Appendix for list of acronyms) Pacific High, located offshore of the San Francisco Bay Area (SFBA), deflects rain-producing synoptic storms northward, producing a dry summer climate in central California (Boucouvala *et al.* 2003). Its subsidence produces an elevated (warm and dry) inversion layer that caps a cool (about 1 km deep) moist marine boundary layer (MBL), whose on-shore GC westerly flows penetrate inland thru mountain passes and gaps for several 100 km (Seaman *et al.* 1995). The inversion is strongest (up to 20 K across a layer of 200-300 m) and its base lowest just off the coast, where upwelling deep-ocean water cools the MBL. Coastal communities, such as San Francisco and Monterey, thus usually remain cool throughout the day and experience fog and/or stratus.

The Central Valley (CV), bounded by the Sierra Nevada (ridge levels to 3200 m) on its east and coastal ranges on its west (Fig. 1), is divided into northern and southern

halves, called the Sacramento Valley (SacV) and San Joaquin Valley (SJV), respectively. The major westward marine-air inflow into the SJV (at its central latitude) accelerates through the narrow Carquinez Strait into the Sacramento River delta (Tanrikulu *et al.* 2000) and then splits northward into the SacV and southward into the SJV. As over-land air temperatures increase due to daytime surface heat fluxes, the GC inversion weakens and disappears within 50 km inland. Mixed-layer depth thus increases from about 200 m AGL (all height given as AGL) along the coast to about 1200 m in the CV (Blumenthal *et al.* 1985).

High CV daytime surface temperatures create meso- α thermal low-pressure centers near Redding and Bakersfield, called the Sacramento (or Schultz) and Fresno eddies, respectively. Resulting pressure-differences between the coast and CV thus create cool onshore sea-breeze flows that augment the onshore GC-flow. The flows are further augmented by inland-directed thermally-driven upslope flows associated with the coastal and inland mountain ranges, sometimes producing convective showers over the inland peaks (Seaman *et al.* 1995).

During nighttime hours, land surfaces cool more rapidly (by IR radiative loss) than the sea, and the now-reversed temperature-differences produce offshore land-breeze flows, also augmented by seaward-directed down-slope mountain flows. Resulting cool drainage flows converge into the CV, and in conjunction with topographically induced thermal wind effects, produce along-valley low-level jets (LLJs) with speeds of 10-30 m s⁻¹ at about 400 m AGL (Lehrman *et al.* 1994). The LLJ transports elevated layers of high-ozone, which cannot exit the SJV because of the high nighttime PBL thermal stabil-

ity. With surface heating and associated boundary layer growth, the elevated aged-ozone mixes down to interact with fresh surface emissions (Niccum *et al.* 1995). Resulting daytime up-valley flows are modified by upslope winds along the Sierra slopes, and thus the coastal ranges provide a ventilation mechanism, as do daytime outflows at both ends of the CV. Low-level horizontal convergence, where the Carquinez Strait and down-slope flows meet, aids in Fresno eddy formation and produces divergence aloft. The eddy recirculates pollutants within the valley, while the divergence provides ventilation (Lehrman *et al.* 2001).

Various intensive field-study campaigns have produced data that have provided increased insights into the diurnal variation of CV mesoscale meteorological features and their relationships with summertime ozone episodes. Tracer studies during August 1980 investigated the origin of SacV pollutants (Lehrman *et al.* 1981). Releases into the SFBA plume passed into either the SJV or SacV. An early morning release was transported into the SJV due to the Sacramento Eddy, which restricted marine air penetration northward into the SacV from early morning to late forenoon. After the eddy degenerated into a southwesterly flow (aided by an unusually strong south to north CV pressure-gradient) into the SacV, a late afternoon release produced extensive SacV concentrations. The extensive carry over of tracer material in the Valley had implications for photochemical reactions on the following morning.

The San Joaquin Valley Air Quality Study (SJVAQS) Atmospheric Utility Signatures, predictions, and Experiments (AUSPEX) provided an observational base that was used by the SJVAQS/AUSPEX Regional Modeling Adaptation Project (SARMAP)

(Blumental and Watson 1991, Ranzier and Thuillier 1991, Venkatram *et al.* 1992, Thuillier *et al.* 1994). Roberts *et al.* (1994) found generally westerly winds on the western side of the southern SacV, with minimum forenoon speeds and peak late afternoon speeds. The 1995 Integrated Monitoring Study (IMS95), a subcomponent of the California Regional PM₁₀/PM_{2.5} Air Quality Study (CRPAQS), was designed to provide the SJV meteorological, (PM and gas phase) air quality, and emission-inventory data required for Eulerian air quality model simulations of conditions during Fall 1995 and Winter 1995-96 (Solomon and Magliano 1999).

Lehrman *et al.* (2001) analyzed NOAA radar wind-profiler data from Visalia (central SJV) and Waterford (northern SJV) during the 30 July-2 August 2000 Central California Ozone Study (CCOS) episode to determine nocturnal LLJ ($> 6 \text{ m s}^{-1}$) and meso-eddy characteristics. The dominant synoptic feature, a 500 hPa synoptic high over the southwestern US, retrograded westward until 1 August, before migrating eastward. Beginning in the evening of 31 July, the two-day northwesterly flow at Visalia was thus disrupted, and flows with a strong southerly component developed. The LLJ developed at Waterford during the evening of 30 July-1 August with peak speeds of 11.4 m s^{-1} at 300 m AGL between 1900 and 2000 PST. The Fresno eddy, defined by an afternoon down-valley flow at Visalia, was developed on all four days.

They also used SacV radar data from Sacramento, Pleasant Grove, and Arbuckle, with the last two situated in the southern end of the Valley. Winds in the lowest 500 m at 0800 and 2200 PST at Arbuckle (mostly northwesterly) and Pleasant Grove (variable, but on averaged southeasterly) were generally light. Winds aloft at Sacramento were mostly

westerly, with moderate speeds ($>3 \text{ m s}^{-1}$) on 30-31 July, when the jet and Fresno eddy formed in the SJV. The low SacV speeds, in conjunction with the SJV jet and eddy, suggests that most air that entered the SJV through the Carquinez Strait then veered south-eastward.

B. Central California modeling studies

Data from the above field studies have been used in diagnostic and numerical mesoscale meteorological models to provide input for CV air quality models. IMS95 SJV data were input into a diagnostic model that provided meteorological fields for the California Institute of Technology-University of California, Davis (CIT-UCD) source-oriented photochemical grid-model (Held *et al.* 2004). Results showed good agreement with most measurements from the 4-6 January 1996 ozone episode, e.g., fractional biases for ozone and PM_{10} were approximately 0.16 and -0.19, respectively.

Prognostic numerical models have also been used to simulate CV flows for air quality applications. Seaman *et al.* (1995) used MM5 with three one-way nested grids (resolutions of 36, 12 and 4 km) for simulations of meteorological conditions during two SJVAQS/ AUSPEX ozone-episodes (air quality simulations were not made). Each domain had 30 vertical layers, with the lowest full-sigma level at 35 m and with 10 layers in the lowest 1.5 km. Four Dimensional Data Assimilation (FDDA) observational nudging incorporated data from 27 radiosondes (every 3-6 h), 12 Doppler sodars (hourly), seven radar wind profilers (hourly), and 159 surface sites (hourly). Surface temperatures were

not nudged, as they adversely affected the Blackadar (1957, 1976) PBL- parameterization.

Although simulated and observed SJV winds showed mostly good agreement, MM5 could not resolve sub-grid flow features in the Carquinez Strait and Altamont Pass areas. Analysis nudging reduced RMS wind speed errors by 15 % to 4.1 m s^{-1} , while FDDA observational nudging further reduced them to 2.8 m s^{-1} . Errors were larger ($> 3 \text{ m s}^{-1}$) in the lowest 750 m, due to the sub-grid terrain influences.

MM5 was also used by Tanrikulu *et al.* (2000) to evaluate the field-coherence technique (FCT) of Stauffer *et al.* (2000) by use of SARMAP data from the 2-7 August 1990 SJV ozone episode. The FCT methodology postulates that with high field-coherence, fewer measurement sites can adequately resolve all dominant mesoscale meteorological characteristics. MM5 was configured with three nested domains (36, 12 and 4 km), with two-way nesting in the outer two domains. All domains had 32 sigma layers, with the first lowest half-sigma level at about 10 m and with 11 layers below 1 km. A 1.5-order TKE PBL scheme was used, as was both analysis nudging and FDDA in the outer two domains. Simulations used either all, half (selection based on FCT results), or no observations. For the no, partial, and full-FDDA simulations, respectively, diurnal-mean surface-temperature biases (MM5 minus observations) were positive at 2.9, 1.1, and 0.7°C , respectively. All biases decreased with height and became negative within (full and partial FDDA cases) or above (no FDDA case) the PBL.

The full- and reduced-FDDA model results produced patterns similar to observed flow fields. Both, however, produced lighter winds than observed in the northern SacV

and southern SJV, and stronger than observed flows through the northern and central SJV and along the slopes of the Sierra Nevada east of the SFBA. Corresponding 10 m-wind speed biases were about: -1.0, -0.1, and -0.2 m s⁻¹, respectively. All biases first increased with height, became positive within the PBL, and finally became negative again, either above or within (no FDDA case) the PBL. Corresponding direction biases, respectively, were about: -4.0, -2.5, and -2.5 deg. While the no-FDDA case directional biases increased with height, the other two were fairly uniform throughout the PBL.

