Validation and Sensitivities of Dynamic Precipitation Simulation for Winter Events over the Folsom Lake Watershed: 1964-1999

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BIOGRAPHICAL SKETCH

Dr. Jianzhong Wang is working as a postdoctoral associate in the Hydrologic Research Center. He was previously a weather model specialist in the Williams Companies. While he was in China, he held a research scientist position in the Institute of Meteorological Science and Technology Information and later in the Institute of Mesoscale Meteorology of Chinese Academy of Meteorological Sciences. He holds a Doctor of Philosophy degree in the atmospheric science from the South Dakota School of Mines and Technology. He obtained his Bachelor of Science degree in atmospheric science from Nanjing University in 1985 and Master of Science degree in the atmospheric science from Chinese Academy of Meteorological Sciences in 1992 in China.

Honors and award includes “Outstanding Young Meteorologist” in 1986 and “National Scientific and Technological Information Second Class Award” in 1991 in China. He has authored and co-authored over 20 publications covering the fields of mesoscale meteorology, hydrometeorology, and numerical weather modeling, etc. He was appointed as a member of the joint planning committee for the Torrential Rainfall Experiment over Both Sides of the Taiwan Straits and Adjacent Area. He was once honored to be a member of National Lecturer Leagues in China in 1986. He is also a member of the American Meteorological Society, and the American Geophysical Union.

ABSTRACT

A total of 62 winter storm events in the period 1964-1999 and over the Folsom Lake watershed located at the windward slope of the Sierra Nevada Mountains were simulated with a 9-km resolution using the mesoscale model MM5. Mean areal precipitation (MAP) over the entire watershed and each of four sub-basins was estimated based on gridded simulated precipitation. The simulated MAP was verified with MAP estimated (a) by the California-Nevada River Forecast Center (CNRFC) for the four sub-basins based on 8 operational precipitation stations, and (b), for the period from 1980 to 1986, on the basis of a denser precipitation observing network deployed by the Sierra Cooperative Pilot Project (SCPP).

A number of sensitivity runs were performed to understand dependence of model precipitation on boundary and initial fields, cold vs. warm start, and microphysical parameterization. The principal findings of the validation analysis are: (a) the MM5 model achieves a good percentage bias score of 103% in simulating Folsom basin MAP when compared to MAP derived from dense precipitation gauge networks; (b) spatial grid resolution higher than 9 km is necessary to reproduce the spatial MAP pattern among sub-basins of the Folsom basin; (c) the model performs better for heavy than for light and moderate precipitation. The analysis also showed significant simulation dependence on the spatial resolution of the boundary and initial fields and on the microphysical scheme used.

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1. Introduction

Wintertime precipitation has a large impact on the annual hydrologic cycle in the mountainous western United States, and the measurement and prediction of its spatio-temporal distribution are necessary prerequisites for any regional or local hydrologic and water resources analysis (e.g., NRC 1988, 1991, 1995; Sharratt et al. 2001; Georgakakos 2003). It is also well known (e.g., Smith 1979; Pandey, et al. 2000) that the local features of topography modulate substantially the spatial distribution of precipitation over the large mountain barrier of the Sierra Nevada, and the scarcity of the precipitation sensors in the mountainous area makes it difficult to delineate finer scale characteristics of precipitation distribution from the point measurements alone (e.g., Hevesi et al. 1992; Tsintikidis et al. 2002).

In this work a numerical dynamical mesoscale model (MM5) is used to produce estimates of the spatiotemporal variability of precipitation over a mountainous hydrologic drainage basin. Basin-scale precipitation simulations are compared to same-scale precipitation estimated from point observations in a series of sensitivity runs for 62 events over the wet periods of the years 1964-1999. The purpose of this analysis is to (a) validate the precipitation simulations of the MM5 model on a hydrologic basin scale in a comprehensive manner, and (b) to identify the statistically significant sensitivities of the numerical simulation to model initial and boundary forcing, and microphysical parameterization, as a function of the density of the precipitation gauge network in the region. These results are pertinent to the development of robust methodologies for precipitation estimation, short-term quantitative precipitation forecasting (QPF) and precipitation downscaling on hydrologic catchment scales over the mountainous terrain of the Sierra Nevada.

There are several MM5 precipitation verification studies reported in the literature. Among the most pertinent for this work, Colle et al. (2000a, 2000b) discuss MM5 precipitation verification over the Pacific Northwest during the 1997-99 cool seasons, and Vellore el al. (2002) present an evaluation and microphysical sensitivity tests of simulated precipitation for a winter precipitation event in the Sierra Nevada. A comprehensive evaluation of precipitation simulation for the Sierra Nevada and on a hydrologic basin scale has not been reported in spite of the stated significance of precipitation simulations for hydrologic and water resources management applications. A major challenge to the validation of simulated precipitation in mountainous terrain is the availability of dense observation networks. In our study, the Sierra Co-operative Pilot Project (SCPP) of the period 1980 -1986 provided such dense precipitation observations over the study area.

The 4,820-km^2 drainage area of Folsom Lake constitutes the application basin for this study (Figure 1a). The Lake is located about 25 miles east of the city of Sacramento (SAC) on the western front of northern Sierra Nevada (Figure 1b), and its drainage basin has steep terrain with an average crest height of 2.2 km and a half width of 100 km (Vellore, et al. 2002). There is a very small number of high passes that interrupt the compact ridgeline, but there are several deep river valleys on the western slope, oriented perpendicular to the mountain range, that constitute the American River drainage (North Fork, Middle Fork and South Fork American River of areas ranging from 886 km^2 to 1550 km^2) (see Figure 1a). Current operational hydrologic forecasts in the Folsom Lake basin are issued by the US National Weather Service (NWS) California Nevada River Forecast Center (CNRFC) based on the estimated mean areal precipitation and temperature (estimated from point observations) over seven sub-basins. The complexity of terrain in the Folsom Lake drainage basin (heretofore called Folsom basin) is in contrast to the availability of only a few continuous-recording operational precipitation stations (see Figure 1a).

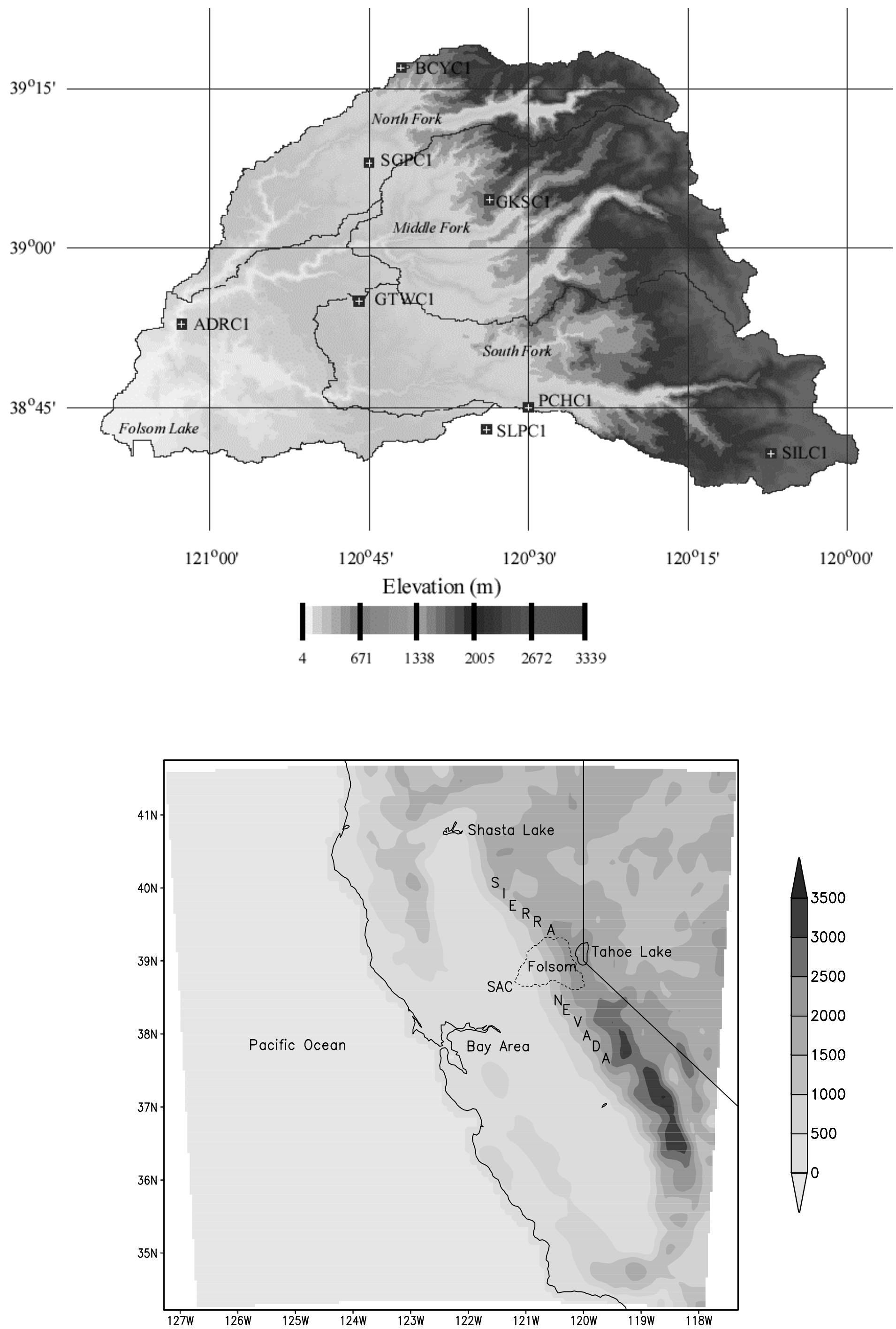

Figure 1. **(a)** (Upper Panel) Folsom basin and four sub-basins for which mean areal precipitation is simulated and observed. The four sub-basins are: the North Fork, the Middle Fork and the South Fork of the American River, and the Local Folsom Lake sub-basin. Eight operational recording precipitation gauge stations, denoted by SLPC1, SILC1, PCHC1, GTWC1, ADRC1, GKSC1, SCGP1, and BCYC1, are also shown here. The resolution of elevation data is 30 second (about 900 meters). **(b)** (Lower Panel) Terrain (shaded) in the 9km model domain.

