Understanding the impact of dam-triggered land use/land cover change on the modification of extreme precipitation

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[1] Two specific questions are addressed in this study regarding dams (artificial reservoirs). (1) Can a dam (artificial reservoir) and the land use/land cover (LULC) changes triggered by it physically alter extreme precipitation? The term extreme precipitation (EP) is used as a way of representing the model-derived upper bound of precipitation that pertains to the engineering definition of the standard probable maximum precipitation (PMP) used in design of dams. (2) Among the commonly experienced LULC changes due to dams, which type of change leads to the most detectable alteration of extreme precipitation? The American River Basin (ARW) and the Folsom dam were selected as a study region. Four scenarios of LULC change (comprising also various reservoir surface areas) were analyzed in a step by step fashion to elucidate the scenario leading to most significant impact on EP. The Regional Atmospheric Modeling System (RAMS, version 6.2) was used to analyze the impact of these LULC scenarios in two modes. In the first mode (called normal), the probable precipitation pattern due to each LULC scenario was identified. The second mode (called moisture-maximized), the PMP pattern represented from a 100% relative humidity profile was generated as an indicator of extreme precipitation (EP). For the particular case of ARW and Folsom dam, irrigation was found as having the most detectable impact on EP (a 5% increase in 72 h total for the normal mode and a 3% increase for the moisture-maximized mode) in and around the ARW watershed. Doubling the reservoir size, on the other hand, brought only a small change in EP. Our RAMS-simulated results demonstrate that LULC changes driven by dams can, in fact, alter the local to regional hydrometeorology as well as extreme precipitation. There is a strong possibility of a positive feedback mechanism initiated by irrigated landscapes located upwind of orographic rain producing watersheds that are impounded by large dams.

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1. Introduction

[2] Dams are large physical barriers constructed across rivers to withhold the flow of river water. The inundated area behind them creates an artificial lake or reservoir [*Oxlade*, 2006]. The storage of large volumes of water retained by dams and reservoirs (hereafter *dams* will be used interchangeably with *artificial reservoirs*) has long been used for various purposes, some of which include hydropower generation, irrigation, flood control and recreation [*Gleick*, 2009]. Dams have always been an important component of human civilization and with an ever increasing population, the demand for new dams or continuing the operation of aging dams in the future is inevitable. In the United States alone, there are a reported 75,000 dams serving different purposes and with a capacity of storing on an average 1 year of runoff volume [*Graf*, 1999].

[3] Although the societal benefits gained from dams are immense, there exists a risk, particularly in the downstream, that needs to be addressed for public safety and infrastructure resilience. While some might argue that dam construction has reached the stage where the risk of structural failure is now almost nonexistent, studies continue to suggest that failures related to extreme hydrologic events (e.g., overtopping or unscheduled opening of spillways) still continue to occur [*Saxena*, 2005]. During its lifespan, a dam is expected to be subjected to varying magnitude of heavy rainfall events and floods. The conventional engineering approach underlying dam design requires that the observed magnitude of a flood encountered should not exceed the design flood event called the probable maximum flood (PMF) that would occur due to a probable maximum precipitation (PMP) event [*National Research Council* (*NRC*), 1985].

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[4] There are uncertainties, however, regarding the standard methods used to estimate PMP [*Ohara et al.*, 2011]. First, PMP estimation procedures that are usually adopted in dam design are derived from a comprehensive database of historic storms records. Those records are assumed to be sufficient enough to represent the extreme storm that is probable from the maximum available moisture that is responsible for generating the storm. Second, values of PMP that are used for dam design are usually provided by a set of hydrometeorological reports (HMRs) which are arguably outdated and lack consideration of newer storm events in a changing climate [*Tomlinson and Kappel*, 2011]. Third, the conventional methods of PMP estimation involve the extrapolation of storms to accommodate the definition of a maximum precipitation amount that can occur physically. The problem associated with such conventional approaches is that the recorded extreme events in the predam era are extrapolated well further into the postdam era and the climatic conditions are assumed to be stationary over time [*Hossain et al.*, 2012]. The postdam, in particular, represents a case where the artificial reservoir and the associated anthropogenic changes in the vicinity may have altered the average hydrometeorological conditions of the region assumed stationary for PMP estimation using predam records. Such changes in the local water cycle have been cited as key reasons that violate the theoretical assumption of PMP exceedance probability of zero within the life time of dams [*Douglas et al.*, 2006; *Federal Emergency Management Agency*, 2004].