Output from the three MM5 simulations were input into the SARMAP Air Quality Model (SAQM), which simulates transport, diffusion, dry deposition, and chemical transformation processes. While observed ozone concentrations were generally overestimated, SAQM performance with the full- and partial-FDDA simulation input was similar and more accurate than with the no-FDDA simulation input.

The Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS) was used by Umeda and Martien (2002) to simulate mesoscale meteorological patterns during the same episode, with an emphasis on SFBA to SJV transport patterns. They used a second-order TKE PBL scheme in three nested domains (down to a 4 km resolution) in 25 layers (lowest full-sigma level at 25 m) up to 20 km. National Centers for Environmental Prediction (NCEP) synoptic analyses provided initialization and boundary fields, and an upper-air (no surface observations used) 4DDA scheme (28 rawinsondes, 12 Doppler sodars, and 12 radar wind-profilers) was used.

Within the SFBA area, RAMS overestimated land-surface temperatures and (contrary to expectations) underestimated sea-breeze speeds, as its horizontal grid spacing

was unable to resolve fine-scale topography features. Data assimilation reduced domain-averaged diurnal-cycle surface-temperature (3.6 to 3.2 K) and 10 m vector wind-speed (2.8 to 2.7 m s⁻¹) RMSEs, with temperature errors larger at inland sites (up to 5 K) than in coastal areas. The RAMS output was input into Variable grid version of Urban Air-shed Model (UAM-V) to simulate ozone patterns during the episode. The FDDA-assisted simulation had a bias of -4.41 ppb, a 5 ppb improvement over the non-FDDA case.

Whereas previous studies have used either MM5 or RAMS to simulate mesoscale transport-patterns from the SFBA to the SacV and/or SJV areas during SARMAP 1990 ozone episodes, the current effort uses Version 3.6.0 of MM5 to investigate transport patterns during a CCOS 2000 episode. Results will be used by Lawrence Berkeley National Laboratory (LBNL) as input for Models-3/Community Multiscale Air Quality (CMAQ) photochemical model (Ching and Byun 1999) simulations to diagnose central-California air-quality impacts from the possible use of distributed energy-generators *in lieu* of new centralized generators. LBNL provides information to government agencies to be used in the formulation of national energy-usage policies.

2. Methodology

The CCOS 2000 field-study contained two ozone episode periods: 30 July to 2 August and 17-22 September 2000. Both were well documented with large observational meteorological data sets (Lehrman *et al.* 2001), but the earlier one was selected for the current study because changes in its upper-level synoptic conditions were less complex than those during the second episode. The selected episode contained ozone exceedances

that sequentially occurred within the SFBA (at Livermore) on 30 July, at Sacramento on 31 July, and in the SJV on 1 August.

MM5 simulations were carried out to achieve the following goals:

- To use the rich observational dataset from the CCOS 2000 field study to better understand mesoscale pollutant transport patterns within and between the SJV, SFBA, and SacV.
- To reproduce the specific observed synoptic and mesoscale changes in the 700 hPa and surface transport patterns that contributed to the observed sequential daily peak-ozone exceedances in the SFBA, at Sacramento, and in the SJV.
- To provide high-resolution (4 km) gridded meteorological fields (e.g., temperature, wind, TKE, and mixing ratio) as input to the CMAQ photochemical modeling system to study impacts on high ozone levels in central California from the planned construction of distributed energy generators.

MM5 is the Fifth-Generation Pennsylvania State University (PSU)/NCAR prognostic mesometeorological model (Dudhia 1993, 2001, Dudhia *et al.* 2003, Grell *et al.* 1994, and Dudhia and Bresch 2002). It is non-hydrostatic, fully compressible (and thus non-Boussinesq), and uses terrain-influenced, vertical sigma-coordinates on a nested horizontal, rectangular Arakawa-Lamb (1977) B staggered-grid. While the term “terrain-following” is normally used, all meso-models are really “terrain influenced,” as their terrain-following surface-boundary flat-tens to horizontal at their model tops (Thunis and Bornstein 1996). Its split leapfrog, semi-implicit time-steps allow sound waves to be treated

semi-implicitly with shorter time steps, while spatial differences are centered and second-order.

The MM5 modeling system first runs preprocessor programs that prepare the inputs required by the main prognostic code. The first pre-processor program TERRAIN first establishes the mesoscale domains and map projection, and then horizontally interpolates regular latitude-longitude terrain elevations and land-use fractions onto those domains. Next, pre-processor REGRID first reads gridded pressure-level large-scale NCEP analysis and forecast variables, and then linearly interpolates them to the MM5 horizontal grid.

RAWINS next blends synoptic rawinsonde and surface observations with preprocessor REGRID output-fields in an objective-analysis scheme that uses banana-shaped weighting-functions (Dudhia *et al.* 2003). Observations are then compared to interpolated “first-guess” NCEP fields, and if a difference exceeds an input threshold-value, the observation is discarded. The current application used threshold values for temperature, wind speed, and pressure of 15 K, 14 m s^{-1} , and 8 hPa, respectively.

INTERPF next transforms REGRID and RAWINS outputs into MM5 inputs. This first entails the vertical linear-interpolation of pressure-level wind, temperature, and moisture data to sigma-levels. Diagnostic-adjustments of base-state (pressure, temperature, and height) variables, as well as of vertical wind speed and perturbation pressure, are next performed. After data reformatting, it outputs the MM5 initial and lower boundary-condition values, as well as lateral boundary-condition values (of the same variables and their tendencies) in a boundary zone.

With the analysis (or grid) nudging scheme in MM5, solutions are nudged toward time-interpolated NCEP gridded output values (that already include synoptic observations assimilated by RAWINS). As large-scale analysis-nudging data are only available at 6 or 12 h intervals, smaller scale upper-level forcings may be missed (Boucouvala *et al.* 2003). MM5 FDDA is based on Newtonian relaxation (or nudging), an assimilation method that relaxes model variables toward non-uniformly distributed (in space and time) mesoscale observations (Stauffer and Seaman 1990, Grell *et al.* 1994, Stauffer *et al.* 2000). It involves the addition of artificial tendency-terms (based on differences between the two variables) to all prognostic equations. It is continuous, as nudging is applied each time step, thus minimizing model “shock.” When applied with analysis nudging, the resulting assimilation system is termed “multiscale FDDA” (Seaman *et al.* 1995).

MM5 was used with a Lambert-conformal map projection (suitable for mid-latitude regions) centered at 37.0°N latitude, 120.5°W longitude. Three nested horizontal domains (grid spacings of 36, 12, and 4 km) are used (Fig. 2), with 55 x 55, 91 x 91, and 190 x 190 grid-points, respectively. Some simulations used analysis-nudging only, thus retaining the CCOS mesoscale observations as a model-evaluation dataset. When analysis-nudging was used, the assimilation scheme in RAWINS was used in all three domains; otherwise it was only used in the outermost domain.

One-way “continuous” nesting was also used, in which only one MM5 simulation is required and in which information is fed to inner domains at each time step with no feed-back to outer domains (Lozej and Bornstein 1999). With “standard” one way nesting, each domain is simulated separately, outputs kept at hourly intervals, and informa-

tion fed to the next inner domain. “Two-way” nesting is continuous one-way nesting, but with feedback to the next outer domain.

Other options selected for all domains include: Dudhia (1993) radiation to account for long- and short-wave cloud-interactions; Dudhia (1993) explicit simple-ice moisture, and Gayno-Seaman (Gayno 1994) level 1.5 PBL TKE. The Grell *et al.* (1994) non-shallow cumulus convection (no equilibrium assumed between cloud-strength and sub-grid PBL forcing) was used only in the outer two domains. The dry convective adjustment scheme, used only in the inner-domain, is a simple removal of super adiabatic layers in horizontal grids at scales < 10 km. US Geological Survey (USGS) terrain-height data were used at the following resolutions: 30 min (~56 km), 10 min (~19 km), and 2 min (4 km) in the outer to inner grids, respectively. Land-use/vegetation types for all three grids were determined from the 24 category USGS distribution.

Output from either the regional meos-ETA model (40 km grid-resolution) or GDAS analysis-system (2.5 deg or 280 km grid-resolution) provided “first guess” initial and boundary-conditions at 12-h intervals. ETA and GDAS are both run at NCEP and archived at NCAR. GDAS fields are produced by an assimilation scheme that uses spectral statistical-interpolation of past and current NWS observations into NCEP spectral Medium Range Forecast (MRF) model-output fields. MRF (and hence GDAS) uses the following unevenly-spaced, normalized (but not scaled) vertical sigma (σ) coordinate of Mesinger and Black (1992):

$$\sigma = \frac{[p - p_t]}{[p_s - p_t]},$$

where p_s is surface pressure and p_t domain-top pressure, given as 1000 and 21 hPa, respectively and where its lowest atmospheric level is at about 995 hPa.