The premise of this work is that mesoscale simulation of precipitation using a numerical dynamical model, such as the MM5, provides a reasonably accurate reproduction of the average magnitude and spatial distribution of precipitation over the complex terrain area of the Folsom basin (Dudhia and Bresch 2002; Kuligowski and Barros 1999; Medina 1992). In this paper our first goal is to study how well dynamical precipitation simulation reproduces observed features of precipitation for the Folsom basin on a sub-basin scale for light, moderate and heavy precipitation, with ground truth that consists of all available precipitation gauges.

Our second goal is to study the factors that effect simulation accuracy for precipitation on hydrologic basin scales. The course spatial resolution and inaccuracy of the model forcing and of water substance measurements (e.g., cloud/rain water content) in the atmosphere and its use for model initialization hinder precipitation simulation. In addition, allowing for spin-up periods also affects model simulations. To a substantial degree, however, shortcomings of implicit and explicit cloud and precipitation parameterization schemes are also responsible for low simulation skill. Vellore et al. (2002) and Colle and Mass (2000a) found that the over-prediction of precipitation on the upwind side and under-prediction on the lee side was a hallmark of all the microphysics schemes in MM5, except for the Dudhia's simple ice scheme, which over-predicts precipitation everywhere.

In section 2, the selected events, the input data to the MM5 model and the mean areal precipitation estimates based on point observations used for validation will be discussed. Information concerning the MM5 model setup is given in section 3. The validation results and the simulation results of various sensitivity runs for all the events are presented and discussed in the main section of the paper, section 4. Concluding remarks are in section 5.

2. Precipitation Events and Data

The events selected for precipitation simulation are hydrologically significant and span the period 1964 to 1999, corresponding to the overlapping period of availability of (a) NCEP Reanalysis I/II Data (1964-) and (b) mean areal precipitation (MAP) validation data (1958 –1999). Before 1979, NCEP Reanalysis I data with 2.5°×2.5° grid spacing and 6-hr time interval are used for initialization, while between 1979 and 1999 NCEP Reanalysis II data area used. The main difference between these two reanalysis datasets is that the former uses simulated precipitation while the latter uses observed precipitation to develop the soil moisture balance. After May 1, 1995, ETA AWIPS analysis data with a 40-km spatial resolution and a 3-hr time interval are also available to produce initial fields and lateral boundary conditions for the model.

Based on US Geological Survey (USGS) daily flow records of the American River within the Folsom basin, 62 hydrologically-significant storm events were selected and ranked based on 2.5 days total mean area precipitation in the entire Folsom basin for precipitation simulation between 1964 and 1999 (see Table 1). The heaviest precipitation event occurred on February 16-18, 1998, with 2.5 days total mean area precipitation in the Folsom basin reaching 283.8 mm. As indicated by shading, there are 21 events that occurred during the SCPP period between 1980 and 1986. Also, there are 12 cases that occurred during the period between May 1995 and May 1999, for which 40-km and 3-hourly ETA analysis data are available for precipitation simulation (also indicated on Table 1).

Table 1: The study precipitation events over the Folsom basin.

Case Number	Peak Flow Date	Folsom Basin 2.5 days MAP (mm)	MAP Ranking	Comments
1	12/23/64	241.3	2	
2	1/6/65	103.1	24	
3	1/29/67	83.1	37	
4	3/167	79.7	38	
5-6	1/20 & 1/26/69	202.6, 91.3	4, 33	
7	12/24/69	129.1	13	
8-12	1/14, 1/16, 1/21, 1/24, 1/27/70	97.5, 134.3, 135.3, 46.8, 44.9	28, 12, 11, 56, 57	
13	3/26/71	97.6	27	
14	1/12/73	127.7	14	
15	11/12/73	90.6	34	
16	12/29/73	53.4	54	
17-18	1/17 & 1/19/74	71.2, 44	43, 58	
19-20	3/2 & 3/30/74	98.3, 61.1	25, 49	
21	4/1/74	59.4	51	
22	3/25/75	76.7	40	
23	1/17/78	67.7	46	
24	1/13/80	168.5	5	SCPP Cases (21 cases)
25	2/19/80	113.5	17	
26	11/24/81	69.9	44	
27-28	12/20 & 12/30/81	160.2, 69	6, 45	
29	2/16/82	108.7	21	
30	03/30/82	96.9	30	
31	4/11/82	117.5	16	
32	12/22/82	135.5	10	
33-35	2/8, 2/13, 2/25/83	74.7, 54.2, 57.8	41, 53, 52	
36-37	3/2 & 3/13/83	48.9, 111.5	55, 19	
38-40	11/17, 11/20 & 11/24/83	123.4, 66.2, 77.4	15, 48, 39	
41-42	12/26 & 12/31/83	108, 29.9	23, 62	
43	2/17/86	283.8	1	
44	3/8/86	154.9	7	
45	3/25/89	60.4	50	
46	3/4/91	66.6	47	
47	1/22/93	38.5	59	
48-49	1/10 & 1/14/95	137.6, 94.7	9, 32	
50	3/10/95	146	8	
51	5/1/95	38.2	60	ETA AWIPS (13 cases)
52-53	2/5 & 2/20/96	89.3, 97	35, 29	
54-55	5/16 & 5/18/96	109.9, 34.9	20, 61	
56	12/12/96	108.3	22	
57-59	1/2, 1/23, & 1/26/97	235.3, 74.5, 98.1	3, 42, 26	
60	2/3/98	96.6	31	
61	3/24/98	88.5	36	
62	2/9/99	113.2	18	

Mean areal precipitation, estimated from eight continuous recording operational precipitation observation stations, was made available for validation by the NWS CNRFC for the period October 1968 - September 1999, and for seven sub-basins of the Folsom basin: upper North Fork, lower North Fork, upper Middle Fork, lower Middle Fork, upper South Fork, and lower South Fork American River, and Local Folsom Lake sub-basin. All the upper Forks consist of the Fork areas with elevations greater than the mean snow line elevation of 1,500m, while all the lower forks consist of the Fork areas with elevations below 1,500m. However, in this study, coarser divisions (i.e., North Fork, Middle Fork, South Fork American River and Local Folsom Lake sub-basins shown in Figure 1a) are implemented to guarantee that there are enough model grid points for computing simulated mean areal precipitation over each of the sub-basins. Area-weighted averages of the upper and lower portion for each sub-basin were used to estimate MAPs. In addition to the observation from the CNRFC operational precipitation gauges, hourly precipitation from 25 precipitation stations is also available for the SCPP period (1980-1986) (Figure 2). Simulated precipitation of the 21 events within this period will be validated against the MAP estimated from all the observed hourly station precipitation. In addition, the MAP for this period as computed from operational and from SCPP station precipitation will be intercompared.

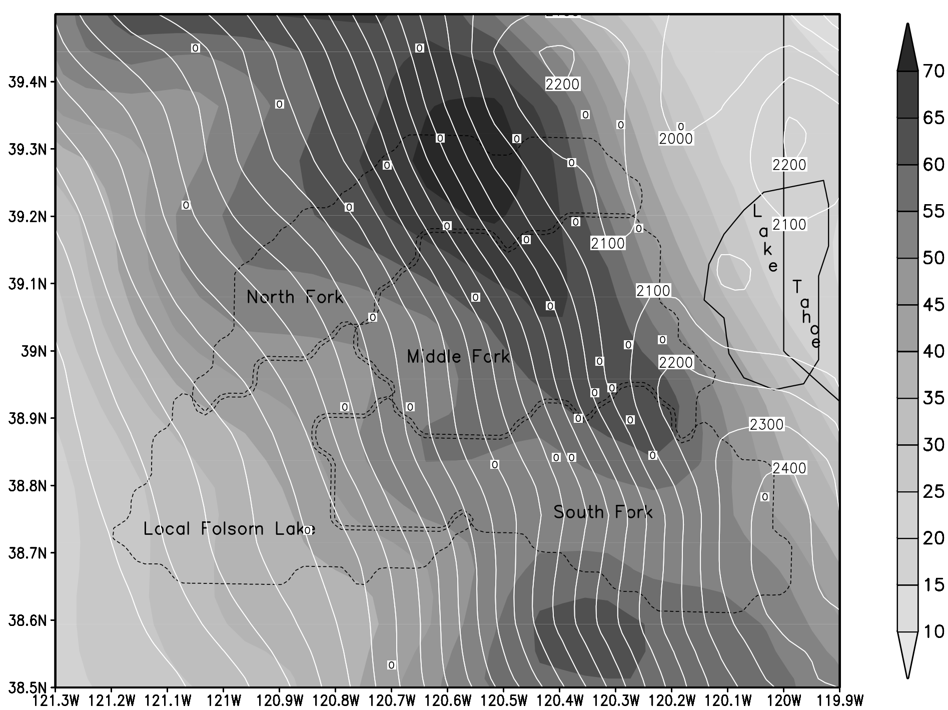

Figure 2. Folsom basin, denoted by dash line, and the neighboring area (e.g. Lake Tahoe) in the 9km model domain. Shaded is the simulated mean daily precipitation (mm) averaged over the 20 SCPP cases. Also shown are the terrain contour lines (white solid line, 100m interval) and the precipitation observation stations (denoted by squares) deployed in the Folsom basin and neighboring areas during the SCPP field experiment

It is noteworthy that instead of verifying the model precipitation simulation at various observation locations by interpolating precipitation from the model grid points to each observation site, a comparison of estimated and simulated MAP over hydrologic basins is implemented in this paper. Brook et al. (1998) suggests that to interpret the numerical model output one may need to effectively smooth it because of the fact that numerical forecasts of highly variable quantities like precipitation are often not entirely deterministic. They further indicated that the best forecast is obtained when all grid points within a radius of R=2 grid points (13 grid points in total) are considered for the spatial averaging.

Simulated precipitation can be verified directly against the observations themselves, or against a gridded analysis of the observations. One could argue that if the model output is to be used directly (i.e. interpolated) to make predictions at point locations, then the observations themselves constitute the most appropriate "truth" for verification. However, model precipitation fields themselves are grid-scale quantities and interpolation introduces weighted averaging, which would sacrifice grid-scale precipitation variability. A resent study by Cherubini et al. (2002) showed that comparing model grid box values to gridded rainfall data was more favorable than comparing interpolated model output to the original point observation. Their results were not sensitive to the method used to assign the observations to the grid, but larger grid boxes led to better verification scores.

