The Impact of Different Physical Parameterizations and Their Interactions on Cold Season QPF in the American River Basin

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ABSTRACT

The most significant precipitation events in California occur during the winter and are often related to synoptic-scale storms from the Pacific Ocean. Because of the terrain characteristics and the fact that the urban and infrastructural expansion is concentrated in lower elevation areas of the California Central Valley, a high risk of flooding is usually associated with these events. In the present study, the area of interest was the American River basin (ARB). The main focus of the present study was to investigate methods for Quantitative Precipitation Forecast (QPF) improvement by estimating the impact that various microphysical schemes, planetary boundary layer (PBL) schemes, and initialization methods have on cold season precipitation, primarily orographically induced. For this purpose, 3-km grid spacing Weather Research and Forecasting (WRF) model simulations of four Hydrometeorological Test bed (HMT) events were used. For each event, four different microphysical schemes and two different PBL schemes were used. All runs were initialized with both a diabatic Local Analysis and Prediction System (LAPS) "hot" start and 40-km eta analyses.

To quantify the impact of physical schemes, their interactions, and initial conditions upon simulated rain volume, the factor separation methodology was used. The results showed that simulated rain volume was particularly affected by changes in microphysical schemes for both initializations. When the initialization was changed from the LAPS to the eta analysis, the change in the PBL scheme and corresponding synergistic terms (which corresponded to the interactions between different microphysical and PBL schemes) resulted in a statistically significant impact on rain volume. In addition, by combining model runs based on the knowledge about their impact on simulated rain volume obtained through the factor separation methodology, the bias in simulated rain volume was reduced.

1. Introduction

The most significant precipitation events in California occur during the winter and are related to synoptic-scale storms from the Pacific Ocean. Because of the large urban and infrastructural expansion in lower elevation areas of the Central Valley, a high risk of flooding is usually associated with these events. The National Oceanic and Atmospheric Administration (NOAA) has established the Hydrometeorological Test bed (HMT)—a series of field projects designed to support research and development toward better observations

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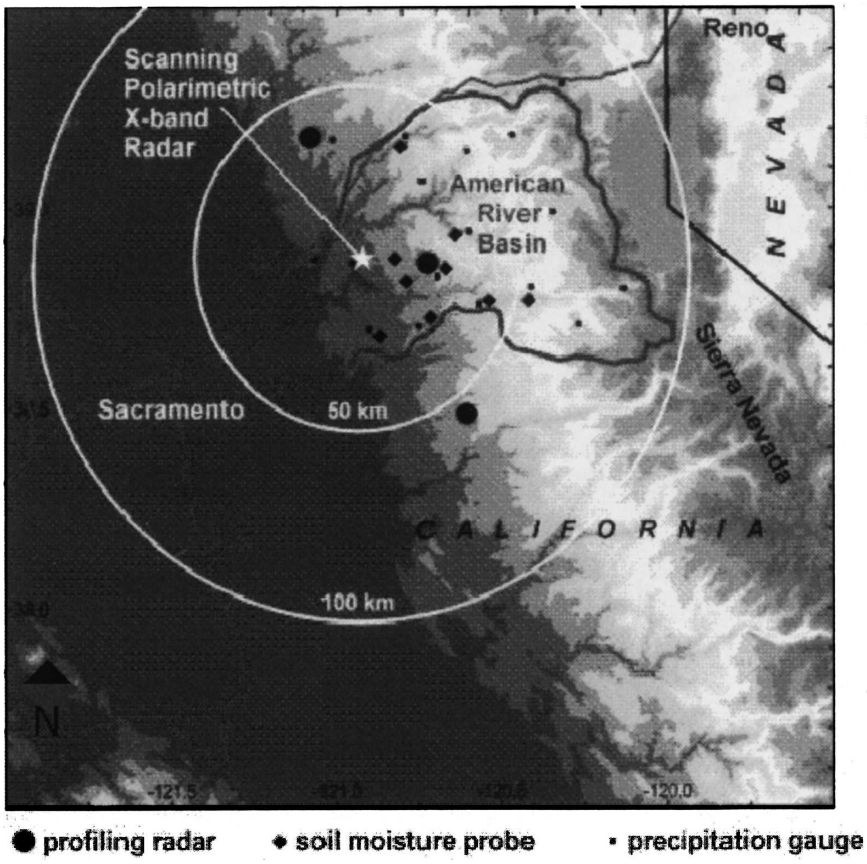

FIG. 1. Domain of integration with area of interest, ARB, indicated.

of precipitating cloud systems and numerical forecasts of precipitation. HMT involves a collaboration of several NOAA laboratories and National Weather Service forecast offices. In the present study, the main area of interest during the HMT field experiments of 2005 December through 2006 March is the American River basin (ARB), which is a mountainous and relatively small (approximately 75 × 75 km) drainage basin between Lake Tahoe and the city of Sacramento in north central California, on the western slope of the Sierra Nevada (Fig. 1).

Heavy cool-season precipitation events in the ARB are often associated with "atmospheric rivers" (Bao et al. 2006; Ralph et al. 2004, 2005) and such events are of primary interest to the HMT field experiments. Atmospheric rivers are elongated regions of high values of vertically integrated water vapor extending from the western tropical and subtropical Pacific into the extratropics. The high values of integrated water vapor are advected into the extratropics within the warm sector of extratropical cyclones. The northwest to southeast orientation of the Sierra Mountain chain is often approximately orthogonal to the wind direction within the warm sector of approaching extratropical cyclones. As a result, sustained rain processes are promoted primarily by orographic lift and secondarily by the dynamic forcing of vertical velocity. In most of these events, the freezing level remains above the surface, leading to very large rain accumulations and runoff.