ETA is initialized by the above described GDAS output-fields. Its σ -coordinate, however, replaces the MRF lower boundary-pressure of p_s by mean sea-level pressure p_{SL} (Mesinger *et al.* 1988), i.e.:

$$\sigma = \frac{[p - p_t]}{[p_{SL} - p_t]}.$$

The replacement smoothes complex-terrain effects, which may not be advantageous when such effects produce vortices important for mesoscale transport processes.

A radiative vertical-motion upper-boundary condition (recommended for grid lengths < 50 km) was used to reduce energy-reflection, thus preventing spurious noise or energy build-up over significant topographic features. The five-layer soil-model option of Dudhia (1996) was used to simulate ground boundary-condition temperatures. Its layers (top to bottom) were 1, 2, 4, 8, and 16 cm deep. Below the bottom grid-level (at 31 cm), substrate temperature is held constant in an additional 32 cm thick layer. The option is similar to the force/restore method (Dudhia 1996), but is more accurate because it explicitly solves the surface energy balance equation, while force-restore only calculates soil heat flux as a residual. Lower boundary sea-surface temperatures (SSTs) came from NCEP analyses via the REGRID preprocessor-program.

Each simulation started at 0500 PDT (1200 UTC) on 28 July 2000 and ran for 7.5 days. The Grid Analysis and Display System (GrADS) graphic system (Doty and Kintter 1992) is used to display MM5 output after 12 h spin-up period. Model-output winds are

plotted in mesoscale format, in which full barbs and flags represent 1 and 5 m s⁻¹, respectively.

The CCOS observations were statistically compared to Domain 3 lowest half-sigma (~10m) temperature, wind speed, and wind direction values from the grid-cell closest to each observational site. The 295 ground-station mesoscale CCOS network (Fig. 3) includes 188 sites with winds measured at 10 m and 107 sites at 2 m (many of which showed incomplete data); corresponding temperature-site totals were 52 and 107, respectively. As winds from the California Irrigation Management System (CIMIS) and Remote Automated Weather Station (RAWS) networks were measured at 2 m, they were not used in the present comparisons. NWS wind and temperature (at the standard levels of 10 and 2 m, respectively) values from 71 NWS sites were also used.

To eliminate the height-differences, a log-law height-correction to the MM5 values was applied by use of gridded MM5 SBL convective heat-flux and friction velocity values. “Surface value” is thus used below to describe 2 m temperature and 10 m wind (observations and MM5) values.

3. Results

Four simulations were carried out:

- Run 1 (hereafter ETA): ETA large-scale forcing without analysis (grid) nudging
- Run 2 (hereafter ETA+GN): ETA large-scale forcing with analysis (grid) nudging every 12 h for temperature and wind in outer two domains
- Run 3 (hereafter GDAS): GDAS large-scale forcing without analysis nudging

- Run 4 (hereafter GDAS+GN): GDAS large-scale forcing with analysis nudging every 12 h for temperature and wind in outer two domains.

Input Domain-1 ETA (Lambert conformal), GDAS (polar stereographic) and current coarse-domain (36 km) grid-boundaries are shown in Table 1. Note that both ETA and GDAS input domains extend well beyond the coarser MM5 domain.

Input ETA and GDAS fields throughout the simulation are first qualitatively compared to observed 700 hPa and surface NWS synoptic pressure-patterns, while concurrent MM5 coarse domain (36 km) patterns are next likewise compared to both fields. Fine domain (4 km) MM5 results are then statistically compared to mesoscale surface-temperature and -wind observations. During a final qualitative comparison, pollutant transport patterns in several fine-domain sub-areas (Fig. 4) are analyzed to understand the observed sequential occurrence of ozone episode days at Livermore in the SFBA (Fig. 5), at Sacramento (Fig. 6), and in the SJV (Fig. 7).

A. Synoptic patterns

On 29 July at 1200 UTC, the 700-hPa NWS analysis showed the western US dominated by the combined effects of the off-shore GC Pacific High and a synoptic high over central Arizona at 34°N, 112°W (Fig. 8), both with central pressure-heights of about 3200 m; a weak “boundary” low- pressure area existed between the two highs at 37°N, 123°W. Coastal and central California winds were dominated by the synoptic high, and thus were mostly southwesterly at about 5 m s^{-1} (10 knots), where one barb on NWS charts is 7-13 knots.

The concurrent 700-hPa GDAS large-scale analysis did capture the offshore GC high, synoptic high over northwest Arizona (at 35°N, 114°W), and “boundary” low, with the latter (Fig. 9) located slightly too-far to the southwest (at 36°N, 124°W). Coastal and central California winds were mostly south southwesterly at about 3 m s^{-1} . The concurrent ETA input also showed the offshore GC high and weak synoptic high over the Nevada-Utah border at 39°N, 114°W, but the “boundary” low was not well reproduced (Fig. 10). Coastal and central California wind velocities were, however, well reproduced.

At 30 July at 1200 UTC (Fig. 11), the central heights of the three systems on the NWS 700 hPa charts had not significantly changed; however, the boundary low moved northwest to 39°N, 125°W, as did the synoptic high to a position over central Nevada at 39°N, 117°W. Wind speeds also did not significantly change, and while the flow was still directed southwesterly in coastal areas, it was now southerly at inland sites over central California.

The concurrent GDAS analysis (Fig. 12) also showed a slight northwest movement of both the boundary low (to 38°N, 125°W) and synoptic high (to southeastern Nevada at 36°N, 115°W, with winds now southerly at 5 m s^{-1}). ETA did intensify the synoptic high (Fig. 13), and also showed the movement into its domain of a synoptic low from (which on the NWS chart and in GDAS was significantly further north) the Gulf of Alaska. This low thus displaced the boundary low southward. Winds were still southerly, but speeds were slightly increased by 1 m s^{-1} .

By 31 July at 1200 UTC (SFBA ozone-episode day), the NWS inland synoptic high slightly strengthened to 3240 m, formed a closed 3210 m contour, and moved west-

ward to the eastern side of the CV at 37°N, 119°W (Fig. 14). Resulting stronger height-gradients increased the now southerly winds to about 6-10 m s⁻¹. On 1 August at 1200 UTC (SacV ozone-episode day), the synoptic high had not moved, but it strengthened by another 20 m to its maximum intensity, and showed two closed height-contours (Fig. 15). Southwesterly winds thus resulted in coastal areas, with southerly flows at inland sites; both were about 5 m s⁻¹.

The concurrent GDAS analysis showed the movement of inland high northward to the border of Nevada and Utah (40°N, 114°W), but did not show the correct pressure-height magnitude change (Fig. 16). Although it positioned the high east of the NWS location, it did create a bulge that extended offshore of southern California. The still unchanged winds (now below observed values by about 2 m s⁻¹) shifted to south-southwesterly (versus observed southerly) in coastal and central California. One day later (Fig. 17), the high moved back south (northern Arizona at 35°N, 113°W) and strengthened its bulge, which slowed the now southwesterly flow to about 3 m s⁻¹. The concurrent ETA analysis on 31 July at 1200 UTC did correctly (in value and position) simulate the observed synoptic high (Fig. 18), and thus accurately reproduced the observed strong southerly winds (9 m s⁻¹) and temperatures. A day later, the increased magnitude (by 20 m) and unchanged position of the NWS inland high was again accurately reproduced (Fig. 19).

By 2 August at 1200 UTC (Fig. 20), the SJV ozone-episode day, the inland synoptic high had split into two weaker (by 50 m) halves. Its northern half moved to northern Nevada (40°N, 117°W), while its southern half progressed eastward to the California-Nevada boarder (37°N, 117°W). Over central California, winds thus shifted to south-

southeasterly and speeds weakened to $2\text{-}5\text{ m s}^{-1}$. In the concurrent GDAS analysis, the now weakened synoptic high (by 10 m) had slightly moved north to a position over southeastern Nevada (Fig. 21). Its previous bulge split-off to create a second high over the SFBA, which slightly shifted winds to south-southeasterly and weakened them to $2\text{-}5\text{ m s}^{-1}$, now in good agreement with NWS speeds. In the ETA results (Fig. 22), the synoptic high had significantly expanded, but weakened (by 60 m), compared to the NWS and GDAS values. Winds shifted to mostly southeasterly and speeds weakened ($1.5\text{-}3.5\text{ m s}^{-1}$) over coastal- and central-California.

By 3 August at 1200 UTC (not shown), after the three-day ozone-episode, the northern NWS high had moved eastward out of area of interest, while the southern high had further weakened to 3200 m and had moved southeastward (to south-central Arizona at 34°N , 113°W). Winds thus shifted to south-southwesterly ($3\text{-}8\text{ m s}^{-1}$) over central California. In the concurrent GDAS analysis, the still unchanged (in magnitude) high had moved over southern-central Arizona (not shown), in agreement with the NWS position. Winds thus shifted to south-southwesterly ($3\text{-}5.5\text{ m s}^{-1}$). In the concurrent ETA analysis, the high had further weakened to a central value of 3190 m and had moved southeastward over Arizona and the southeast desert of California (not shown). Winds thus shifted to southerly at $5\text{-}6.5\text{ m s}^{-1}$ over central California.