Mean areal precipitation (MAP) over a basin/sub-basin is an important quantity commonly used in hydrological simulations. Instead of a grid box, hydrologic basins of various scales are used as natural "boxes" for averaging the observed and simulated precipitation. This approach provides another verification method for simulated precipitation. MAP comparison has several advantages over single point comparison involving interpolation from grid points. Firstly, the model-simulated precipitation itself is a simulation of mean areal precipitation over the grid area and not a single point value. The interpolation from model grids to points itself is a type of averaging or smoothing, and, therefore, it is not able to reproduce the spatial variation of observed point precipitation, especially in the steep mountainous area where precipitation spatial variability is significant. Secondly, the MAP, estimated from either model grid points or single point observations, has less variance and allows better comparisons. Thirdly, single point precipitation measurement is quite often not representative of the volume of precipitation falling over a given catchment area, and this is rarely the case, especially in mountainous areas. Although there are several techniques to estimate MAP from point measurements (e.g., Bras 1990), the MAP estimate uncertainty increases substantially as the number of point measurements decreases in all cases. Section 4 (Results) discusses this issue in more detail using available operational and SCPP data.

3. Model Setup

The MM5 model, developed by the Pennsylvania State University and the National Center for Atmospheric Research (PSU/NCAR), is used to make the dynamical precipitation simulations. This mesoscale model is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation (Dudhia 1993). From January 1964 to March 1995, only NCEP reanalysis data (every 6 hr) are available to create the model initialization and boundary fields. Due to the coarse resolution of the data, which is 2.5°×2.5°, three grids (81 km, 27 km, 9 km grid spacing) are used for a one-way nesting down to the finest resolution of simulation (9 km). The domains used for the simulations are shown in Figure 3 and the domain size for all three grids is 91×91×23. Colle and Mass (2000a) examined the effect of vertical resolution. They found that for the 8-24h forecast period, the 29-level run (4km) generated 10%-30% less precipitation along the windward slopes than the 38-level run. An increase in the number of vertical levels from 38 to 57 resulted in 20-40% less precipitation over the upper western slopes and crest of the Cascades. As part of this work, we also made sensitivity tests with the vertical resolution for the 03/20/82 case. We found that the 38 vertical layer run over-predicts the observed MAP for the entire Folsom Basin by about 50% and the 23 vertical run simulates 15% more precipitation than the observed MAP. Simulation with the coarser embedded resolution grid provides lateral boundary condition for the finer resolution grid, which is updated every 3 hours.

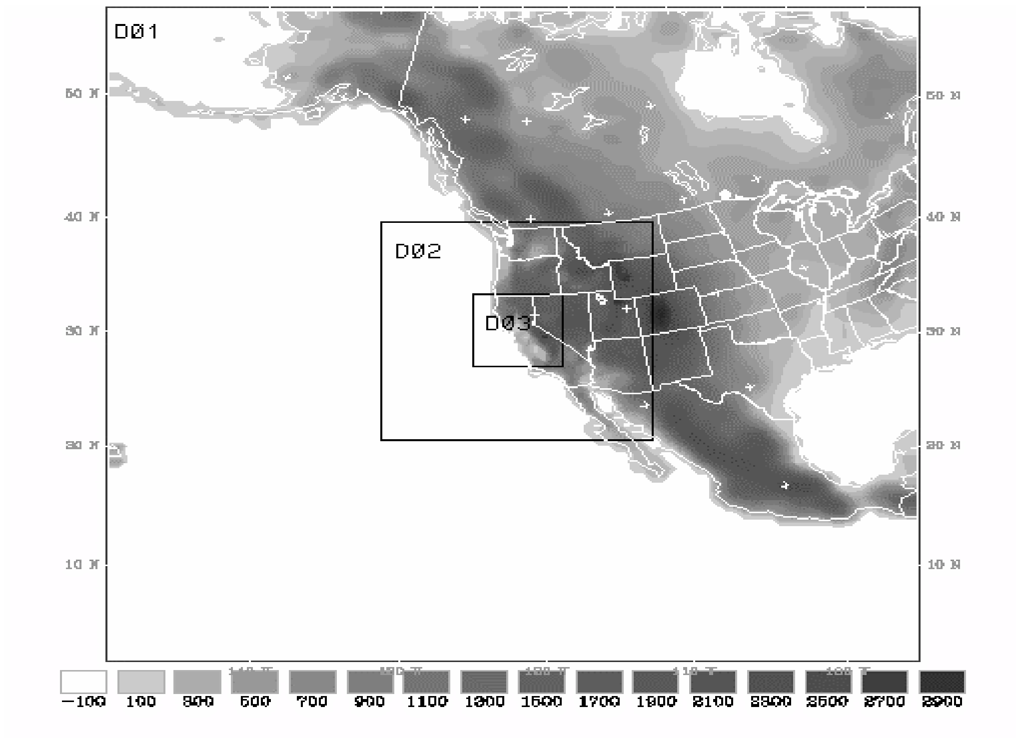

Figure 3. Terrain (shaded) and the domains for three grids at 81km, 27km and 9km resolution, labeled by D01, D02 and D03, respectively.

For the 9-km resolution simulation, the Goddard ice microphysics scheme with the graupel option (Lin et al. 1983, Tao et al. 1989,1993) and the Kain-Fritsch convective parameterization (Kain and Fritsch 1993) are turned on together to produce precipitation simulations. Other model physics in the model setup includes Mellor-Yamada PBL parameterization scheme (Mellor and Yamada 1982) and a 5-layer soil model (Dudhia 1996). After May 1995, 40-km ETA analysis data are also available for model initialization and lateral boundary conditions (updated every 3 hours). In these cases, only a 10-km grid with the same grid center point and the same dimension as the above 9-km grid is used to produce precipitation and surface temperature simulation. All other model features are as described above.

For each event and for all the sensitivity runs made, the model was initialized at 12Z of the day prior to the peak flow date. The model simulation period is 2.5 days for all the events simulated and the quantity of interest is event-total MAP for each of the four sub-basins and for the entire Folsom basin in Figure 1a. For the 9-km finest resolution grid, the number of grid points within each sub-basin are: 12, 14, 18, and 20 for the Local Folsom Lake sub-basin, and the North, Middle and South Forks of the American River, respectively. For the 10-km grid used in conjunction with the 40-km ETA forcing data, the analogous numbers are: 11, 10, 14, and 15. In all cases, the arithmetic mean was used to estimate sub-basin mean areal precipitation.

4. Results

Figure 4 shows the simulated and observed mean area precipitation during the 2.25-day model simulation period for the Folsom basin for all the ranked precipitation events. For the entire basin, among 62 simulations initialized with NCEP Reanalysis data (1969-1999), 47 cases overestimate precipitation, compared to the observed MAP with relative error ranging from 1.3% to 186.30%. The relative errors of the remaining 15 underestimation cases are between –0.3% to –44.3%. The median and mean of relative errors for the 62 cases are 38% and 44.69%. Therefore, generally, the MM5 overestimates the observed MAP by about 50%. Case studies reported in Vellore et al. (2002) and Colle and Mass (2000a) also showed overestimation of precipitation over upslope mountainous areas by the MM5 model. However, it is emphasized that not all cases simulated in this work show MAP overestimation.

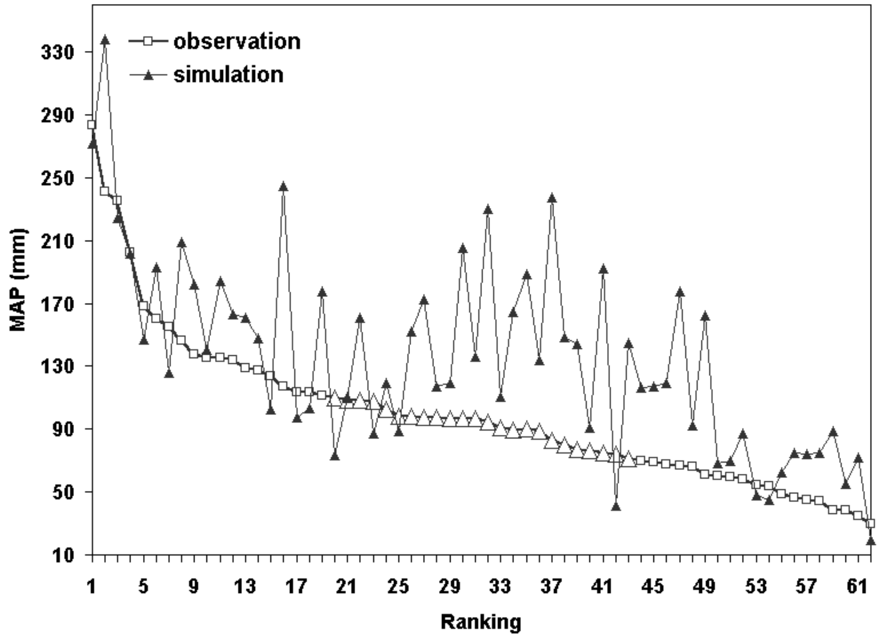

Figure 4: Simulated and observed event-total MAP (mm) for the entire basin. Moderate observed precipitation events are denoted by empty triangle

The computed mean relative errors for the four sub-basins of Local, North Fork, Middle Fork and South Fork are: 39.4%, 36.4%, 46.9%, and 67.2%, respectively. The bias is 16.9, 32.2, 43.3, and 50.7mm, respectively. The standard deviation of error is 36.7, 46.3, 46.5, and 53.3 mm, respectively. Therefore, Local and North Fork had better simulation of event-total precipitation and South Fork had the worst, with the relative error of the latter being near double that of the former. This is likely a combination of model errors and observation errors, which will be discussed later.