The main objective of the present study is to investigate methods for Quantitative Precipitation Forecast (QPF) improvement over the ARB area by estimating the impact of various microphysical schemes, PBL schemes, and initializations for rain events that are caused by synoptic conditions that resemble atmospheric rivers. For these events, the information about the rain volume over the river basin directly impacts decisions on Folsom dam and Sacramento reservoir operations. Therefore, in order to quantify the impact of varying physical schemes and initial conditions, the factor separation methodology formulated by Stein and Alpert (1993) was applied to rain volume. For this purpose, high-resolution [3-km grid spacing Advanced Research Weather Research and Forecasting (WRF) model (ARW) dynamic core (Skamarock et al. 2005; Wicker and Skamarock 2002; Michalakes et al. 1998)

and 32 vertical levels] simulations of 4 HMT events were examined. For each event, a set of eight WRF model configurations was created by varying the microphysical and PBL schemes. The method used in the present study is discussed in section 2, with results in section 3 and a concluding discussion and summary in the final section.

2. Methodology

To quantify the impact of microphysical and PBL schemes on simulated cold season rainfall, four HMT intensive observing periods, each with synoptic characteristics similar to atmospheric river events, were selected for further study. For this purpose, the WRF-ARW model with four different microphysics and two different PBL schemes was used. The integration domain covered a region of roughly 500 km × 500 km centered over central California (Fig. 1). For each case, the following microphysical schemes were used: Lin et al. (1983) modified by Rutledge and Hobbs (1984), Ferrier et al. (2002), WRF single-moment 6-class (WSM6; Hong et al. 2004), and Thompson et al. (2004). For each of the four microphysics configurations, two different PBL schemes were used: the local mixing eta PBL scheme, often referred to as Mellor–Yamada–Janjic 2.5 Janjic (2001), and the nonlocal mixing Yonsei University (YSU) PBL scheme (Noh et al. 2003) as an improved version of the medium-range forecasting model (MRF) PBL scheme (Troen and Mahrt 1986).

All model runs were initialized at 0000 UTC with both diabatic Local Analysis and Prediction System (LAPS) "hot" start (Jian et al. 2003) and 40-km eta "cold" start analyses. The 40-km eta analysis was also used for specifying the lateral boundary conditions. The LAPS hot start technique is based on a three-dimensional analysis of cloud attributes (i.e., coverage, type, and mixing ratios), which includes methods for estimating in-cloud vertical motions. By using a variational adjustment procedure (involving dynamic balancing and a mass conservation constraint), horizontal wind fields and the mass field are adjusted to produce divergence consistent with the specified cloud updraft properties (depth, magnitude, and shape of the updraft profiles). The LAPS procedures, in particular, enable initialization of hydrometeors and balanced circulations driven by latent heating. This triggers an immediate activation of microphysical schemes and the development of grid-resolved precipitation at early forecast times of runs initialized with LAPS analyses. On the other hand, for runs initialized with eta analyses, the model dynamics start off with an unsaturated initial state. Therefore, a delay in the activation of microphysics and production of precipitation should be expected.

TABLE 1. Notation used for different physical schemes and initializations in the present study. Physical schemes used in the "control" configuration are marked with "*".

Physical scheme/Initialization	Notation
PBL scheme	
ETA PBL	ETA
YSU PBL*	YSU
Microphysics scheme	
Lin et al. Microphysics*	MPL
Ferrier microphysics	MPF
WSM6 microphysics	MPW
Thompson microphysics	MPT
Initialization	
40-km NCEP Eta	eta
LAPS "hot" start	LAPS

In the present study, the model setup using the LAPS analysis [the Lin et al. (1983) microphysical scheme and the YSU (Noh et al. 2003) PBL scheme] was chosen as the "control" configuration. The abbreviations for runs using different combinations of the physical schemes are found in Table 1. For the rainfall validation, observed, 6-h, accumulated precipitation fields from the National Centers for Environmental Prediction (NCEP) Stage IV analysis (Baldwin and Mitchell 1997) were used. In mountainous areas, such as the ARB, the Stage IV precipitation may be underestimated due to a limited number of gauges and limited radar coverage as well as radar signal blockage. The comparison between the Stage IV and gauge data for the events of interest indicated that Stage IV 6-h accumulations agreed well with gauge data, whereas shorter accumulation periods suffered from inconsistencies that negatively impacted the comparison with model data. For this reason, we chose to analyze predictor performance on 6-h accumulations.

To quantify the impact of different microphysical schemes as well as the impact due to the *interactions* between the microphysics and PBL schemes, the factor separation methodology formulated by Stein and Alpert (1993) was adopted. Based on this methodology,

$$f_{xy} - f_0 = (f_x - f_0) + (f_y - f_0) + f^*_{xy}, \qquad (1)$$

where f_0 represents the control configuration simulated rainfall amount, f_{xy} represents the rainfall amount simulated by a run with changes in both physical schemes of interest (two physical schemes changed compared to the control configuration), f_x stands for the rainfall amount produced by a run that has one of the two physical schemes of interest changed (as compared to the control configuration), f_y represents the rainfall amounts simulated by a run with another physical scheme of interest changed (as compared to the control configuration), and f^*_{xy} represents a synergistic term $[f^*_{xy} = f_{xy} - (f_x + f_y) + f_0]$ reflecting, in the present

study, the rainfall amount associated with the nonlinear interaction between the microphysical and PBL schemes. This term may be thought of as the difference between the actual rainfall occurring in the run in which two schemes have been changed and the rainfall expected by adding the impacts of each individual change. Assuming a continuum of physical schemes, Eq. (1) is then equivalent to Taylor's series second-order expansion in two variables. The first two terms on the right-hand side (RHS) of Eq. (1) represent the contribution of the first-order derivatives, while the third term (synergistic term) is a mixed second-order derivative (the nonmixed second-order derivatives are zero). In essence, if the synergistic term is equal to zero, no interaction occurs between the two changed physical schemes.