The NWS surface analysis on 29 July at 1200 UTC (Fig. 23) showed a weak (central pressure of 1020 hPa) offshore GC high as the surface-projection of the upper level GC high; a synoptic cold front was located northeast of the high. A weak (central pressure of 1010 hPa) inverted thermal low-pressure trough (with two north-south axes) ex-

tended from the US-Mexico border northward into the southeast desert of California. The resulting on-shore pressure gradient created mostly weak ($<2 \text{ m s}^{-1}$ or $<4 \text{ kt}$) northwesterly winds over coastal central-California, with temperatures ranging from 18°C (64°F) at Sacramento to 16°C at Reno.

The concurrent GDAS surface analysis showed the offshore GC high with a central pressure of 1020 hPa and with a synoptic cold front located to its northeast (Fig. 24). The thermal-low had a central pressure of 1008 hPa (slightly deeper than the NWS value), with a northward-pointing axis into the southeast desert area of California. Prevailing CV and central California winds were northwesterly at $3\text{-}4 \text{ m s}^{-1}$ (stronger than observed), while temperatures ranged from 15°C at Sacramento to 12°C at Reno ($3\text{-}4^{\circ}\text{C}$ cooler than observed).

In the concurrent ETA analysis, the offshore high (1020 hPa) and synoptic cold front were shown on the western domain-edge (Fig. 25). The thermal-low had a central pressure of 1006 hPa (4 hPa deeper than observed), with two axes extending northward, as observed. Winds over Central California were thus northwesterly at $3\text{-}5 \text{ m s}^{-1}$, stronger than observed and temperatures were 16°C at Sacramento and 12°C at Reno ($2\text{-}4^{\circ}\text{C}$ colder than observed).

No significant changes occurred on the NWS surface charts during the next 42 h, but by 1200 UTC on 31 July (SFBA ozone-episode day), the offshore GC high had intensified (by 4 hPa) and moved northward, as the approaching synoptic cold front off the Washington and Oregon coast passed to its east (Fig. 26). The thermal low had moved northward and intensified into a closed low (1008 hPa central pressure) over the SJV,

with an axis extending to the California-Oregon border. Such warm core lows weaken with height and turn into upper-level highs, as reflected in the concurrent intensification of the synoptic high at 700 hPa (discussed above). Subsidence from this upper level high thus increased inland surface temperatures within the low by about 4°C, and the resulting increased surface (as at 700 hPa) pressure-gradient increased the still northwesterly winds to about 5 m s⁻¹.

The concurrent GDAS analysis correctly showed the northward movement and intensification of the offshore GC high (Fig. 27). On the other hand (contrary to the observations), its thermal low had not moved, but central pressure weakened by 2 hPa. It expanded westward, thus increasing pressure gradients over northern California, so that its still north-northwesterly winds increased to 3-6 m s⁻¹. Temperatures increased (as observed) by about 3°C over both Sacramento and Reno.

The concurrent ETA showed a similar (to GDAS) movement and intensification of the offshore GC high (Fig. 28). It also showed a similar weakening of the thermal low, which was associated with a correct northward movement to the southeastern California-Nevada border. Its final position was thus still too far to the east. A closed low (not seen in NWS observations) did form over northern California on the through-axis, which increased coastal pressure-gradients. The still northwesterly winds over central and coastal California thus increased to about 4-7 m s⁻¹, while local temperatures increased by about 4°C.

By 1 August 1200 UTC (Sacramento ozone-episode day), the offshore NWS surface GC high intensified slightly and shifted back eastward behind the cold front that ad-

vanced southeastward through Oregon (Fig. 29). While the thermal-low filled slightly, overall coastal pressure gradients increased, slightly increasing the still northwesterly coastal flows to about 6 m s^{-1} . Temperatures continued to increase by $2\text{-}4^{\circ}\text{C}$, due to continued subsidence warming from the upper level high.

The concurrent GDAS analysis again showed intensification of the GC high, which moved northward almost completely out of the domain (Fig. 30) and which showed further weakening of the thermal low (now located over southeast California) by another 2 hPa. The closed low (seen in the previous day ETA analysis) had formed over the SFBA (central pressure of 1012 hPa), and thus winds over central California shifted back to northwesterly and weakened to 2 m s^{-1} , while temperatures further increased by another 2°C . In the concurrent ETA analysis, the offshore GC high and the thermal low over the SFBA both intensified (Fig. 31), thus increasing coastal pressure gradients (as observed). The still northwesterly SFBA winds were slightly weakened (by 1 m s^{-1}), while temperatures increased to 22°C over Sacramento and 18°C over Reno.

Thirty hours later on the 2nd August at 1800 UTC (SJV ozone-episode day), the surface GC high again migrated westward, while the thermal trough moved slightly northward, but did not change in intensity (Fig. 32). By 3 August at 1200 UTC, the surface GC high migrated northwestward, and the thermal trough was almost completely dissipated (not shown). As the upper level high had dissipated, its subsidence weakened and temperatures decreased (from their peaks two days before) by about 10°C at Reno. In the GDAS analysis on 2 August at 1200 UTC, the offshore GC was still off the coarse model domain, and while the thermal trough intensity was unchanged, it had slightly

moved northward (Fig. 33). By 3 August at 1200 UTC, the thermal trough was dissipated completely (not shown). The coastal pressure gradient thus weakened that allowed coastal winds ($2\text{--}3\text{ m s}^{-1}$) to shift south southeasterly over coastal and central California (not shown); temperatures also decreased by $3\text{--}4^{\circ}\text{C}$.

The concurrent ETA analysis on 2 August at 1200 UTC showed similar movement of the unchanged thermal trough northward (Fig. 34). By 3 August at 1200 UTC, the surface thermal trough had completely dissipated (not shown) and temperatures were decreased by 4°C .

In summary, the low-resolution GDAS model (Table 2) generally accurately reproduced the location and developmental-changes of the 700 hPa NWS synoptic-forcing better than the higher-resolution ETA did, e.g., during 29-30 July it accurately reproduced the 700 hPa movements and strengths of the offshore GC high, inland synoptic high, and boundary-low. During 31 July-1 August (Livermore and SacV episode days, respectively), however, GDAS positioned the 700 hPa synoptic-high position somewhat too far northeast, while ETA placed it in the correct location. The GDAS high, however, did bulge offshore of southern California, and thus produced only slight SFBA wind direction errors (south-southwesterly versus southerly observed). During 2 August (SJV episode day) and 3 August, GDAS accurately reproduced the splitting synoptic high, while ETA prematurely dissipated it. GC surface high location and developmental changes were also generally well captured by both models, but while ETA showed a weak closed-low over northern California on 31 July (not shown on NWS chart), GDAS

delayed its formation by a day. Both correctly simulated its peak intensity on 1 August, but ETA better captured its subsequent movement.

While ETA large-scale surface-fields somewhat better reproduced NWS patterns, 700 hPa synoptic-forcing was better reproduced by GDAS. Since MM5, however, will be used to reproduce mesoscale surface patterns, it is better to use the larger-scale model-forcing that better represents the upper-level synoptic forcing. The subsequent analyses of MM5 results will thus focus on the GDAS-driven simulations.

B. Domain 1

NWS charts can only give approximate pressure-center locations for GC and synoptic (700 hPa and surface) highs and lows. They are thus unable to show the detailed SFBA, Carquinez Strait, and SJV flow-patterns that resulted in the current observed sequence of CCOS ozone episodes. MM5 mesoscale simulations are thus used to refine the temporal variations in positions and strengths of these synoptic highs and lows. MM5 coarse domain (36 km) results are also used to examine the 700 hPa synoptic high pressure systems, while fine domain (4 km) results are used to examine the surface thermal eddies, convergence zones, and flows from SFBA to the SacV and SJV.

Domain 1 results will be discussed for the GDAS+GN simulation, as it best reproduced the CV cyclonic eddies that dominated SacV and SJV surface transport patterns. This section discusses the wind (charts shown) and temperature (charts not shown) results from the outer (36 km) domain.

Twelve hours into the simulation, at 29 July at 1200 UTC (Fig.35), MM5 correctly located the offshore 700 hPa GC high centered at roughly 33°N (off domain to

west). It also reproduced the inland synoptic high over western Arizona (34°N, 113°W, versus 34°N, 112°W observed). This caused the off-shore boundary-low to be centered slightly southwest (35°N, 124°W) of its observed position at 36°N, 123°W. Despite these deviations, MM5 winds were south southeasterly over the coast at about 3-4 m s⁻¹ and southerly over central California at about 4-7 m s⁻¹ (versus observed southerly at about 5 m s⁻¹). SFBA temperatures were also well reproduced, but values were too low over Reno (4 versus 13°C).

The MM5 surface cold-frontal position over coastal Oregon (Fig. 36) coincided with the NWS position (Fig. 23). The observed northwest-southeast oriented axis of the weak thermal-low was also captured, and the prevailing northwesterly offshore (at about 6 m s⁻¹) and inland (at 1-2 m s⁻¹) flows were also well captured, but MM5 temperatures were 21°C in Sacramento and 17°C in Reno (versus the observed values of 18 and 16°C, respectively).