Similar to Colle et al. (2000b), the percentage bias score, B_p, is also computed. For a given MAP threshold, it can be defined as

$$B_p = \sum_{n=1}^{N} P_n / \sum_{n=1}^{N} X_n \qquad (1)$$

where X_n is the observed MAP for the n^{th} event over the entire basin or each sub-basin, P_n is the simulated MAP for the same event and basin, and N is the total number of occurrences of observations and forecasts for MAP reaching or exceeding the given threshold. In this case, we set the threshold to 0.0 mm and N represents the total number of events. This score is designed to determine the magnitude of the model precipitation simulation errors. If B_p > 100% (<100%), the model overestimates (underestimates) the MAP over the basin of interest. For the 62 cases examined and the entire Folsom basin, B_p is 136%. Therefore, on average, the model overestimates MAP in the Folsom basin by 36%. The B_p for the sub-basins of Local Folsom Lake, and the North, Middle, and South Forks of the American River takes the values 125%, 129%, 140%, and 154%, respectively. This result confirms that the MM5 model overestimates precipitation for all the sub-basins, with a better MAP simulation over the North Fork and Local Folsom Lake sub-basins than in the Middle and South Fork sub-basin.

It is of interest to study the performance of the MM5 model for light, moderate, and heavy precipitation events. The 62 cases were divided into three groups: light precipitation (MAP for the entire basin in 2.25 days<70mm), moderate precipitation (MAP between 70mm and 110mm, denoted by empty "Δ" in Fig.4), and heavy precipitation (MAP>110mm). There are 19, 24, and 19 storm events for light, moderate, and, heavy precipitation, respectively. The mean relative errors for light, moderate and severe cases over the Folsom basin are 58%, 56%, and 17%, respectively. The bias percentage scores (B_p) for these three categories are 161%, 152%, and 115%. Therefore, the model simulates heavy precipitation events significantly better than light and moderate precipitation events. This is in part due to systematic simulation errors. These intrinsic errors, if assumed to be the same for these three categories of precipitation, account for higher percentage for the case of simulated light precipitation than for the case of simulated heavy precipitation. The less organization and lower predictability of light and moderate precipitation than heavy precipitation events is also a source of worse model performance in simulating light to moderate precipitation events. In any case, although case studies involving heavy precipitation events may be more meaningful for hydrologic flood forecast applications, research to improve model precipitation simulation and forecast should also focus on the improvement of simulations of light to moderate precipitation, as water supply and other longer-term hydrologic forecast applications would substantially benefit from such improvements.

Another feature that can be found from the gauge-estimated event-set (62 events) average MAP for the above four sub-basins is that the MAP over the North Fork (112mm) is the highest followed by the Middle Fork (109mm) and the South Fork (94mm). The Local Folsom Lake basin has the lowest MAP (69mm). The field of climatological means of hourly precipitation estimates estimated with a dense rain gauge network during the SCPP period also shows a precipitation ridge along the Sierra Nevada with a peak of about 1.90mm/h in the North Fork sub-catchment near the border with the Middle Fork sub-catchment (see Figure 5 in Tsintikidis et al. 2002). As opposed to the estimated MAP, the model simulates more MAP in the Middle Fork (152mm) than in the North Fork (145mm) and the simulated MAP in North Fork is not higher than that of the South Fork (145mm). In accordance with the gauge-estimated MAP, the model simulates the lowest precipitation means over the low-lying and flatter-terrain Local Folsom Lake sub-basin (86mm).

To simulate the observed difference in precipitation between different sub-basins with similar topography is difficult because even the 9-km resolution of terrain is still not enough to resolve differences in relevant topographic characteristics (slope, aspect, etc.) among these three Fork basins (see Figure 2). A 3-km resolution MM5 simulation for the 03/30/82 case revealed that the North Fork receives more precipitation (205.3mm) than the Middle Fork (193.8mm) and the Middle Fork more than the South Fork (145.1 mm), different from the result at the 9-km resolution, which is 205.0, 221.7, and 205.4 mm for the North, Middle and South Fork, respectively. Therefore, terrain resolution or/and model grid spacing could exert significant influence on the spatial distribution of simulated precipitation on hydrologic-basin scales. This error was also found in precipitation predictions of the operational ETA model, for which the smoothing of terrain causes the misplacement of precipitation in the vicinity of complex terrain (Staudenmaier and Mittelstadt, 1997). However, more simulations are needed to identify significant and persistent modification of the spatial distribution of simulated precipitation as a result of changes in model horizontal resolution.

Simulation errors in large scale dynamical and thermodynamical fields such as wind and moisture could cause errors in the temporal and spatial distribution of simulated precipitation. Meyers and Cotton (1992) in their two-dimensional model sensitivity experiments highlighted the importance of initializing with a wind profile, which is representative of the inflow boundary environment. Colle et al. (2000b) illustrated that there is significant increase in model skill through eliminating the cases for which the 850mb wind errors exceeded strict criteria at two sounding sites. In this work and similar to the practice of Colle et al., the simulated 36-hr wind velocity and wind direction biases with respect to the observed sounding at the nearest upstream RAOB site, Oakland, CA were calculated for all 62 cases (Fig. 5a-b). There are 30 (37) cases with wind speed bias (absolute value) 40% less than the observed wind speed and with wind direction bias less than 30° at 850mb (700mb). Therefore, it seems that the wind simulation at 700mb is better than at 850mb, probably due to the more complex structure of 850mb wind field induced by PBL. Only 22 cases are qualified for meeting the above criteria at 850mb and 700mb at the same time. The simulated-precipitation Bp for these 22 cases is 129%, in contrast to the Bp scores 161%, 152%, and

115% obtained for light, moderate, and heavy precipitation events. Therefore, it seems that the model does a better job in simulating precipitation when it is able to reproduce the large-scale dynamical wind field well. However, among these 22 cases, 2 cases fall into light precipitation, 12 into moderate precipitation and 8 into heavy precipitation category. The Bp score for these 14 light-moderate precipitation cases is 153%. Therefore, better simulation of large scale dynamical fields by the model does not necessarily mean improvement of simulation of light-to-moderate precipitation. This can also be seen from the scatter plots of the simulated MAP relative error for the entire domain vs. wind speed and direction bias (Figure 5c-d). There is no clear relationship between wind biases and the relative error of simulated MAP, especially for the wind direction bias.