The factor separation method was applied to simulated rain volume over the ARB area. Rain volume is defined as the rain depth at each grid point within the ARB area multiplied by the grid cell area and added together for all grid points. As part of the evaluation of changes in rain volume due to variations in both physical schemes (microphysics and PBL) and changes in initial conditions, statistical significance testing was performed. For this purpose, a resampling method suggested by Hamill (1999) was used. The null hypothesis was that the difference in rain volume between the control configuration and changed model configuration was equal to zero. Based on the null hypotheses, the test statistics and resampled distributions were formed. The factor separation results for all 6-h periods were combined together in a pool. The resampled statistics were formed by randomly choosing from the pool a number of factors that included a configuration of interest (i.e., model runs using a particular microphysics) and then averaging them. This procedure was repeated 1000 times. Finally, the hypothesis of the difference in rain volume was tested by determining the location of the average value within the resampled distribution, or in other words, by calculating the corresponding p value.

The notation presented in Table 1 will be used to indicate different model configurations.

3. Results

a. *Sensitivity of simulated rain volume to physical scheme changes under different initial conditions*

1) Subjective analysis of different microphysical schemes' performance in ARB

Six-hour accumulated rainfall from runs using different microphysical schemes for the 0000–0600 h simulation period for the 27 February 2006 case initialized at 0000 UTC with the LAPS and eta analyses is presented in Figs. 2 and 3, respectively. In Fig. 2d, the Stage IV data for the period of interest are shown. The ARB area is indicated by the box in Fig. 2a. The simulated precipitation fields from the model runs using various microphysics and initialized with different analyses (Figs. 2, 3a–d) are characterized with much more structure compared to the observations (Fig. 2e). This relates to the previously discussed limitations of the Stage IV data in mountainous regions. Furthermore, runs initialized with the eta analysis were characterized with heavier amounts over the northwestern part of the domain than the runs initialized with LAPS analysis, while the amounts were lighter in the ARB area. For example, the location of the precipitation peak observed slightly southwest of Lake Tahoe was generally depicted by all model runs, but simulated amounts differed notably. The observed rainfall peak was characterized by a relatively large area of 15-mm amounts and a very limited area of 20 mm. The control configuration (Fig. 2a) had the peak displaced southward and the maximum amount was between 30 and 40 mm. Within the ARB area, the model run using the same configuration as the control configuration but initialized with the eta analysis had a very similar solution (Fig. 3a). The model runs using MPF (Figs. 2, 3b) simulated the location of the precipitation peak correctly but the amounts were too light (around 10 mm). The model run initialized with the LAPS analysis and using MPW (Fig. 2c) produced a very similar solution to the control configuration, except that the peak amounts were not as excessive. On the other hand, the model run using MPW but initialized with the eta analysis (Fig. 3c) was characterized with a large underprediction (5 mm). The MPT run initialized with the LAPS analysis simulated the peak location and the amount very well, while the MPT run initialized with the eta analysis was too light. A similar type of behavior among runs using different microphysics was frequently observed, such as the MPL microphysics tendency to simulate more rain compared to other microphysics.

2) Quantitative results

The factor separation methodology was applied to 6-h simulations valid at 0600, 1200, 1800, and 2400 UTC. Figure 4 illustrates changes in 24-h accumulated rain volume (obtained by adding up 6-h simulations averaged over all cases) due to individual changes in physical schemes, as expressed by $(f_x - f_0)$ or $(f_y - f_0)$, and due to synergistic interactions between 2 physical schemes, as expressed by f^*_{xy} in Eq. (1). Values in Fig. 4 are expressed as relative percentages of the control