A day later, on 30 July at 1200 UTC (Fig. 37), the eastern edge of the 700 hPa offshore GC high (center outside of the western domain edge, with central latitude at 34°N) matched its position on the NWS chart (Fig. 11). The offshore boundary-low (at 39°N, 125°W) was correctly located, but the synoptic inland-high moved too slow and thus was somewhat to the southeast (relative to the NWS position) over southern Nevada (at 36°N, 114°W). Modeled coastal winds were southerly (versus observed southwesterly) at 6 m s⁻¹, or 1 m s⁻¹ above the range of speeds represented by “one-barb” (7-13 knots) on NWS charts; inland southerly flows were correctly captured. Temperatures were

over-predicted in coastal areas by 2-3°C from the observed 12°C over Oakland, but were significantly under-predicted over the Sierras.

The concurrent MM5 GC surface high had its eastern edge correctly simulated at 37°N, 130°W (Fig. 38). A flow pattern consistent with the observed inverted thermal-trough was also well predicted, with northwesterly coastal flow (3-5 m s⁻¹, compared to the observed “one-barb” value) and with down-slope flow off the western CV mountains (not shown). Temperatures, however, were slightly under-predicted by about 1°C, compared to observed values of 20°C at Sacramento and 19°C at Reno.

By 31 July at 1200 UTC (Livermore ozone day), the synoptic high strengthened as observed, but was centered (35°N, 116°W) too far to southeast over the southeastern corner of California (versus its observed position in the CV) (Fig. 39). Flow around its offshore western edge thus produced the now south-southwesterly winds over southern California (versus southerly observed flow in Fig. 14). The south-southwesterly (correctly simulated) winds over central California ranged from 7 m s⁻¹ over the coast (significantly under-predicted from the observed values of about 5 m s⁻¹) to slightly over-predicted (at 12 m s⁻¹) at inland areas. Temperatures were still over-predicted by 2°C over Oakland and significantly under-predicted (6 versus 16°C) at Reno.

The surface GC-high (Fig. 40) moved northward as observed and strengthened (its winds increased), while the inverted thermal-low had a north-south oriented axis as observed (Fig. 26). The closed low had about the same intensity as observed, but its center had moved northward of its observed position (north of the southeast desert area).

Temperatures were now only slightly under predicted (by about 1°C) over Sacramento and correctly captured over Reno.

By 1 August at 1200 UTC (Sacramento ozone day), the synoptic high (Fig. 41) was on the western side of the SJV (east of Monterey at 36°N, 121°W), a bit southwest of the NWS position (Fig. 15). The southwest coastal flow now matched the observed direction with speeds fairly accurately predicted at about 6 m s⁻¹. Coastal temperatures were well predicted, but still significantly under-predicted over Reno. The surface low had moved north and weakened (Fig. 42), as observed (Fig. 29). Coastal wind speeds were about 6 m s⁻¹, in good agreement as in NWS, with inland observed speeds (at about 2 m s⁻¹) increased due to increased pressure gradients north of the inland inverted thermal-low. Coastal temperatures were reproduced as observed, whereas inland values (24°C) were under-predicted by about 2°C.

On 2 August at 1200 UTC (southern SJV ozone day), the high had split, as observed. Its eastern half (which did not affect SFBA flows) was located at 37°N, 115°W (Fig. 43), southeast of its observed location (Fig. 20). The western half was just offshore at a site southwest of Monterey (36°N, 122°W), significantly west of the NWS position over the California-Nevada border (37°N, 117°W). While flows were easterly (as observed) over the LA Basin, they were southwesterly over the SFBA (while the one observation shows southerly). Decreased temperature values were well predicted over the coast, but values over Reno were still significantly under predicted. The surface low (Fig. 44) had moved southward (although it was observed in Fig. 32 to move northward). Consequently, the simulated southwesterly offshore flow west of LA was no longer northwesterly,

and simulated temperatures ranged from 22°C near the coast, 28°C over SJV, to 20°C near Reno.

By 3 August at 1200 UTC (not shown), the eastern high had further moved southeasterly towards central Arizona (33°N, 112°W), a bit southeast of the observed position (34°N, 113°W, not shown). Its western half, on the other hand, weakened, moved northward, and turned into a small closed circulation over the SFBA. Winds thus shifted to southwesterly over the SFBA (4-7.5 m s⁻¹), as compared to the observed south-southeasterly flow (2.5-7.5 m s⁻¹). The surface thermal low weakened and moved eastward (although observations showed the low as dissipated), and a new offshore low had developed west of the SFBA (not shown). Simulated winds thus shifted to south-southwesterly over the SFBA coast (2 m s⁻¹), compared to observed (not shown) southwesterly flow, (at 1-3 m s⁻¹), over central California.

In summary, MM5 coarse Domain 1 results generally accurately showed the development and northward movement of both the 700 hPa GC and synoptic highs during the ozone episode period. Development of the synoptic high increased subsidence heating, which strengthened the predicted surface inverted thermal-trough. Its movements were also well reproduced, as was that of the surface GC high.

C. Domain 3

This section compares CCOS observed mesoscale patterns with Domain 3 MM5 results. As mesoscale flows are best reproduced when simulated temperatures are most accurate (Pielke 1984, Bornstein *et al.* 1996), the first comparisons involve MM5 half-sigma temperatures.

1) SURFACE TEMPERATURES

Domain-average observed and simulated surface temperatures for all four simulations after a 36 h spin-up period (Fig. 45) show expected smooth diurnal temperature-waves, indicative of minimal cloud cover. The observations also show a well-defined upward trend in daytime-maximum and nighttime-minimum temperatures (with both peaking on 2 August) that arose from subsidence-induced heating from the movement into the area of the 700 hPa synoptic high and its subsequent strengthening. The warming coincided with the three peak-ozone days, as high temperatures are associated with northern California ozone episodes (Seaman *et al.* 1995, Tanrikulu *et al.* 2000, Lehrman *et al.* 2001, Umeda and Martien 2002).

Only the GDAS+GN simulation does show the entire warming trend, as it peaks on 1 August. All four, however, generally underestimate the daytime (0800-1900 PST) maxima by about 3.5 K and overestimate the nighttime (2000-0700 PST) minima by about 2.5 K. The max nighttime over-prediction (Fig. 45) is from ETA (3.1 K), while the max daytime under-prediction (Fig. 46) is from GDAS+GN (about 3.8 K). The smallest daytime under-prediction is from ETA+GN (3.0 K), while both GDAS simulations produced the smallest nighttime over-prediction (1.5 K).

Differences in the error between simulations were thus smaller than the individual differences from the observations. Since the GDAS+GN MM5 simulation was shown above to best capture the Domain 1 mesoscale CV 700 hPa eddies that control CV surface transport patterns, the rest of this surface-temperature analysis focuses on its results.

A new comparison was thus carried out that used only GDAS+GN 10 m MM5 temperature values at grid-points closest to each of the 52 sites with observation at 10 m. This produced (Fig. 47) increased observed peak-daytime (unexpected) and nighttime (expected) temperatures by 1.0 and 0.9°C, respectively, which slightly increased (Fig. 48) the peak nighttime over-prediction to 2.5°C, but greatly increased the peak daytime under-prediction to 6.2°C. These bias-increases probably arose as networks of 10 m temperature observations are operated by non-meteorologists (e.g., hydrologists).

Another comparison was thus carried that used uncorrected GDAS+GN MM5 values at grid points closest to each of the NWS 71 sites (with 2 m observations). Results (Fig. 49) show increases of observed daytime and nighttime temperatures of 0.3 and 0.2°C, respectively, which reduced the peak nighttime over-prediction to 1.1°C, but increased the peak daytime under-prediction to 3.1°C (Fig. 50). A log-law height correction was thus carried on the GDAS+GN MM5 values at the grid points closest to the NWS sites. Results (Fig. 49) show a 0.9°C increase of peak MM5 daytime temperature and a 0.2°C decrease of nighttime temperatures. This thus reduced average daytime and nighttime biases to -2.3 and 0.9°C, respectively (Fig. 50).

Remaining overestimations of nighttime minimum temperatures are probably due to too-high initial input soil-moisture contents from TERRAIN, which provide an average of the input NCEP surface-temperature values for the simulation period. The procedure thus fails to account for the increased time-lag with soil depth (order of weeks at 1 m) (Arya 1988), which produces too high MM5 summer deep-soil temperatures. To solve

this problem, initial deep soil temperatures should be lowered by an amount twice the average overestimated minimum-temperature value (Boucouvala *et al.* 2003).

Remaining daytime underestimations of maximum temperatures are probably due to too-high input initial soil moisture content values. Excess soil moisture produces a too-large atmospheric vertical latent heat-flux and hence a too-small sensible heat-flux. Lowering MM5 input initial soil moisture content to a reasonable value thus solves this problem (Jacobson 1999).

2) UPPER LEVEL FLOW

This section evaluates the GDAS+GN MM5 simulation of the upper level ($\sigma = 0.6555$, 700 hPa, or 3000 m) synoptic forcing with respect to driving surface mesoscale transport patterns that would contribute to the observed sequential ozone peaks. Afternoon flows will be analyzed, as summertime peak ozone levels usually occur at around 1400 PDT.

After 36 h into the simulation, i.e., on 30 July (pre-episode day) at 0000 UTC (1600 PST), results showed undisturbed prevailing 700 hPa southerly wind flows over coastal and central California (Fig. 51). By 31 July at 0700 UTC (Livermore episode day), (Fig. 52) a weak low (not seen on NWS charts) formed in the southeastern SJV. At 2100 UTC (Livermore episode afternoon), the low was replaced by a weak high over the SJV (versus the Nevada/California border in Domain 1) with a northeast-southwest oriented 'bulge' south of Monterey (north of Monterey in Domain 1) (Fig. 53). Winds were thus south southwesterly (versus observed southerly flows) over the SFBA.