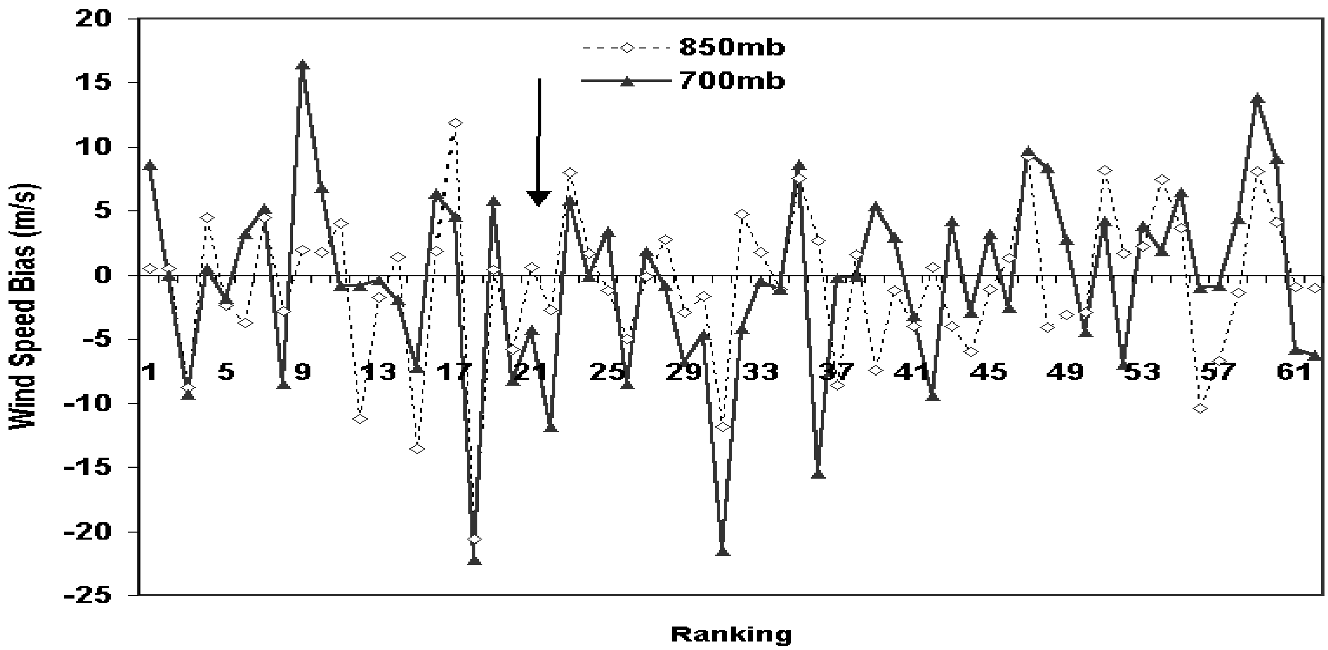

Fig. 5a

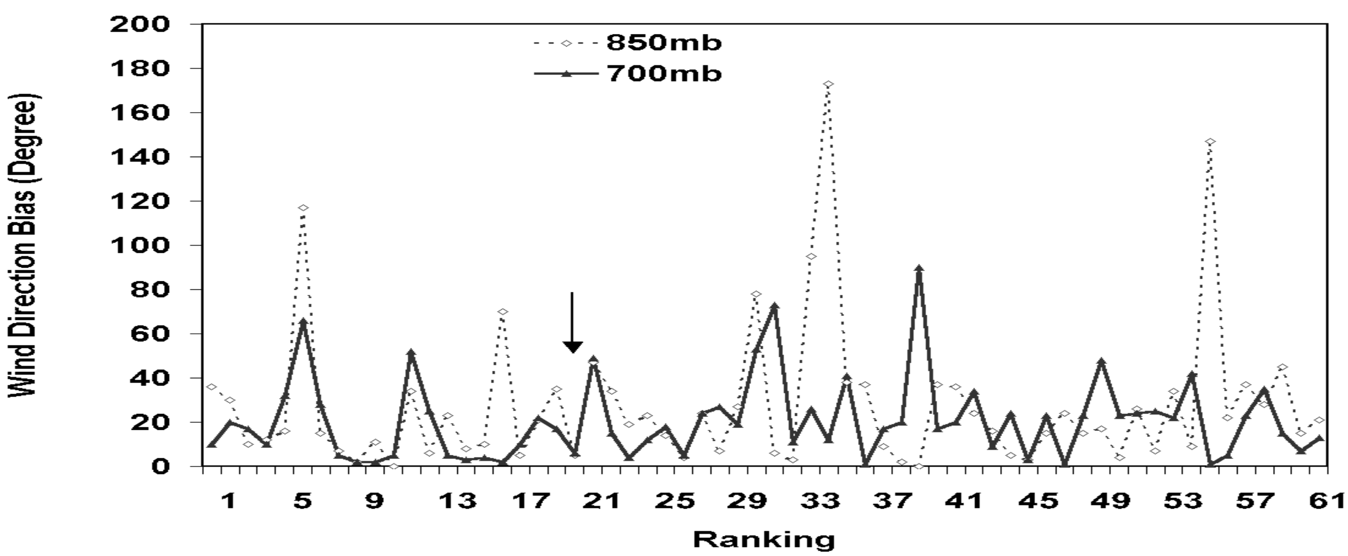

Fig. 5b

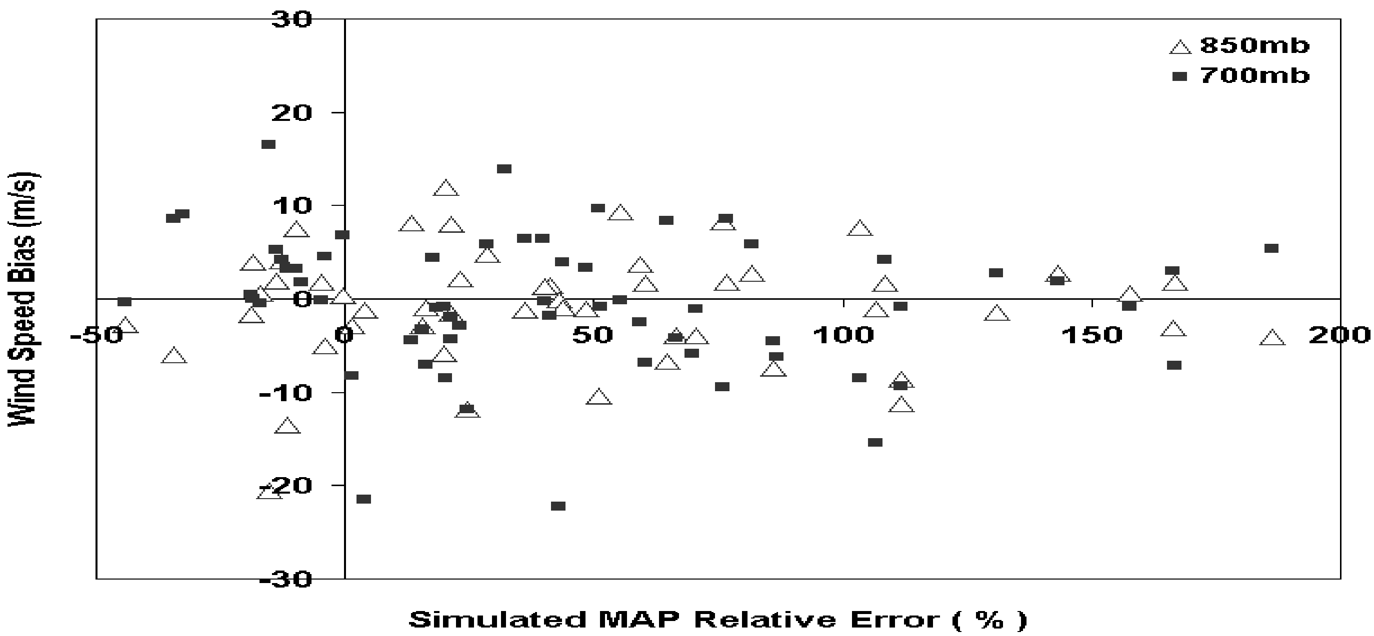

Fig. 5c

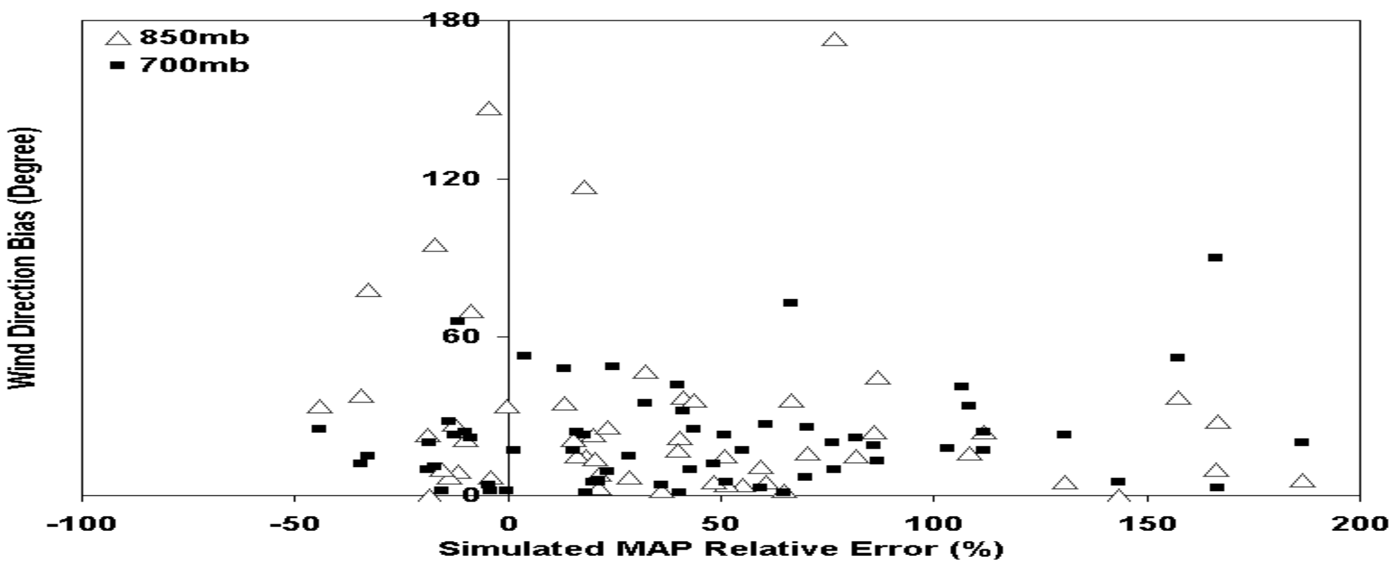

Fig. 5d

Figure 5: (a)-(b) Bias between the observed and simulated wind speed/direction at 850mb and 700mb at the RAOB site of Oakland, CA. The abscissa is the ranking of case based on CNRFC MAP (see Table 1). The cases before the arrow are heavy precipitation events. **(c)-(d)** Scatter plots of wind speed and wind direction biases vs. the relative error of simulated MAP for the entire Folsom basin.

The following sections discuss a number of sensitivity analysis results in an effort to shed light into the model behavior and the factors that affect mean areal precipitation simulation on hydrologic-basin scales.

4.1 Sensitivity to Precipitation Observing Network

The previous performance evaluation assumes that the estimated MAP for the above sub-basins as computed from observations recorded in eight operational precipitation gauges is perfect. In fact, there is precipitation gauge under-catch, which can result in particularly large precipitation underestimates in mountainous terrain where the winds are high and precipitation is frequently frozen (Groisman and Legates 1994). In addition and as mentioned earlier, scarcity and spatial imbalance of precipitation stations used for computing MAP can also cause significant error in the MAP estimate from gauge data. Figure 1 shows the location of the eight operational precipitation stations available to estimate the CNRFC MAP used in the previous validation. Comprehensive analysis by Tsintikidis et al. (2002) found that on average over the Folsom basin the sparse network underestimates precipitation, with the highest uncertainty of MAP estimation existing for the southwestern (Local Folsom Lake sub-basin) and southeastern parts of the watershed (South Fork sub-basin). Reasonably low uncertainty exists for estimated MAP in the north (North Fork sub-basin), northeast, east and south central parts of the Folsom basin.

These findings suggest that one possible reason for the apparently worse simulation performance over the South Fork sub-basin and best simulation performance over the North Fork sub-basin is due to the poor (good) precipitation observation coverage in South Fork (North Fork). Colle et al. (2000b) point out that the verification results are sensitive to whether high elevation SNOTEL data is included in the analysis. Fortunately, the Sierra Cooperative Pilot Project (SCPP), implemented between 1980 and 1986, provided a dense network of hourly precipitation observations, which were utilized by Tsintikidis et al. (2002) for their analyses and which were made available for this research. There were 42 additional hourly precipitation gauges deployed within the Folsom basin during the experiment period but only 25 gauges are located in the Folsom Lake watershed with 2, 5,10, and 8 stations in the Folsom Lake Local Basin, North Fork, Middle Fork and South Fork, respectively (See Figure 2). Because there are not enough rain gauges in the Local Basin, the comparison between the SCPP MAP and the CNRFC MAP for this sub-basin is omitted. Among the selected storm events for simulation in this study, there are 21 cases that occurred within the SCPP period, of which the December 30, 1983, storm did not have SCPP data and was excluded from the analysis. Using hourly precipitation data from SCPP and for the remaining 20 events, the mean areal precipitation for the entire basin is re-computed based on the arithmetic mean method. Figure 6 shows the new estimated MAP over the entire Folsom basin for each event together with the previously used operational CNRFC MAP estimates, and with the computed new relative errors.