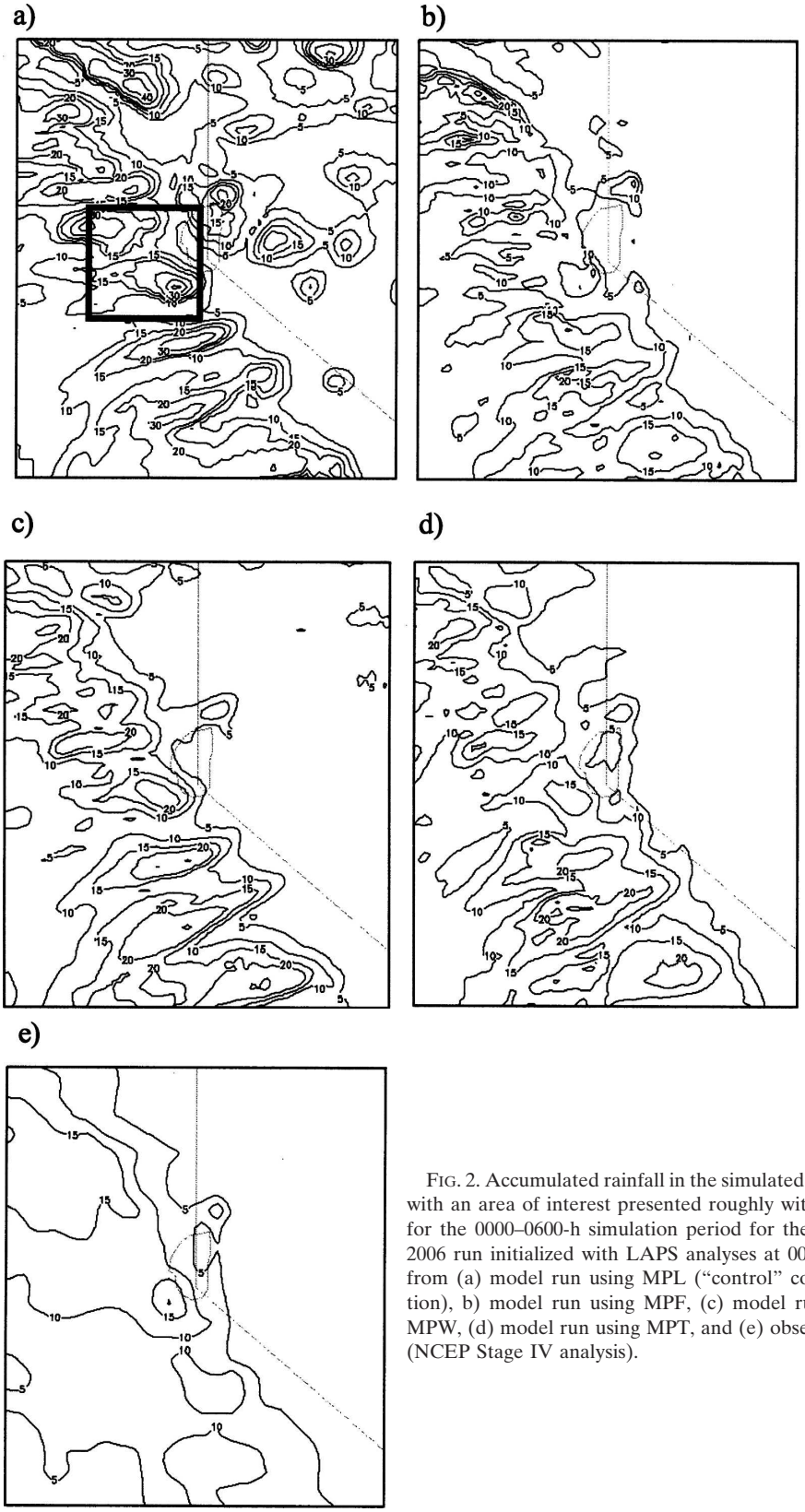

FIG. 2. Accumulated rainfall in the simulated domain, with an area of interest presented roughly with a box, for the 0000–0600-h simulation period for the 27 Feb 2006 run initialized with LAPS analyses at 0000 UTC from (a) model run using MPL ("control" configuration), b) model run using MPF, (c) model run using MPW, (d) model run using MPT, and (e) observations (NCEP Stage IV analysis).

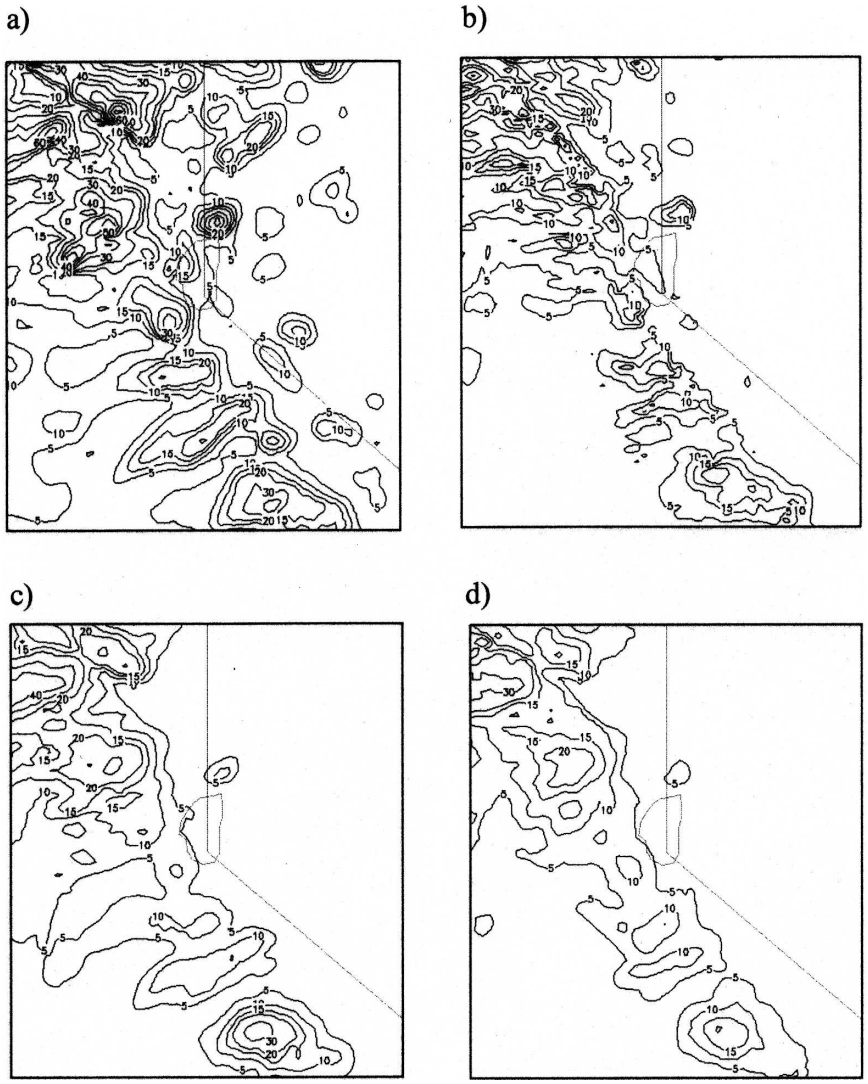

FIG. 3. As in Fig. 2, except for the model runs initialized with the eta analysis.