[5] Apart from the problems encountered in conventional PMP estimation techniques (A. T. Woldemichael and F. Hossain, Mesoscale meteorological modeling of land-atmosphere interaction for simulation of probable maximum precipitation for artificial reservoirs, submitted to *Atmospheric Research*, 2011), there is also a potential impact of the reservoir on the local climate triggered by atmospheric feedback mechanisms that may physically modify the extreme hydroclimatology of the region. Studies on this phenomenon require comprehensive observational and modeling assessments [*Degu et al.*, 2011; *Hossain et al.*, 2010; *Hossain*, 2010]. Previous studies on this respect include the work of *Degu and Hossain* [2012] that tried to investigate if dams alter the frequency of downwind precipitation through quantitative assessment of in situ precipitation records. The study concluded that depending on the specific climatic region, there have been systematic increases of precipitation frequency in the postdam era. In another study, *DeAngelis et al.* [2010] reported from observational records that irrigation in the Great Plains from the Ogallala aquifer had increased precipitation frequency downwind. Other studies indicate that the hydrometeorological variables like evaporation, precipitation and humidity are the first-order atmospheric descriptors to show an increase in the post dam period while temperature and wind speed may also show a gradual decrease [*Degu et al.*, 2011; *Yusuf and Salami*, 2009]. To identify the root causes of any postdam alteration, the various atmospheric and local-scale feedbacks need to be systematically broken down and analyzed in hierarchical fashion for any dam attribution study. As a first cut, it is thus crucial to investigate the key variations in the local climate that are observed in the postdam era (immediately after the construction of a dam) when compared to the predam era.

[6] Factors responsible for the changes in the postdam era manifest themselves over a long period of time since anthropogenic (human-induced) alterations around dams, particularly of the land surface, take place continuously after the commissioning of the dam. The immediate effect that is observed is that a previously dry landscape is instantly filled with the reservoir water. One direct influence of these artificial reservoirs is on the intensification of open water evaporation and the enhancement of moisture supply for precipitation. Recently, there have been studies reported that have traced the origins of heavy precipitation through the tracking of evaporated moisture [*Kunstmann and Knoche*, 2011; *Gangoiti et al.*, 2011a, 2011b]. Many such studies use the method of back trajectory analysis of precipitation recycling to identify the relative contribution of local evaporation to the local precipitation process [*Brubaker et al.*, 2001; *Dirmeyer and Brubaker*, 1999]. *Kunstmann and Knoche* [2011] reported up to an 8% open water evaporation contribution from the Lake Volta region of West Africa to the total precipitation in the region. Although it cannot be guaranteed that evaporated water will return back to the target region (i.e., an impounded watershed) all at once due to advection effects, a considerable amount may find its way back to the vicinity of the reservoir system. The seasonal and spatial variability of evaporation feedback to precipitation is also well documented in the works of *Eltahir and Bras* [1996]. They pointed out that there is, in fact, evaporation feedback on precipitation although it varies in geographical location, season of the year and the scale of analysis considered.

[7] There are many other changes that appear in the postdam era to constitute as anthropogenic land use and land cover (LULC) changes around the dams. All dams are constructed to serve a specific or multiple purposes. One such purpose is irrigation. The feedback mechanism between the presence of irrigation and the resulting modification (usually an enhancement) of precipitation is primarily due to the increased evapotranspiration [*DeAngelis et al.*, 2010; *Pielke and Avissar*, 1990; *Gero et al.*, 2006]. There is also an increased surface temperature gradient between the irrigated and nonirrigated surface that allows for more moisture transport and hence precipitable water [*Cotton and Pielke*, 2007; *Adegoke et al.*, 2007; *Ozdogan et al.*, 2010]. The contrast between the dry nonirrigated and wet irrigated land patches also initiate regional level circulations that help in the development of convective systems [*Chen and Avissar*, 1994]. There have been other studies that report the impact from irrigation on global climate [*Puma and Cook*, 2010].

[8] Urbanization can also be intensified in the vicinity of dams. Due to reduced risk of floods, the downstream area of dams become safer places to settle and expand development, hence accelerating the "urban sprawl" [*Seto et al.*, 2011]. Such a change leads to a detectable change in the surface properties of urban areas by increasing its roughness as compared to the prior undeveloped area [*Shepherd*, 2005]. With an increase in surface roughness, there is a slow near-surface wind that encourages convergence and assists in convective cell formation. Modified surface conditions due to urbanization also results in substantial modification to the surface Albedo. Moreover, emissions from industries, automobiles and buildings facilitate the formation of cloud condensation nuclei and can create the precipitation-conducive urban heat island (UHI) effect [*Marshall et al.*, 2004; *Lin et al.*, 2011; *Huff*, 1986; *Rosenfeld et al.*, 1995]. Because

urbanization, in many cases, is often sustained with the supply of impounded surface water from large dams, the potential urban-induced precipitation feedback effect in the vicinity of dams is a worthwhile topic to investigate.

[9] While we understand fairly well the impact of the local-regional impact on climate of the aforementioned LULC change scenarios (e.g., irrigation, urbanization), the implications with respect to large dams is not as well understood. Considering that dams are a ubiquitous phenomenon (almost a million plus around the world today), it is important to gain this understanding if the long-term operational resilience of the aging dam infrastructure of the U.S. and around the world is to be achieved. *Hossain et al.* [2012] have articulated that observational and modeling studies involving the presence (or absence) of large dams and their associated LULC change should be the key to understanding how the historical impact of dams on climate will play out in the future for better dam building and operations. What adds to the complexity of the problem are the combined effects that may aggregate or negate the individual LULC change-driven feedbacks. Thus, a major advantage of a hierarchical (step by step) investigation is to systematically "rank" each of these dam-triggered LULC-driven feedbacks in terms of precipitation modification. A numerical modeling approach to simulating the atmospheric feedbacks is the appropriate choice to investigate different feedback mechanisms due to its flexibility in setting up various scenarios pertaining to both LULC changes as well as perturbations in the prognostic atmospheric variables [*Niyogi et al.*, 2009; *Chang et al.*, 2009; Woldemichael and Hossain, submitted manuscript, 2011].