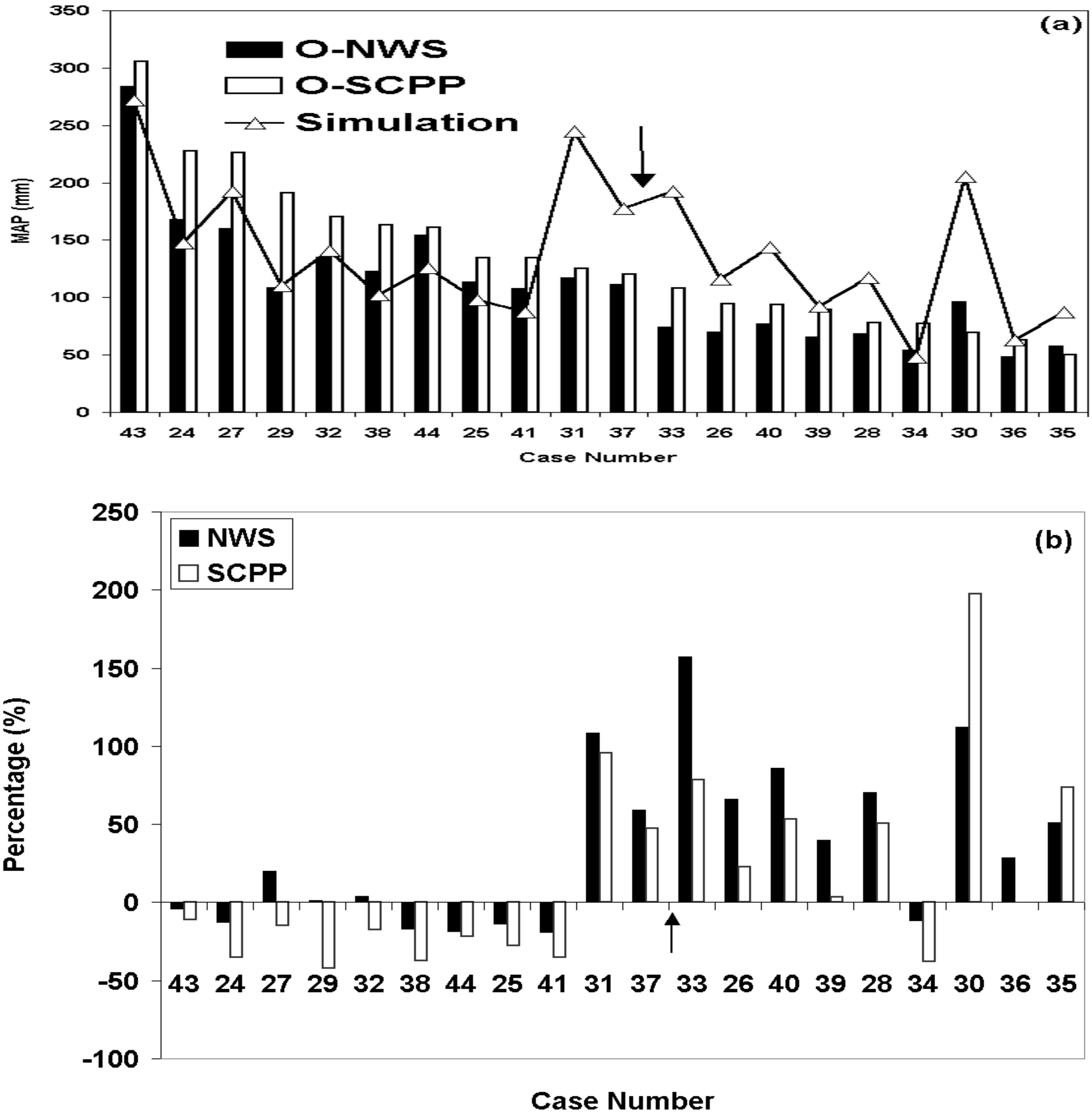

Figure 6 (a) SCPP MAP (O-SCPP in mm), CNRFC MAP (O-NWS in mm) and simulation for 20 SCPP storm events for the entire basin. **(b)** Also shown are the relative simulation errors (percentage, %) of the MM5 MAP with respect to the CNRFC MAP (NWS) and the SCPP MAP (SCPP) for the entire basin. The case numbers on the abscissa follow the order of ranking based on SCPP MAP and the cases before the arrow are heavy precipitation events in (a) and (b).

By comparing the estimated MAP from CNRFC and from SCPP for the entire basin, it is found that for all the cases but the 3/30/82 and 2/25/83 cases the CNRFC MAP is less than SCPP MAP with a relative error between –4 % and –43 %. Therefore, in almost all the cases, the MAP in the entire domain is underestimated by the CNRFC MAP. For the SCPP 20 events and for the entire Folsom basin, the median and mean relative errors of the MM5 simulations with respect to the estimated MAP from CNRFC, are 21 % and 35% and there are 7 cases which underestimate the observations. In contrast, with respect to the SCPP MAP, the median and mean relative errors are –6% and 17% and there are 10 underestimation cases. Therefore, significant reduction of relative errors and of the apparent MM5 overestimation is noted due to the finer set of verification data from the SCPP field experiment.

Based on the research by Goodison et al. (1981), for rainfall, the NWS gauge under-catch ranges from less than 10% for light winds (< 3m s^{-1}) to 20% for strong wind cases (10 m s^{-1}). For snow, even at moderate wind speeds (4 m s^{-1}), over 40% (60%) of the water mass is missed for shielded (unshielded) gauges. Colle et al. (2000b) pointed out that for a 40% under-catch at high elevations, with frequent snow and high winds, model over-prediction is not certain until the model produces more than 167% of the measured prediction. Therefore, for the mountainous area of Folsom Lake Basin located at the upslope of the Sierra Nevada Range, if a precipitation under-catch of 16% is taken into account, there are three more cases, 11/14/81, 3/2/83, and 11/20/83 that move from the overestimation category into the underestimation category. If so, among the 20 cases, the MM5 underestimated upslope precipitation in 13 events (on average by 68%), and most likely overestimated precipitation in only 7 events (on average by 32%), with only 2 cases showing more than 100% over-estimation.

However, among 20 cases, the numbers of heavy, moderate and light precipitation events are 11, 6,and 3, respectively, based on SCPP MAP in the Folsom basin. Therefore, the dominating events in the SCPP cases are heavy precipitation cases among which 9 cases are underestimated by the model. Only one underestimate case (case 34) falls into moderate precipitation category. The average relative errors of model simulation of event total MAP with respect to SCPP MAP are -13%, 31%, and, 95% for heavy, moderate, and light precipitation events, respectively. This is consistent with the findings of the above validation of all 62 cases.

The bias percentages of model simulation compared to CNRFC MAP for the North, Middle, and the South Fork are 119.6%, 129.6%, and 139.8%. They are 95.2%, 117.2%, and 117.3% compared to SCPP MAP. Therefore, similar to the results obtained for all 62 cases, the model over-simulates MAP for all three sub-catchments except for the North Fork with SCPP MAP. It confirms that the model has better performance in the North Fork than the other two sub-basins. The SCPP-event averaged MAPs simulated by the model for the North, Middle and South Fork are 148.1, 155.3, 145.2mm, with the Middle Fork receiving more precipitation than the North Fork, although the SCPP-event averaged gridded model precipitation has a maximum in the North Fork (see Figure 2). As mentioned earlier, higher model resolution may correct this trend.

The SCPP-event averaged MAPs from SCPP and CNRFC observations for the North, Middle and South Fork are 155.6, 132.5, and 123.8mm for SCPP and 123.8, 119.8, and 103.9 mm for CNRFC. It is possible that there is an overestimation of the observed MAPs in the North Fork during the SCPP period due to the availability of only five observation stations within the North Fork and with no observations available within the western portion of this sub-basin where much less precipitation falls than in the northern and eastern portion (see Figure 2).

All of the sub-basins studied in this work are on windward slopes of the Sierra. Thus, our results pertaining to over- or under-prediction on windward slopes are different from previous published case study results (Vellore et al. 2002), and from the continuous MM5 run result for the two cold seasons in the Pacific Norwest by Colle et al. (2000b). In Colle et al. simulations, the NCEP 48-km or 32-km ETA model was used to initialize and provide boundary conditions for the 12-km MM5 (33 vertical layers). The Dudhia simple ice microphysics scheme (Dudhia 1989) and the Kain-Fritsch cumulus parameterization scheme (Kain and Fritsch 1993) were implemented in that study to simulate precipitation. Colle et al. found that the12-km resolution has significant over-prediction for light to moderate precipitation events but no widespread over-prediction for heavy precipitation over the upper windward slopes of the higher terrain. Their validation was done using point data and interpolation of model grid results to the observation sites (see Figure 10a in the Colle et al. 2000b paper). It is admittedly difficult to make a direct comparison between their continuous run and our event simulation results for multiple cases because of different model setup and initialization. However, it is clear that whether the MM5 model over-predicts precipitation in the upslope side of the Sierra Nevada is conditional on the particular storm event studied, the accuracy of the validation data, the appropriateness of comparison method, the choice of the parameterization scheme for precipitation production and development and other factors (e.g. large scale simulation error in wind and moisture, vertical resolution of model, et al.) (Colle *et al*. 2000b).

4.2 Sensitivity to Initial and Boundary Fields

Because of the finer spatial (40 km) and temporal (3 hours) resolution of ETA AWIPS analysis data, it only takes one grid (10km), instead of the three nesting grids (81 km, 27 km, and 9 km) required with the 2.5^o NCEP reanalysis data, to reach the resolution set for precipitation simulation over the Folsom basin. It is of interest to quantify the improvement of basin precipitation simulations that initialization using the 3-hourly 40-km ETA data brings compared to the 6-hourly 2.5^o NCEP reanalysis data. Among the selected events of Table 1, there are 12 storm events that occurred between May 1995 and 1999, when the 40-km ETA analysis data are available. For this sensitivity analysis, in turn ETA AWIPS analysis and NCEP reanalysis data were utilized to produce initial conditions and provide boundary conditions for the MM5. It is tacitly assumed that the difference in final-grid resolution between the two cases (ETA analysis at 10 km and NCEP reanalysis at 9 km) will not produce significant differences of the basin-scale precipitation simulations.

Figure 7a-b shows the simulation results from ETA AWIPS and NCEP reanalysis data. The average relative error of simulation is 32.5% for NCEP reanalysis data and 10.1 % for ETA AWIPS data. We also computed the root mean square error (*R*):

$$R = \sqrt{\frac{\sum_{n=1,N} (P_n - X_n)^2}{N}} \qquad (2)$$

where X_n is the observed MAP for each case over the entire basin or each sub-basin, and P_n is the simulated MAP. *R* measures the magnitude of the difference between the simulation and the observed values, and is greatly affected by large simulation errors. The *R*-values for NCEP analysis and ETA AWIPS scenarios are 44.7 mm and 27.7 mm, respectively. The ratio of *R* to the averaged observed MAP for all cases, which reflects the variability of simulation error, is 0.45 for NCEP reanalysis and 0.28 for ETA AWIPS. Therefore, overall, the simulations with ETA AWIPS forcing appear to be significantly better than the ones using NCEP reanalysis forcing, indicating the strong influence of the boundary resolution on the simulated spatial precipitation distribution.