By 0600 UTC on 1 August (night before Sacramento ozone episode), the bulge extended offshore over central California from the high, now eastward in a position over southern Nevada (Fig. 54); and southwesterly flow still existed over coastal and central California. Seven hours later, the bulge had weakened (Fig. 55), but the southwesterly flow still prevailed. By 2100 UTC (Sacramento episode afternoon), the high had moved west to the coast (versus a bulge from the CV to the coast in Domain 1) (Fig. 56). Winds thus became westerly (versus observed southerly) from the SFBA into Sacramento. A Fresno eddy formed in the middle of the SJV (north of its Domain 1 position) from a combination of the onshore, down-slope, and down-valley flows. The northerly flow from the SFBA into the SJV was blocked by the northeasterly flow on the western side of the eddy.

On 2 August at 0200 UTC (SJV ozone episode day), the Fresno low moved northward (Fig. 57), allowing the northerly flow from the SFBA into the central SJV. By 0600 UTC, the Fresno eddy had moved northeastward over Sierras on the eastern side of the SJV (Fig. 58). Some SFBA flow was still directed to Sacramento, and the northerly flow on the western eddy-edge started to allow a weak SFBA flow into the SJV. By 1200 UTC, the high had moved southward to offshore-Monterey and the Fresno eddy continued to move to the northwest (Fig. 59). While the SFBA flow was thus now blocked by the eddy from moving to Sacramento, more of the flow entered the SJV.

By 2 August at 2100 UTC (Fig. 60) (SJV ozone episode afternoon), the coastal high moved eastward over Monterey. The Fresno eddy had moved north (becoming the Sacramento eddy), enlarged, strengthened, and still increasing the SFBA flow to SJV.

By 3 August at 0600 UTC (post ozone-episode day), the flows had started to return to a normal mainly westerly flow over coastal and central California (Fig. 61). Fifteen hours later (2100 UTC), the region had shifted back to a normal southerly flow, as both the synoptic high and Fresno eddy had dissipated (Fig. 62).

In summary, 700 hPa upper level Domain 3 results showed that the combined effects from the formation and evolution of both an offshore high and Fresno eddy produced a changes in the flow from the SFBA that could explain the observed sequence of ozone episode days at Livermore, Sacramento, and SJV. While the initial southerly flow did not produce transport from the SFBA to any of these sites, formation of the high first directed flow eastward to Livermore and then to Sacramento, while the eddy blocked flow into SJV. As the eddy moved north, it then blocked SFBA flow into Sacramento and redirected it into the SJV. The MM5 GDAS+GN surface results will thus be analyzed to show their skill in reproducing the observed mesoscale sea/land and mountain/valley breezes, and their associated convergence/divergence zones.

3) SURFACE FLOW

Day-to-day changes in the Domain 3 mesoscale winds are able to explain the Livermore ozone episode. By 30 July at 2100 UTC (pre-episode afternoon), MM5 surface winds around Livermore (Fig. 63) included strong (3 m.s^{-1}): westerly sea breezes through the GGG, north-northeasterly flow from the Carquinez Strait, and northerly upslope-flows on the east-facing slopes on the hills east of the city. These created a confluence zone along the hill-tops east of the city. Four hours later (1800 PDT), a uniform west to east sea-breeze flow (at $4\text{-}5 \text{ m s}^{-1}$) existed over the entire area (Fig. 64).

By 31 July, 2100 UTC (Livermore episode-afternoon), surface directions in the area were similar to that of the previous day, except that speeds were reduced to about 1.5 m s^{-1} and the confluence was thus increased (Fig. 65). Four hours later, a uniform west to east sea breeze flow (at $3\text{--}4 \text{ m s}^{-1}$) existed over the area (Fig. 66). On 1 August at 2100 UTC (Sacramento episode afternoon), the same direction patterns again existed as before, except that speeds were again increased to about 3 m s^{-1} (Fig. 67). That evening (Fig. 68), the sea breeze was weaker than on the previous evenings (2 versus 4 m s^{-1}), and thus the confluence zone remained just east of hills east of Livermore (i.e., in the CV).

Day-to-day changes in Domain 3 mesoscale winds are also able to explain the Sacramento ozone episode. During the Livermore episode day (1 August at 0100 UTC), flow from the SFBA to Sacramento was blocked by a small (but critically located) area of easterly opposing flow, which formed a confluence zone east of the Carquinez Strait (Fig. 69). During the Sacramento episode day (2 August at 0100 UTC), however, SFBA flow penetrated to Sacramento, as no opposing flow from the east existed (Fig. 70). The Fresno eddy, which had moved into the southeast corner of the domain, had no influence on the Sacramento flow patterns. During the SJV episode day (2 August at 2100 UTC), SFBA flow to Sacramento was weak, and was blocked by a Sacramento eddy (Fig. 71), which is northward relocated Fresno eddy.

Day-to-day changes in Domain 3 mesoscale winds are finally also able to explain the SJV ozone episode. During the early morning hours of the Livermore episode day (31 July at 1200 UTC), while the flow (Fig. 72) showed SFBA to SJV transport, speeds were too fast for high ozone levels to remain in the valley. By 1 August at 1200 UTC

(Sacramento episode night), SFBA to SJV transport was blocked due to strengthening of the Fresno eddy over the SJV, which produced low-speed variable direction flows in the middle of the valley (Fig. 73). By 2 August at 1200 UTC (SJV episode night), however, SFBA to SJV transport and southerly flow from southern SJV formed a confluence zone over the central SJV (Fig. 74).

While day-to-day changes in MM5 mesoscale surface flow patterns can be used to explain the observed sequential ozone episodes, it is also necessary to perform speed and direction statistical-comparisons. Domain-average observed all-station and corresponding GDAS+GN surface speeds (Fig. 75) show the expected diurnal variations with high daytime and low nighttime speeds. MM5 max daytime and min nighttime speeds, however, do occur several hours after their corresponding observations. In addition, while observed speeds show almost no day-to-day trends, MM5 values show increased values during the night preceding the Livermore episode and on the following episode day (1 August). Biases (excluding post-episode 3 August) ranged between 0.0 and an MM5 nighttime over-prediction of 3.4 m s^{-1} (Fig. 76).

As a number of observations were not taken at the 10 m MM5 level, the above comparison was redone to exclude sites with observed 2-m wind speeds. Results (Fig. 75) show only slight (expected) increases in both observed and MM5 speeds, and thus the range of biases (again excluding 3 August) was virtually unchanged at -0.3 (daytime under-prediction) to 3.3 (nighttime over-prediction) m s^{-1} (Fig. 76).

As many anemometers have threshold-values of about 1.5 m s^{-1} , it is unreasonable to include observed speeds less than that value in statistical comparisons. The compare-

son was thus again redone without cases with observed speeds $< 1.5 \text{ m s}^{-1}$. Results (Fig. 77) show improved (lower-speed) MM5 values, with nighttime min speeds that occur at times more in agreement with observations. Nighttime peak MM5 over-prediction biases (again excluding 3 August) thus decreased to 2.2 m s^{-1} , (Fig. 78) daytime under-predictions remained about the same.

A final comparison was carried out by use of MM5 values at grid-points closest to each of the 71 NWS sites, which have the best observations (and are at 10 m), for both all values available and values above the threshold. The above-threshold NWS values (Fig. 79), as expected, produced the smallest (again excluding 3 August) peak and average nighttime MM5 over-prediction bias (Fig. 80) of 1.7 and 1.0 m s^{-1} , respectively. Corresponding daytime under-prediction biases, however, increased to about -1.2 and -0.4 m s^{-1} .

Domain-averaged observed all-stations and corresponding GDAS+GN surface wind directions (Fig. 81) show generally westerly flow patterns during daytime periods. Observed wind directions showed two nights (1 and 2 August) with variable (mostly-easterly) low-speed flows, while MM5 showed concurrent northwesterly flows. Peak MM5 daytime and nighttime biases (running three-point averages, e.g., 0300 PST average uses 0200-0400 PST hourly values) were thus positive (clockwise) at 70 and 160 deg, respectively (Fig. 82). Use of only 10 m observed winds with corresponding MM5 values (Fig. 81) produced slightly increased biases (Fig. 82). When only observed 10 m speeds faster than the threshold-value (Fig. 83) were compared with corresponding MM5 values, daytime biases were around 45 deg, while peak nighttime values from 2-3 August increased to 195 deg (Fig. 84).

The final wind direction comparisons were of MM5 values at grid-points closest to each 71 NWS site, for both all NWS sites and only above threshold-values. Above-threshold NWS results were better than the former cases, except during the nights of 30 July and 2 August (Fig. 85). The all-NWS data, however, did show marked improvements over the entire simulation period, with peak daytime and nighttime biases (Fig. 86) of -25 and 50 deg, respectively; and with corresponding average values of only -1 and 4 deg.