configuration (MPL-YSU). The results indicate that all changes in microphysics [from MPL (f_0) to MPF (f_1), MPW (f_2), and MPT (f_3)] resulted in a simulated rain volume decrease for both initial conditions, while the opposite was indicated when changing the PBL schemes. Synergistic terms, which correspond to the interactions between different microphysics and the ETA PBL scheme (f_4), were generally small. For runs initialized with LAPS analyses, a decrease in simulated rainfall due to changes in microphysics should have a positive impact on the overall simulation skill because the model runs using MPL were characterized by a large rain volume over prediction (Table 2). On the other hand, results in Table 2 show that the opposite would be expected for runs initialized with eta analyses.

Results from statistical significance testing are presented in Table 3. Based on the fact that the cutoff for statistical significance is arbitrary, results that were characterized by a 95% confidence level and higher in the present study are considered to be statistically significant. Table 3 indicates that for both initializations, changing from MPL to MPF and to MPT had a statistically significant impact on simulated rain volume with a confidence level higher than 95%. A decrease in simulated rain volume due to a change from MPL to MPW did not appear to be statistically significant (p values of 0.16 and 0.12 for runs initialized with LAPS and eta analyses, respectively).

For both initial conditions, a change from YSU to ETA produced a positive, relatively large but not statistically significant impact on simulated rain volume (with p values of 0.72 and 0.16 for runs initialized with

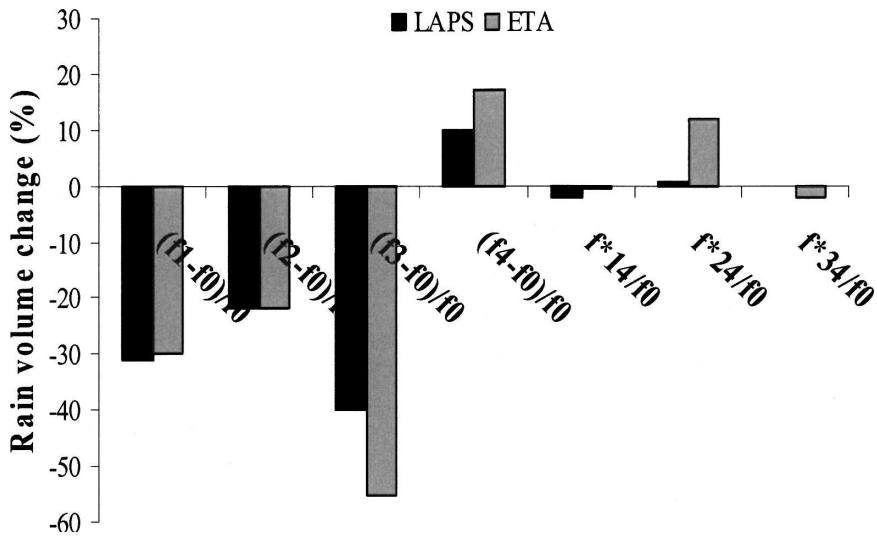

FIG. 4. 24-h (based on four 6-h simulations averaged together) percentage changes in ARB rain volume, averaged over 4 cases, due to physics changes (f_1 represents simulated rain volume from MPF-YSU run, f_2 represents simulated rain volume from MPW-YSU, f_3 represents simulated rain volume from MPT-YSU, and f_4 represents simulated rain volume from MPL-ETA run) for two different initializations (LAPS and eta). Here f_0 represents simulated rain volume from the "control" configuration (MPL-YSU). Here f^*_{14}, f^*_{24}, and f^*_{34} represent synergistic terms that correspond to the interactions between MPF, MPW, and MPT with ETA, respectively.

LAPS and eta analyses, respectively). This relatively large impact on simulated rain volume might be related to the fact that the ETA PBL scheme tends to simulate PBLs that are too moist and too shallow (Bright and Mullen 2002; Jankov et al. 2005). In other words, the choice of the PBL scheme can substantially affect temperature and moisture profiles in the lower troposphere, which could interact with the microphysics to influence the simulation of precipitation. In addition, this relatively large increase in simulated rain volume due to a change from YSU to ETA was especially evident in runs initialized with eta analyses.

Interactions between MPF and MPT microphysics with the ETA PBL scheme resulted in a rather small negative impact on simulated rain volume for both initializations. On the other hand, the interaction between MPW and ETA PBL schemes had a relatively large positive impact on simulated rain volume, at least for runs initialized with eta analyses. The relatively large and positive synergistic term, which corresponds to the interaction between MPW microphysics and the ETA PBL scheme, indicates that the decrease in simulated rain volume associated with the change from MPL to MPW might be largely reduced when the ETA PBL scheme is used instead of the YSU scheme. Still, none of the synergistic term magnitudes was large enough to be characterized as statistically significant.