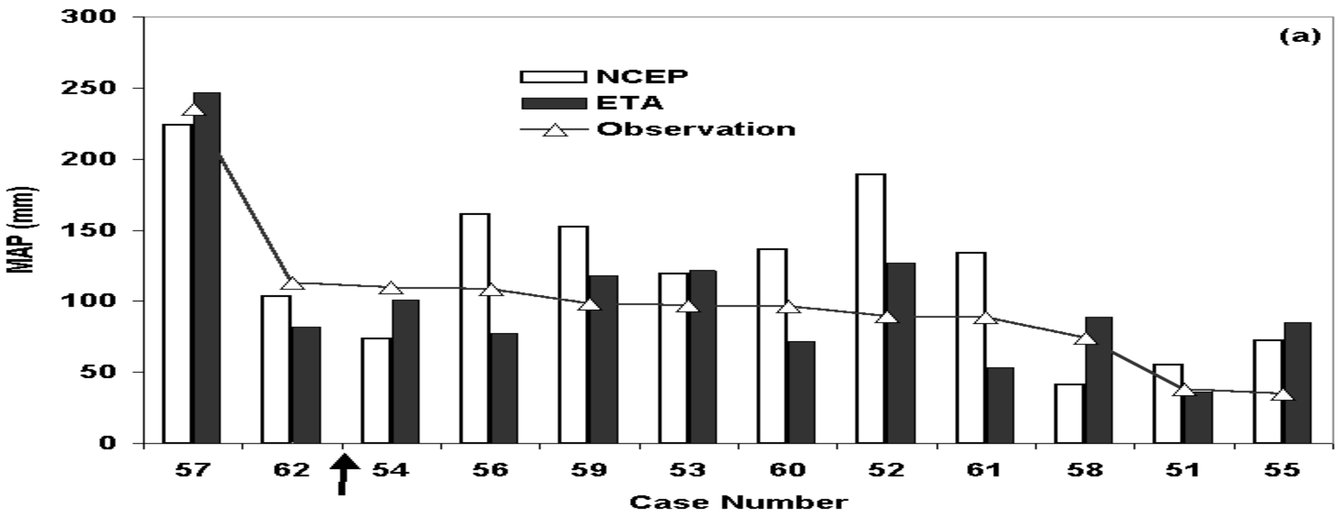

Fig. 7a

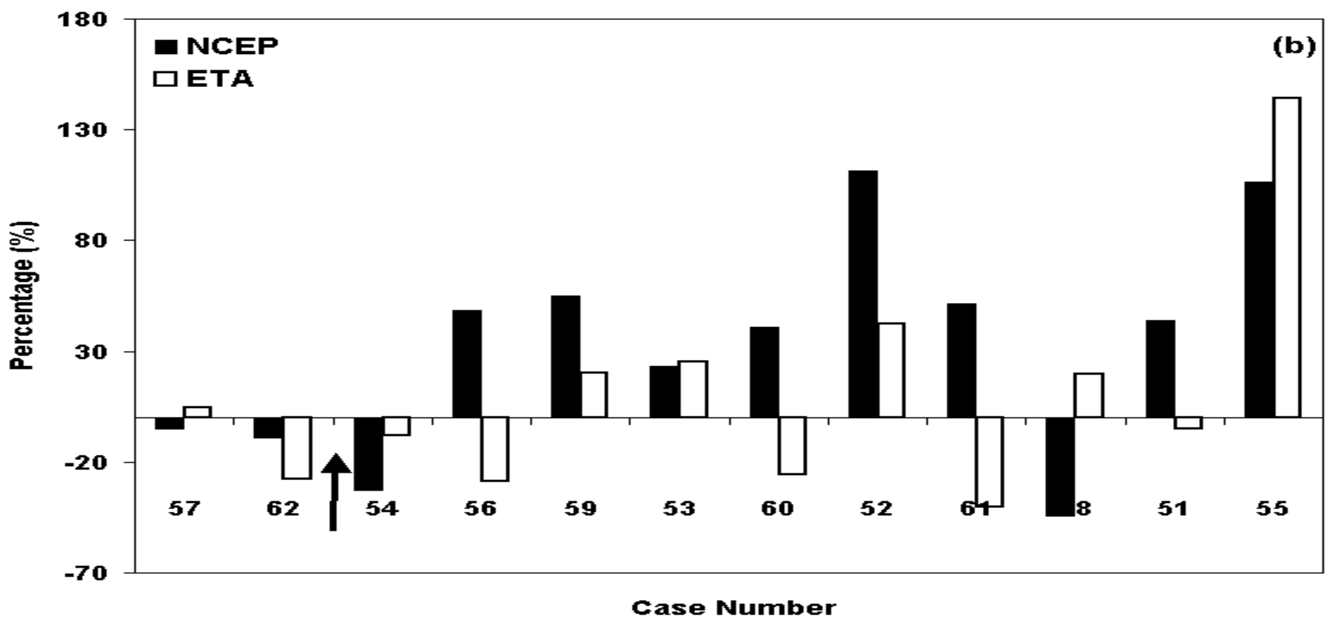

Fig. 7b

Figure 7 (a) Observations and simulations of the entire Folsom basin event total precipitation using NCEP reanalysis (NCEP) and ETA AWIPS analysis (ETA) forcing. **(b)** The corresponding relative errors of each of the two simulations. The case numbers on the abscissa follow the order of ranking based on CNRFC MAP and the cases before the arrow are heavy precipitation events in (a) and (b).

To study the statistical significance of the differences, a statistical *t*-test is implemented to verify whether the means of the two simulation groups are statistically different from each other. The formula for the *t*-test is shown below:

$$t = \frac{\overline{P}_N - \overline{P}_E}{\sqrt{\frac{Var_N}{n_N} + \frac{Var_E}{n_E}}} \quad (3)$$

where $\overline{P_N}, Var_N, n_N$ are the mean (123), variance (3073), and sample size (12) (respectively) of the precipitation simulations using NCEP reanalysis forcing. $\overline{P_E}, Var_E, n_E$ are the mean (102), variance (2841), and sample size (12) (respectively) for the ETA AWIPS forcing simulations. The computed *t* value is 0.947. Therefore, the difference in the mean between the simulations with (a) NCEP reanalysis and (b) ETA AWIPS forcing is significant at the 80% confidence level (or equivalently at the 20% risk level).

Interestingly, among 12 cases, there are 7 cases (Case 51, 54, 56, 57, 58, 60, 61) in which the simulations with NCEP Reanalysis and ETA analysis fall in different simulation error category (under-prediction or over-prediction). Therefore, the initialization of the model is among the key factors that determine the error structure of model simulations. That is, whether the model over-simulates or under-simulates precipitation is heavily dependent on the resolution of the model boundary and initial fields.

4.3 Sensitivity to Microphysics Schemes

As mentioned in the Model Setup section, the previous results were obtained using the Goddard microphysical scheme developed at the GSFC (Goddard Space Flight Center). In this subsection we inter compare various microphysical parameterization schemes for the 21 SCPP events. In addition to the GSFC scheme, there are several other options in MM5 for microphysical parameterizations. Similar to the GSFC microphysics scheme, the Reisner2 scheme originally developed by Reisner et al. (1998) and the Schultz (1995) microphysics scheme also predict mixing ratio of cloud, rain, ice, and graupel/hail with different complexity. The Schultz scheme is a simpler but fairly efficient algorithm and is being implemented in the operational NCEP ETA model. In the Reisner2 scheme, a variable slope intercept N_0 for the particle size distribution (PSD) is adopted in contrast to the fixed-slope intercept used in the GSFC scheme. The former scheme also predicts number concentration of cloud ice.

The Folsom basin simulated precipitation and relative errors with the above three microphysical schemes compared to the two precipitation observation sets are shown in Figure 8a-c. The bias percentages of the MAP simulation for the three microphysics schemes (GSFC, Reisner2, and Schultz), compared to the estimated CNRFC MAP are 126%, 112%, and 131%, respectively. Compared to the estimated SCPP MAP, the three bias percentages are 103%, 92%, and 107%. That is, the Reisner2 microphysics scheme simulates about 11% less precipitation than the GSFC scheme and 8% less than the SCPP estimate. The Schultz scheme simulates about 4% more precipitation than the GSFC scheme and 7% more than the SCPP estimate. As compared to the CNRFC MAP estimates, all the three schemes over-simulate the observed precipitation: the Schultz scheme by 31%, the GSFC by 26%, and the Reisner2 by 12%. The GSFC scheme has the best performance in MAP simulations in this region. The Reisner2 scheme tends to under-simulate and the Schultz scheme tends to over-simulate the observed precipitation at the upslope of Sierra Nevada Ranges.