4. Conclusion

The 30 July to 2 August 2000 ozone episode of the Central California Ozone Study (CCOS) field observational program was selected for study because of its large well-documented observational meso-meteorological data-sets and because of its ozone exceedances at locations in the SFBA (at Livermore), Sacramento, and SJV. Version 3.6.0 of MM5 was used with three (one-way) nested horizontal domains (grid spacings of 36, 12, and 4 km), analysis-nudging, and level 1.5 TKE. As observational nudging was not used, the CCOS observations were used as a model-evaluation dataset. Four MM5 simulations were initialized and driven by large-scale fields from either the high-resolution ETA or low-resolution GDAS, with or without analysis nudging in the outer two domains (at 12 h intervals) for temperature and wind.

GDAS was generally more accurately than ETA in reproducing the movement and development of the key 700 hPa inland synoptic high during most simulation days. ETA, however, better reproduced its position during the 31 July Livermore and 1 August Sacramento ozone-episode days, but dissipated it prematurely on the 2 August SJV epi-

sode day. GC surface conditions were also generally well captured by both models, but while ETA formed the key thermal low over northern California on 31 July, GDAS delayed its formation by a day. Both correctly simulated its peak intensity on 1 August, but ETA better captured its subsequent movement.

These differences could have arisen due to an ETA versus GDAS difference in σ -vertical coordinate. While GDAS uses MRF output, in which surface pressure is the lower boundary condition, ETA uses mean sea-level pressure, which smoothes complex-terrain topographic-effects. Smoothing may not be advantageous when (as in central California) topographic induced surface vortices are important for mesoscale transport processes.

MM5 initialized by GDAS with analysis-nudging generally accurately showed the development and northward movement of the 700 hPa synoptic high during the episode period. Its development increased subsidence heating, which strengthened the predicted surface inverted thermal-trough, whose movements it also well reproduced. Predicted fine-domain surface temperature, wind speed, and wind direction were statistically compared against the CCOS observations. The best correlations were found when a temperature log-law height correction was used with GDAS analysis-nudged MM5 values at grid points closest to the 71 NWS (2 m) sites. These results showed an average -2.3°C bias (underestimation) for modeled daytime max temperatures and a 0.9°C bias (overestimation) for nighttime min values.

The overestimated nighttime values are due to too-high initial input deep-soil temperatures, which must be lowered by an amount equal to twice the average bias. The

daytime underestimated values are probably due to too-high input initial soil moisture content, which produces too-large atmospheric vertical latent heat-fluxes and hence too-small sensible heat-fluxes. A reduced input initial soil-moisture content would solve this problem.

Fine-domain surface wind velocities showed that combined effects from formation and evolution of the offshore mesoscale high and Fresno eddy, which produced changes in the flow from the SFBA that could explain the observed sequence of ozone-episode days at Livermore, Sacramento, and SJV. The initial southerly flow did not produce surface transport from the SFBA to any of these sites, but formation of the high first directed flow eastward to Livermore and then to Sacramento on the next day, while the eddy blocked flow into SJV. As the eddy moved north on the third day, it blocked SFBA flow into Sacramento and redirected it into the SJV.

These flow-changes thus reproduced the mesoscale surface transport patterns over central California that could explain the sequence of ozone episodes over SFBA, SacV, and SJV. The Livermore ozone episode was observed to occur due to strong confluence of three flows: southward from the Carquinez Strait, eastward through the GGG, and upslope from the eastern side of hills east of the city. Transport from the SFBA to SacV on its episode afternoon arose due to the strengthening of the south to north oriented pressure gradient, breakdown of easterly opposing flow over Sacramento, and shifting south-eastward and strengthening of the Fresno eddy over the SJV, which had blocked. During the SJV episode day, SFBA transport into the Valley was allowed when the Fresno eddy moved northward and thus the south to north directed pressure gradient started to weak-

en. MM5 wind speeds correlated best with above-threshold ($>1.5 \text{ m s}^{-1}$) NWS data, with an average nighttime over-prediction of 1 m s^{-1} and an average daytime under-prediction of -0.4 m s^{-1} . MM5 wind directions correlated best, however, with all the NWS data, with average daytime and nighttime biases of only -1 and 4 deg.

Results could be further improved with observational-nudging of temperatures, wind velocities, and humidities. In addition, current input surface roughness values in MM5 are too small for complex topographic regions such as California. Increases in these values will decrease the currently somewhat large overestimated nighttime wind speeds.

Finally, even though MM5 has reproduced mesoscale transport patterns consistent with the sequentially observed ozone exceedances in central California, this does not prove that the inter-basin transport of precursor emissions caused these exceedances. More insight would be provided if the current MM5 results were used to drive Lagrangian-particle dispersion and/or photochemical air quality models.

REFERENCES

- Arakawa, A., and V. R. Lamb, 1977: Computational design of the basic dynamical processes of the UCLA general circulation model. *Methods Comput. Phys.*, **17**, 173-265.
- Arya, 1988: *Introduction to Micrometeorology*. Academic Press, NYC, 307 pp.
- Blackadar, A. K., 1957: Boundary layer wind maxima and their significance for growth of nocturnal boundary layers. *Bull. Amer. Meteor. Soc.*, **38**, 283-290.
- Blackadar, A. K., 1976: Modeling the nocturnal boundary layer. Preprints, Third Symposium on Atmospheric Turbulence and Air Quality, Raleigh, NC, 19-22 October, *Amer. Meteor. Soc.*, Boston, 46-49.
- Blumenthal, D. L., T. B. Smith, D. E. Lehrman, R. A. Rasmussen, G. Z. Whitten, and R. A. Baxter, 1985: Southern San Joaquin Valley ozone study. Sonoma Technology, Inc. Final Report STI-94100-510-FR to Western Oil and Gas Association, 143 pp.
- Blumenthal, D. L., and J. G. Watson, 1991: SJVAQS/AUSPEX collaborative field study plan. 84th Annual Meeting and exhibition of AWMA. Vancouver, B.C., 16-21 June, Paper No. 91-70.6, 21 pp.
- Bornstein, R., P. Thunis, P. Grossi, and G. Schayes, 1996: Development of the topographic vorticity-model mesoscale (TVM) model. *J. Appl. Meteor.*, **35**, 1824-34.
- Boucouvala, D., R. Bornstein, J. Wilkinson, and D. Miller, 2003: MM5 simulations of a SCOS97-NARSTO episode. *Atmos. Environ.*, **37**, 1-23.

- Ching, J., and D. Byun, 1999: Science algorithms of the EPA model-3 community multi-scale air quality (CMAQ) modeling system. AMD/NERL US EPA Report, RTP, NC 27711, EPA/600/R-99/030 [<http://www.epa.gov/asmdnerl/models3/doc/science/science.html>]
- Doty, B., and J. L. Kinter, III, 1992: The Grid Analysis and Display System (GrADS): A practical tool for earth science visualization. Eighth International Conference on Interactive Information and Procession Systems, Atlanta, Georgia, 5-10 Jan.
- Dudhia, J., 1993: A Nonhydrostatic Version of the Penn State–NCAR Mesoscale Model: Validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev.*, **121**, 1493–1513.
- Dudhia, J., 1996: A multi-layer soil temperature model for MM5. *Preprints, Sixth PSU/NCAR Mesoscale Model Users' Workshop*, 22-24 July, Boulder, Colorado, 49-50 [<http://www.mmm.ucar.edu/mm5/mm5v2/whatisnewinv2.html>].
- Dudhia, J., 2001: Mesoscale model nesting and boundary conditions. National Center for Atmospheric Research, Boulder, Colorado, USA [<http://meteo.usc.es/documents/jm.pdf>].
- Dudhia, J., and J. F. Bresch, 2002: A global version of the PSU-NCAR mesoscale model. *Mon. Wea. Rev.*, **130**, 2898-3007.
- Dudhia, J., D. Gill, K. Manning, W. Wang, and C. Bruyene, 2003: PSU/NCAR Mesoscale Modeling System Tutorial Class Notes (MM5 modeling system version 3) [<http://www.mmm.ucar.edu/mm5/documents/tutorial-v3-notes.html>].

- Gayno, G., 1994: Development of a higher-order, fog-producing boundary layer model suitable for use in numerical weather prediction. MS Thesis, Penn. State University, 104 pp.
- Grell, G., J. Dudhia, and D. Stauffer, 1994: A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR/TN-398+STR, 117 pp [<http://www.mmm.ucar.edu/mm5/doc1.html>].
- Held T., Q. Ying, A. Kaduwela, and M. Kleeman, 2004: Modeling particulate matter in the SJV with a source-oriented externally mixed 3-D photochemical grid model. *Atmos. Environ.*, **38**, 3689-3711.
- Jacobson, M. Z., 1999: Effects of soil moisture on temperatures, winds, and pollutant concentrations in Los Angeles. *J. Appl. Meteor.*, **38**, 607-616.
- Lehrman, D., B. Knith, and D. Fairely, 2001: Characterization of the CCOS 2000 measurement period. Interim report (Contract 01-2CCOS), Technical and Business Systems, Inc., 38 pp.
- Lehrman, D. E., T. B. Smith, W. R. Knuth, and C. E. Dorman, 1994: Meteorological analysis of the San Joaquin Valley air quality study, Atmospheric utilities signatures, Predictions and experiments program (SJVAQS/AUSPEX). Technical and Business Systems, Inc., Final Rep., 231 pp.
- Lehrman, D. E., T. B. Smith, D. D. Reible, and F. H. Shair, 1981: A study of the origin and fate of air pollutants in the California's Sacramento Valley. Report for California Air Resources Board, MRI 81 FR-1842, Vol. II, 134 pp.