In addition, a more detailed analysis of the impact on

TABLE 2. Rain volume over the ARB area calculated from Stage IV analyses and from the "control" configuration simulations initialized with both LAPS and eta analyses.

ARB rain volume ($\times 10^9$ m^3)	Valid time (h) 06	12	18	00
Stage IV	4	5	12	9
"Control" configuration–LAPS	7	10	19	15
"Control" configuration–eta	3	4	9	9

TABLE 3. P values calculated for all physical changes (see Fig. 1 caption for details). Values presented in bold-underline and bold faces indicate results that are statistically significant at 99% and 95% confidence levels, respectively. The sign in front of the p values indicates if the change resulted in an increase or decrease in rain volume.

Term	Physical changes	LAPS	Eta-40 km
		p value	
$(f_1 - f_0)/f_0$	MPL to MPF	**−0.006**	**−0.004**
$(f_2 - f_0)/f_0$	MPL to MPW	−0.16	−0.12
$(f_3 - f_0)/f_0$	MPL to MPT	**−0.02**	**−0.005**
$(f_4 - f_0)/f_0$	YSU to ETA	+0.72	+0.16
	Synersgistic inetractions		
f^*_{14}/f_0	MPF–ETA	−0.11	−0.87
f^*_{24}/f_0	MPW–ETA	+0.29	+0.12
f^*_{34}/f_0	MPT–ETA	−0.31	−0.75

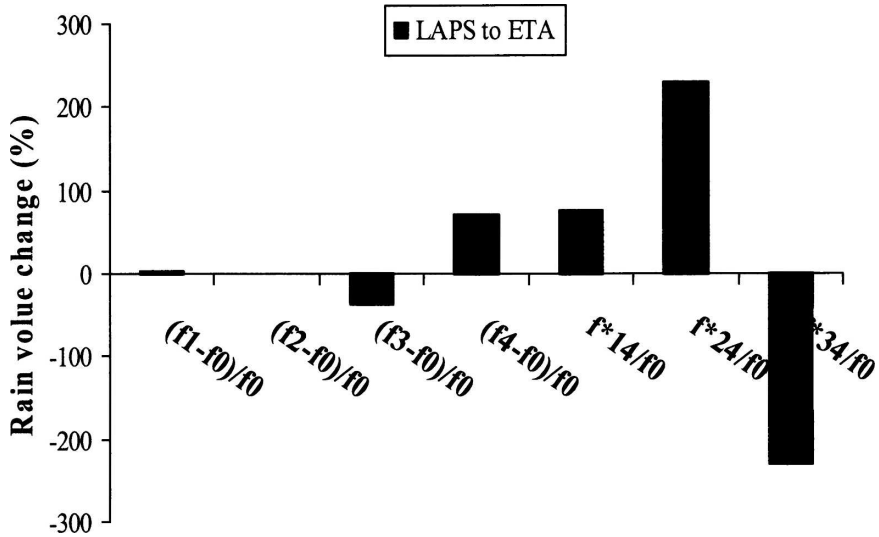

FIG. 5. As in Fig. 2, except for the change in rain volume due to change from the LAPS to eta initial conditions.

simulated rain volume due to changes in initial conditions was performed. For the same choices of physical schemes, the impact on simulated rain volume due to the change from the LAPS to eta analysis was evaluated. Similarly, as in Fig. 4, values in Fig. 5 represent relative percentages of the control configuration (MPL-YSU) when initial conditions were changed from LAPS to eta. As previously mentioned, by switching to the eta analysis, the change in the PBL scheme resulted in a much larger impact. Also, change in the initial conditions resulted in a notable impact on synergistic terms, much larger than any detected impact due to changes in physical schemes.

In terms of statistical significance testing (Table 4), changing from MPL to MPT under the variation in initial conditions resulted in a statistically significant (95% confidence level) decrease of rain volume. A change in the PBL scheme produced a statistically significant increase in rain volume with a confidence level of higher than 95%. With regard to synergistic terms, two out of three resulted in a positive, statistically significant (confidence levels higher than 95%) impact on rain volume. The only exception was the synergistic term related to the interaction between MPT and ETA, which resulted in a statistically significant (99% confidence level) decrease of rain volume.

3) ILLUSTRATIVE DIAGNSOTICS

The results generally point toward a large sensitivity of simulated rain volume to changes in microphysics from MPL to MPF and MPT for both initializations. On the other hand, for both initializations, changing from MPL to MPW did not affect simulated rain volume significantly. To learn more about the differences among the available microphysics options, a time series of volume integrals of water vapor and cloud matter and the area integral of precipitation for the American River basin were computed and then compared to the control configuration (Fig. 6). The integrated quantities do not constitute a complete water mass budget. Departures from that would include flux divergence across the volume boundaries, numerical (nonphysical) sources and sinks, and effects arising from changes to the integrated amounts incurred in the time between the formation of descending condensate aloft and its arrival at the ground. Assuming these processes are smaller than the three computed quantities, and considering that the detailed analyses of performance of different microphysics are beyond the scope of the present study, the time series illustrates some aspects of the various explicit precipitation algorithms.

The effect of changing from MPL to MPF decreased

TABLE 4. As in Table 3 except for the change in initial conditions from the LAPS to eta analysis.