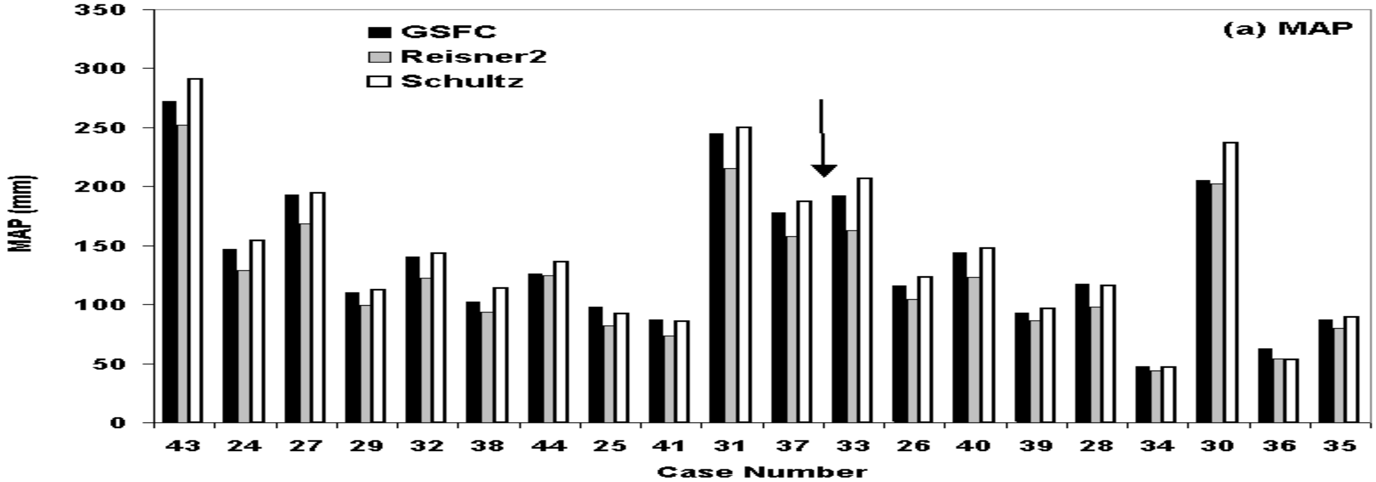

Fig. 8a

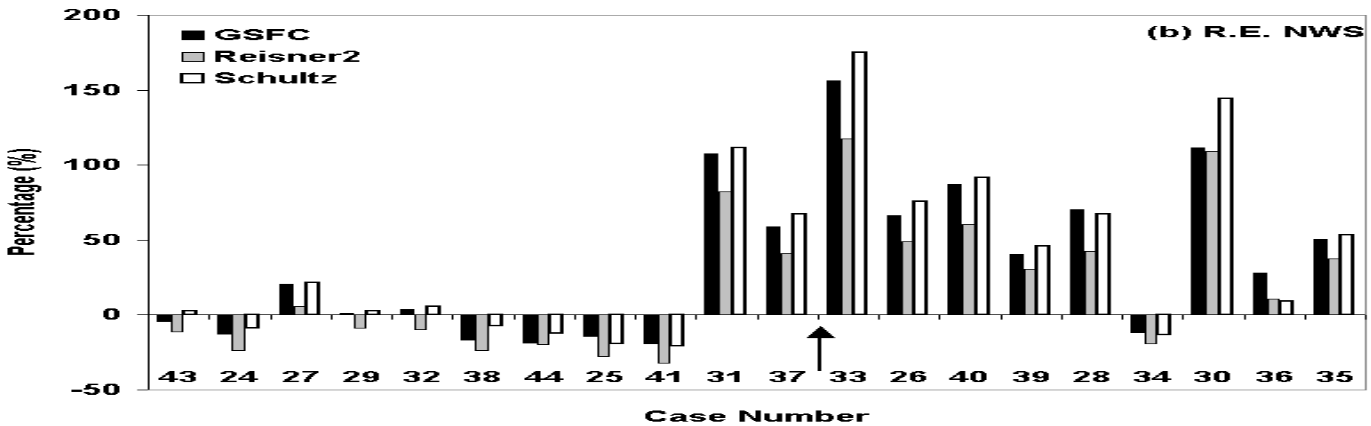

Fig. 8b

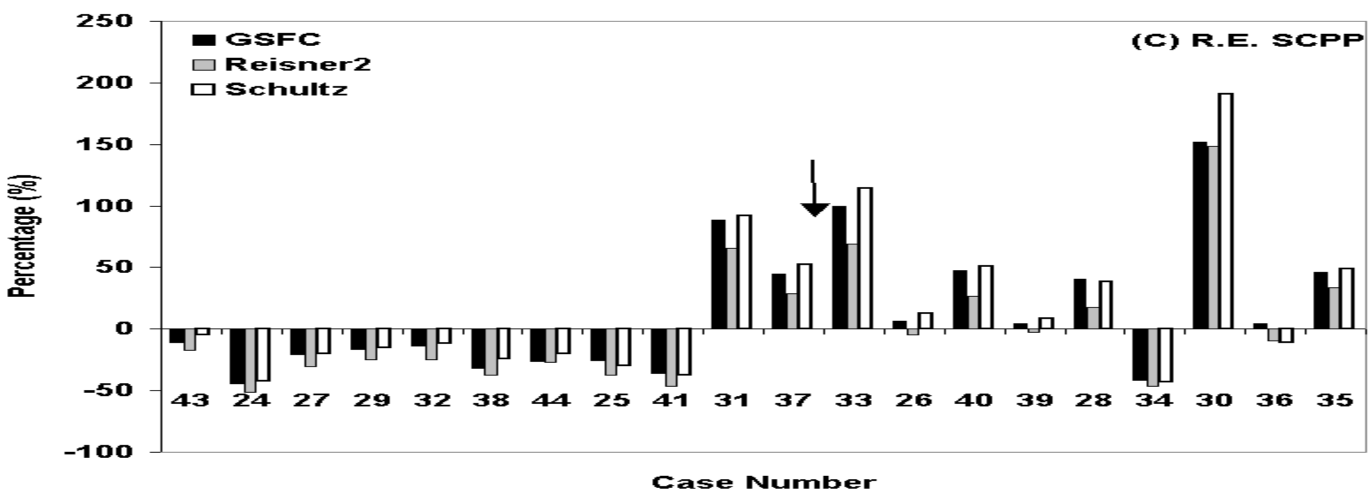

Fig. 8c

Figure 8 (a) Simulated MAP over the entire Folsom Basin for the 21 SCPP cases using the three microphysics schemes (GSFC, Reisner2, and Schultz). **(b)-(c)** Relative errors with respect to the estimated MAP from CNRFC (R.E. NWS) and SCPP (R.E. SCPP). The case numbers on the abscissa follow the order of ranking based on SCPP MAP and the cases before the arrow are heavy precipitation events in (a) -(c).

One of reasons that the Reisner2 scheme produces about 10% less precipitation than the GSFC scheme is the difference between the formulas of terminal velocity of snow particles. The Reisner2 formula gives 11.5% less fall speed than the GSFC formula for a 2mm snow particle. The Reisner mixed phase microphysics scheme adopted the fall speed expression from Locatelli and Hobbs (1974) for unrimed radiating assemblages of plates, side plane, bullets, and columns, namely,

$$V=11.72\ D^{0.41}\ \ (m/s) \qquad (4)$$

where the unit of the snow diameter D is m. In the GSFC microphysics scheme, the following relationship of snow terminal velocity V for graupel-like snow of hexagonal type (Locatelli and Hobbs, 1972) is used:

$$V= 152.93\ D^{0.25}\ \ (cm\ s^{-1}) \qquad (5)$$

where the unit of the snow diameter D is cm. Since snow particles are readily carried by the horizontal flow, small differences in fall speed may substantially influence where the precipitation ultimately reaches the ground. Colle and Mass (2000a) found that the 20% reduction in fall speeds shifted precipitation from the windward side of major barriers to the lee side, with 10-20% less precipitation on the windward side and 10-60% more near the crest and at the immediate lee of the barriers. Among the 20 study events of the SCPP period (12/30/83 case excluded), the GSFC, Reisner2, and Schultz scheme all have the same 6 under-simulation cases for the CNRFC MAP, and have 10,12, and 11 under-simulation cases, respectively, for the SCPP MAP. Therefore, in any case the model does not overwhelmingly over-simulate or under-simulate precipitation as a result of microphysical parameterization over the upslope of the Sierra Nevada at the Folsom Lake watershed.

5. Concluding Remarks

In this study the mesoscale model MM5 is used to simulate orographic precipitation in the 4,820-km^2 Folsom Lake watershed located on the windward slope of Sierra Nevada for 62 winter storm events in the period 1964-1999. The event-total (2.5 days) mean areal precipitation for the Folsom basin and four major sub-basins (of area ranging from 886 km^2 to 1550 km^2) was computed based on 9km resolution of the gridded simulation fields and comparison with the estimated MAP by operational procedures of the CNRFC based on point observations was made. Emphasis was placed on the validation and sensitivity analysis with respect to average event-total basin and sub-basin MAP, as appropriate for water resources applications of MM5 precipitation simulations in the region.

Although the simulated MAP for all the sub-basins, on average, overestimates the observation-derived MAP, there is still a fair amount of cases (15/62) underestimating precipitation on the steep terrain of this watershed. The model simulates best heavy precipitation events and overestimates MAP consistently for light and moderate precipitation events. Different performance was found for each sub-basin, with the North Fork exhibiting the best percent bias of 125% and the South Fork the worst percent bias of 154%. We conclude that model MAPs on smaller scales (886 km^2 – 1,550 km^2) do not always reproduce the spatial patterns of gauge-estimated MAPs within Folsom basin and preliminary results indicate that spatial model resolution down to 3 km or denser observation network may be necessary.

Inter comparison of the estimated basin MAP from 8 operational rain gauges and from the dense precipitation observing network of the Sierra Co-Operative Pilot Project, showed that the precipitation overestimation by the model in the upslope of the Sierra Nevada is reduced significantly from 26% to 3% as a result of more accurate estimation of the true MAP. Taking into consideration an expected 16% mean under-catch of precipitation gauges, the model actually underestimates the MAP over the Folsom Basin in most SCPP cases due to heavy precipitation events dominating. We conclude therefore that the quality of the MAP validation data very significantly affects assessments of over- or underestimation of actual average event-total MAP in the region, and that for this watershed it is most likely for the MM5 model to underestimate (overestimate) the actual MAP for most of the heavy (light-moderate) winter precipitation events.

Sensitivity analysis with respect to model initialization and boundary condition datasets reveals that the 40-km ETA analysis data has a statistically-significant advantage over the 2.5^o NCEP reanalysis data at the 80% confidence level. The reliable estimation of the upstream wind is significant for the development of the correct simulation pattern of mean areal rainfall. The average event-total basin MAP model is also found sensitive to the MM5 cold microphysics schemes used but this sensitivity was less than that due to changes in model initial and boundary fields.

Overall, the results of this study suggest that the MM5 model with a 10-km final resolution provides reasonable average event-total MAP simulations for the 4,280-km^2 Folsom basin especially for heavy precipitation events and with operational ETA analysis providing initial and boundary fields. Therefore, its use for the estimation and short-term forecast of mean areal precipitation over the Folsom Lake watershed in conjunction with available precipitation station observations is warranted. In addition, the results of this study lend credence to analyses of mesoscale atmospheric circulation, hydrologic cycle and microphysical effects that are based on MM5 dynamical simulations of heavy upslope precipitation events in the region. On going research uses the MM5 for a variety of atmospheric diagnostic studies pertaining to the formation and evolution of heavy winter precipitation events over the Folsom basin.

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