- Lozej, C., and R. Bornstein, 1999: Comparison of nesting techniques within a meteorological model. *Air Pollution VII*, WIT, Southampton, UK, 1009-1021.
- Mesinger, R., and T. L. Black, 1992: On the impact of forecast accuracy of the step Mountain (Eta) vs. sigma coordinate. *Meteor. Atmos. Phys.*, **50**, 47-60.
- Mesinger, F., Z. I. Janjic, S. Nickovic, D. Gavrilov, and D. G. Deaven, 1988: The step-mountain coordinate: model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment. *Mon. Wea. Rev.*, **116**, 1493-1518.
- McNerny, G. L., and A. J. Ranzieri, 1991: A description of ozone concentrations during an air pollution event in California's San Joaquin Valley based on preliminary data from the San Joaquin Valley Air Quality Study/Atmospheric Utility Signatures, Predictions and Experiments. 84th Annual AWMA Meeting, Vancouver, B.C., 16-21 June, Paper No. 91-71.4, 14 pp.
- Niccum, E., M., 1995: The influence of meteorology on the air quality in the San Luis Obispo County southwestern San Joaquin Valley Region for 3-6 August 1990. *J. Appl. Meteor.*, **34**, 1834-1847.
- Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.*, **56**, 527-530.
- Pielke, R. A., 1984: *Mesoscale Meteorological Modeling*. Academic Press, NY, 267 pp.
- Quint, M. M., W. R. Loudon, and D. Wade, 1993: Transportation activity Modeling for the San Joaquin Valley emission inventory. Paper No. 93-RP-149.04, 86th AWMA Annual Meeting, Denver, CO, 13-18 June, 8 pp.

Ranzieri, J. E., and R. Thuillier, 1991: San Joaquin Valley Air Quality Study (SJVAQS) and Atmospheric Utility Signatures, Predictions, and Experiments (AUPEX): A Collaborative Modeling Program. 84th AWMA Annual Meeting, Vancouver, BC, 16-21 June, paper No. 91-90.5, 27 pp.

Roberts, P. T.; C. G.; Lindsey, and T. B., Smith, 1994. Analyses of San Joaquin Valley Air Quality and Meteorology. Planning and Managing Regional Air Quality Modeling and Measurement Studies: In Perspective of the San Joaquin Valley Air Quality Study and AUSPEX, ed. by P. A. Solomon, Lewis Publishers, Chelsea, MI pp. 483-506.

Seaman, N. L., D. R. Stauffer, and A. M. Lario-Gibbs, 1995: A multiscale four-dimensional data assimilation system applied in the San Joaquin Valley during SAR-MAP. Part I: Modeling Design and Basic Performance Characteristics. *J. Appl. Meteor.*, **34**, 1739-1761.

Solomon, P.A., and K. L. Mangliano, 1999: The 1995-Integrated Monitoring Study (IMS95) of the California Regional PM₁₀/PM_{2.5} Air Quality Study (CRPAQS): Study overview. *Atmos. Environ.*, **33**, 4747-4756.

Stauffer, D. R., and N. L. Seaman, 1990: Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: Experiments with Synoptic-Scale Data. *J. Appl. Meteor.*, **118**, 1250-1277.

Stauffer, D. R., N. L. Seaman, G. K. Hunter, S. M. Leidner, and A. Lario-Gibbs, 2000: A field-coherence technique for meteorological field-program design for air quality studies. Part I: Description and interpretation. *J. Appl. Meteor.*, **39**, 297-316.

- Tanrikulu, S., D. R. Stauffer, N. L. Seaman, and A. J. Ranzieri, 2000: A field-coherence technique for meteorological field-program design for air quality studies. Part II: Evaluation in the San Joaquin Valley. *J. Appl. Meteor.*, **39**, 317-333.
- Thuillier, R. H., D. L. Blumenthal, P. T. Roberts, A. W. Gertler, and J. Watson, 1994: Meteorological field measurements program for SJVAQS/AUSPEX. Final Report No. 009-.2-93.4, Pacific Gas and Electric C., Research and Development Publications, San Ramon, CA, 208 pp.
- Thunis, P., and R. Bornstein, 1996: Hierarchy of mesoscale flow assumptions and equations. *J. Atmos. Sci.*, **53**, 380–397.
- Umeda, T., and P. T. Martien, 2002: Evaluation of a data assimilation technique for a mesoscale meteorological model used for air quality modeling. *J. Appl. Meteor.*, **41**, 12-29.
- Venkatram, A., N. L. Seaman, J. Chang, N. Lincoln, T. W. Tesche, P. Roth, A. Ranzieri, R. Thuillier, A. Hansen, and S. Ziman, 1992: Design of the SARMAP modeling system. 85th Annual meeting of AWMA, 21-26 June, Kansas City, MO, 14 pp.

Appendix A: ACRONYMS

AGL	Above Ground Level
AUSPEX	Atmospheric Utility Signatures, Prediction, and Experiments
BC	Boundary Condition
CCOS	Central California Ozone Study
CIMIS	California Irrigation Management Information System
CIT-UCD	California Institute of Technology-University of California, Davis
CMAQ	Community Multiscale Air Quality model
CRPAQS	California Regional PM ₁₀ /PM _{2.5} Air Quality Study
CV	Central Valley
ETA	η -large scale model
GC	General Circulation
GDAS	Global Data Assimilation System
GGG	Golden Gate Gap
GN	Grid (or analysis) Nudging
GrADS	Grid Analysis and Display System
FCT	Field-Coherence Technique
FDDA	Four Dimensional Data Assimilation
IC	Initial Condition
IMS95	1995 Integrated Monitoring Study
IR	Infrared Radiation

LBNL	Lawrence Berkeley National Laboratory
LLJ	Low Level Jet
MBL	Marine Boundary Layer
MM5	Fifth-generation Mesoscale Meteorological Model
MRF	Medium Range Forecast model
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PBL	Planetary Boundary Layer
PDT	Pacific Day-Light-Saving Time
PGF	Pressure Gradient Force
PST	Pacific Standard Time
PSU	Pennsylvania State University
RAWS	Remote Automated Weather Station
RMSE	Root Mean Square Error
SAQM	SARMAP Air Quality Model
SacV	Sacramento Valley
SARMAP	SJVAQS-AUSPEX Regional Modeling Adaptation Project
SEBE	Surface Energy Balance Equation
SFBA	San Francisco Bay Area
SJV	San Joaquin Valley
SJVAQS	San Joaquin Valley Air Quality Study

SST	Sea Surface Temperature
TKE	Turbulent Kinetic Energy
UAM-V	Variable-grid version of the Urban Air-shed Model
USGS	United States Geological Survey
UTC	Coordinated Universal Time

Appendix B: Tables

Table 1: Domain boundaries for: MM5 (coarsest domain), ETA, and GDAS.

Model	Corner			
	SW	NW	NE	SE
MM5	27.8230°N, 130.1280°W	45.1500°N, 133.1520°W	45.1500°N, 107.8480°W	27.8230°N, 110.8720°W
ETA	12.1900°N, 133.4600°W	57.3290°N, 154.1500°W	57.3290°N, 49.4167°W	12.1900°N, 66.1500°W
GDAS	20.8257°S, 34.5489°W	20.8257°S, 125.0000°W	20.8257°S, 145.0000°E	20.8257°S, 55.0000°E

Table 2. NWS and MM5 locations of 700 hPa synoptic high-pressure system at 1200 UTC.

Date (2000)	NWS (°N, °W)	MM5 (°N, °W)	MM5 error
29 July	34, 112	None	Missing
30 July	39, 117	36, 114	Somewhat to SE
31 July	37, 119	35, 116	Too far to SE
1 August	37, 119	36, 121	Somewhat to SW
2 August	37, 117	36, 122	Significantly W
3 August	34, 113	33, 112	Somewhat to SE

Appendix C: Figures

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fi. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28

Fig. 30

Fig. 31

Fig. 33

Fig. 34

Fig. 35

Fig. 36

Fig. 37

Fig. 38

Fig. 39

Fig. 40

Fig. 41

Fig. 42

Fig. 43

Fig. 44

Fig. 45

Fig. 46

Fig. 47

Fig. 48

Hour (PST)
Fig. 49

Fig. 50

Fig. 51

Fig. 52

Fig. 53

Fig. 54

Fig. 55

Fig. 56

Fig. 57

Fig. 58

Fig. 59

Fig. 60

Fig. 61

Fig. 62

Fig. 63

Fig. 64

Fig. 65

Fig. 66

Fig. 67

Fig. 68

Fig. 69

Fig. 70

Fig. 72

Fig. 73

Fig. 74

Hour (PST)

Fig. 75

Fig. 76

Fig. 77

Fig. 78

Fig. 79

Fig. 80

Fig. 81

Fig. 82

Fig. 83

—■— MM5GDAS.10m-OBS.10m>1.5

Fig. 84

Fig. 85

Fig. 86