Term	Physical Changes	LAPS to eta-40 km
$(f_1 - f_0)/f_0$	MPL to MPF	0.81
$(f_2 - f_0)/f_0$	MPL to MPW	0.92
$(f_3 - f_0)/f_0$	MPL to MPT	**−0.05**
$(f_4 - f_0)/f_0$	YSU to ETA	**0.002**
	Synersgistic interactions	
f^*_{14}/f_0	MPF–ETA	**0.002**
f^*_{24}/f_0	MPW–ETA	**0.0001**
f^*_{34}/f_0	MPT–ETA	**−0.0006**

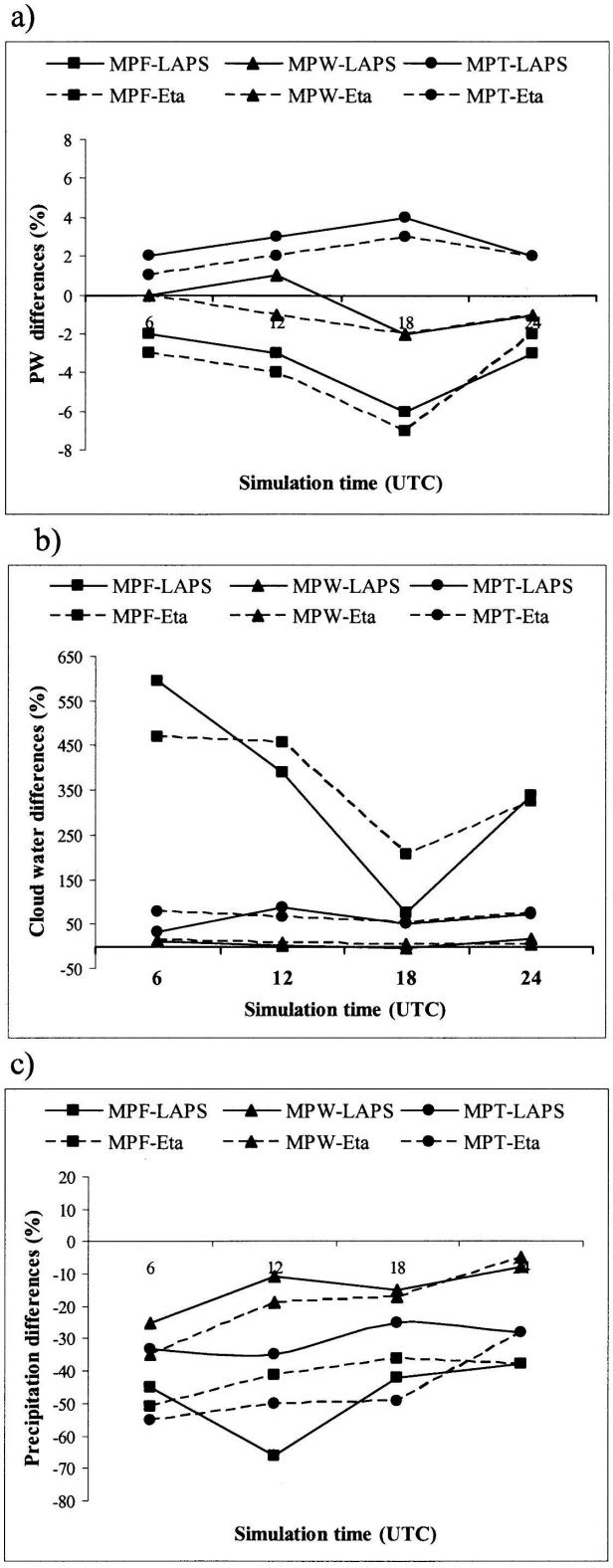

FIG. 6. Time series of differences in (a) precipitable water, (b) cloud water, and (c) precipitation between the "control" configuration and runs using MPF, MPW, and MPT. The results are averaged over 4 cases and presented in percentages as a relative fraction of the "control" configuration.

the precipitation, decreased the vapor, and greatly increased the cloud liquid. Changing from MPL to MPW resulted in slightly less precipitation, about the same vapor amount, and about the same cloud matter. Changing from MPL to MPT produced less precipitation but greater amounts of cloud and vapor. Taken together, these results indicate that for these cases, the MPF and MPT schemes produced less precipitation and more cloud matter than the MPL and MPW schemes, which is consistent with the results presented earlier. Indications were similar in runs with dry initialization (dashed lines) compared to diabatic initialization (solid lines).

b. Use of the factor separation methodology results in bias reduction

As previously discussed, the results from the factor separation method indicate that for both initializations, changes in microphysical schemes from MPL to MPF and MPT resulted in a statistically significant impact on simulated rain volume. The impact reduced the precipitation amount. Based on the fact that the control configuration almost always overpredicted the rain volume (Table 2), this negative impact on simulated rain volume due to changes in microphysics should have resulted in a better rain volume estimation.

The factor separation method results related to the variation in initial conditions showed that by switching from the LAPS to the eta analysis, the change from YSU to ETA resulted in a positive, statistically significant impact on rain volume. More importantly, under these conditions, the interaction between different physical schemes became important (statistically significant synergistic terms). Two out of three interactions (the interactions between ETA PBL and both MPF and MPW) resulted in a positive impact on simulated rain volume. Note that the model run using the control physical configuration (MPL-YSU) and initialized with the eta analysis was characterized with a slight underprediction of rain volume compared to the observations (Table 2).

Given these results, it was worthwhile to investigate if this knowledge about the impact that different initializations and physical schemes have on simulated rain volume can be used to reduce the large bias associated with the control configuration simulation. To test this, three different combinations of the model configurations were created based on the magnitude and the sign of the impact that different physical schemes and initial conditions had on the simulated rain volume, and the mean absolute error (MAE) was calculated. The three different configuration combinations included runs initialized with the LAPS analysis using MPT and

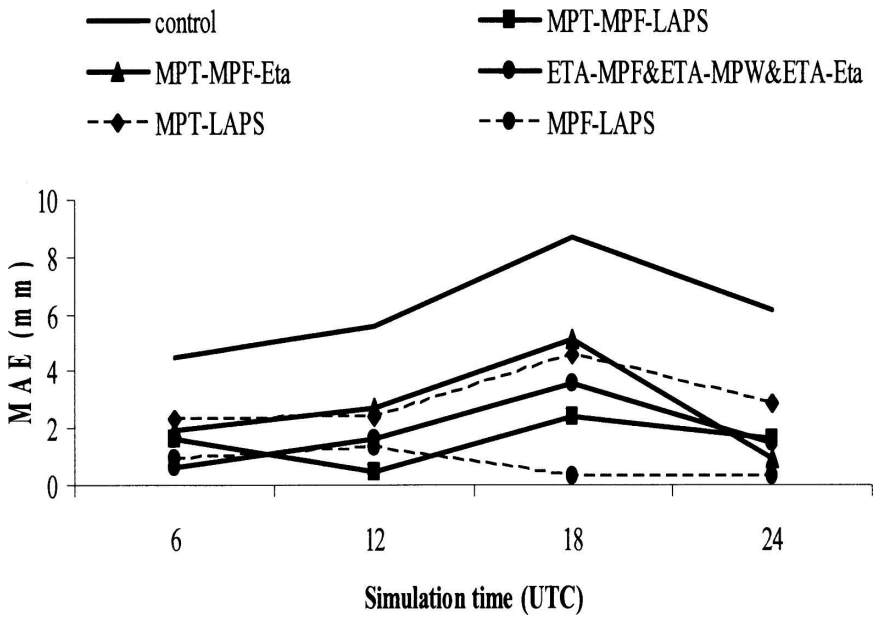

FIG. 7. Absolute error for four, 6-h simulation periods for the "control" configuration, the model runs using MPF and MPT, and mean absolute error for the three different model configuration combinations based on the results form the factor separation method.

MPF microphysics (MPT-MPF-LAPS), runs initialized with the eta analysis using MPT and MPF microphysics (MPT-MPF-eta), and runs using the ETA PBL scheme combined with three microphysics (MPL, MPF, and MPW) and initialized with the eta analysis (ETA-MPF&ETA-MPW&ETA-eta). Absolute error values for the control configuration and configurations using MPF and MPT, together with the MAE for the three combinations of runs, are presented in Fig. 7.

By merely changing the microphysical scheme from MPL to both MPF and MPT, the wet bias was notably reduced (dashed lines). Moreover, if the model runs using both MPF and MPT were combined, more variety in spatial scales would be obtained and the wet bias would still be notably reduced. The same logic could be applied for the third combination of the model runs initialized with the eta analysis. This may imply a potential use of the factor separation methodology in selecting members of mixed-physics and mixed-initial conditions ensembles for orographically induced rainfall forecasts in order to reduce the bias.

4. Summary and conclusions

To improve QPF, the present study quantified the impact of different initial conditions and various microphysical schemes and their interactions with different PBL schemes on the cold season, mainly orographically induced rainfall. The main focus of the study was on the improvement of rain volume over the ARB area in California, an area characterized by the high risk of flooding. For this purpose, high-resolution (3-km horizontal grid spacing and 32 vertical levels) WRF-ARW model simulations of four HMT events were performed. For each case four different microphysical schemes were used (MPL, MPF, MPW, and MPT) and two different PBL schemes (YSU and ETA). All runs were initialized with both the diabatic Local Analysis and Prediction System (LAPS) "hot" start and 40-km Eta Model analyses.

To quantify the impacts on simulated rain volume due to changes in initial conditions, microphysics, PBL schemes, as well as the interactions between the two different physical schemes (synergy), the factor separation method was used. For this purpose, the model run initialized with the LAPS analysis and using MPL and YSU was chosen as the "control" configuration. The factor separation method results indicated that for both initializations, the largest, negative, and statistically significant impact on simulated rain volume was due to changes from MPL to MPF and to MPT. Essentially, the factor separation results pointed toward a statistically significant difference in performance between MPL and both MPF and MPT schemes under these specific conditions. To investigate this in more detail, analyses of precipitable and cloud water tendencies over the area of interest for the four different microphysics were performed. The results showed that MPL

had a tendency to convert all available precipitable water into precipitation almost instantaneously, while both MPF and MPT tended to keep the majority of available precipitable water as supercooled water or snow. This was especially the case for MPF. With regard to MPW, its performance was very similar to the performance of MPL, which explains the lack of statistically significant differences of simulated rain volume between the two. It is noteworthy that the precipitable and cloud water tendencies were almost identical for the two different initial conditions. With regard to changes in initial conditions, by switching from the LAPS to the eta analysis, the change in the PBL scheme as well as all corresponding synergistic effects appeared to be statistically significant.

Furthermore, the factor separation results were used to investigate if the results of the impact of different initializations and physical schemes on simulated rain volume could be used to lessen a large bias associated with the control configuration simulation. Using the knowledge about the magnitude and sign of the impact that different physical schemes and initial conditions had on the simulated rain volume, three different combinations of model runs were created and the MAE was calculated. The results showed a decrease in MAE for the model combinations that were judiciously selected. These results may imply a potential for bias reduction when using the factor separation methodology to select members of mixed-physics and mixed-initial conditions ensembles for orographically induced rainfall forecasts.

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