[10] Various numerical modeling approaches in the past have been implemented to investigate the effect of LULC changes. For example, regional models like RAMS (Regional Atmospheric Modeling system) have been used to model the effect of land use heterogeneities on the local climate, vegetation and stream flows on and near the impact areas [*Stohlgren et al.*, 1998; *Narisma and Pitman*, 2006; *Schneider et al.*, 2004; *Pielke et al.*, 1999; *Marshall et al.*, 2004). *Douglas et al.* [2006] investigated irrigation effects on the spatial and temporal variability of vapor and energy fluxes in India. Their study suggested that irrigation practice in the area has caused an increase in the vapor flux both in the summer and winter seasons. *Stohlgren et al.* [1998] reported that irrigated croplands are responsible for lower temperature and increase atmospheric moisture flux that ultimately result in local cooling and precipitation enhancement in adjacent regions.

[11] Numerical atmospheric models have recently been used in replicating the standard methods to estimate PMP. Most often, this is accomplished through perturbing the moisture terms in the initial and lateral conditions to represent the maximum possible precipitation amount (hereafter called *moisture maximization*) defined as PMP. For example, the moisture maximization adopted in the study made by *Cotton et al.* [2003] used RAMS and involved increasing the relative humidity to 90% at the lateral and boundary conditions up to the 500 mbar level. *Ohara et al.* [2011] implemented relative humidity maximization to a 100% level through the various pressure levels by using the fifth generation Penn State/NCAR Mesoscale Model (MM5). *Abbs* [1999] used RAMS to maximize moisture through increasing temperature fields in the model and tried to evaluate the assumptions underlying the standard PMP estimation methods.

[12] This study seeks answers to two specific science questions regarding dams and artificial reservoirs. (1) Can a dam (artificial reservoir) and the LULC changes triggered by it physically alter extreme precipitation? (2) Among the commonly experienced LULC changes due to dams, which type of change leads to the most detectable alteration of extreme precipitation? The study presents a systematic approach of moisture maximization through physical modeling and tries to prioritize the commonly observed LULC changes that are likely to have a detectable effect on the modification of extreme precipitation. The paper is organized in as follows: section 2 presents the study region. Section 3 presents the data and methodology used in the study. Section 4 discusses the findings. Finally, section 5 gives the conclusion and recommendations of the work.

2. Study Region

[13] The Folsom dam and reservoir on the American River was selected for this study. The dam is located 20 miles northeast of the city of Sacramento, California [*Ferrari*, 2005] (Figure 1). It is a concrete dam which was constructed in 1955. The reservoir impounds the American River above Folsom dam which is divided into three forks as North, Middle and South, and covers a watershed area of 4823 km^2 [*U.S. Army Corps of Engineers* (*USACE*), 2005]. The reservoir is multipurpose serving irrigation, water supply, power generation, flood protection and recreation. The design of Folsom dam was based on the records of storms from the 1905–1949 period [*Redmond*, 1997]. See Figure 1 for the elevation map for American River Watershed (ARW) and the Folsom dam.

[14] During the postdam era, the American River has experienced seven 3 day flows that have surpassed the maximum amount recorded in the design period of 1905–1949 [*Redmond*, 1997]. Such frequent exceedance resulted in a revised design return period of 500 years (assigned during the design phase) to a recent revision of 75–80 years [*Redmond*, 1997; *NRC*, 1999]. The recurring nature of such flooding episodes has put approximately $40 billion worth of Sacramento property downstream of the dam at high risk. For example, the 1997 flood damages that occurred in California and Nevada (due to a combination of atmospheric rivers and rain-on-snow effect) were estimated at more than $2 billion [*U.S. Geological Survey* (*USGS*), 1998]. Such undesirable flooding events have led to consideration of expensive remedial measures such as increasing Folsom dam storage capacity, increasing the levee capacity of Sacramento River and relocation of development further away from designated floodplain.

[15] There are a number of underlying hydrometeorological factors that have contributed to the flooding episodes such as the one observed during 1996–1997. One factor is the "rain on snow" effect that was deemed responsible for the melting of about 80% of the snow accumulated on the peaks of the Sierra Nevada. This rain on snow effect resulted in a rapid propagation of mountainous runoff downstream [*Horton*, 1997]. Another factor is that of Atmospheric Rivers (AR), which accounts for the advective transport of water vapor along highly concentrated streamlines [*Dettinger et al.*, 2012]. The ARs that typically extend over much of California

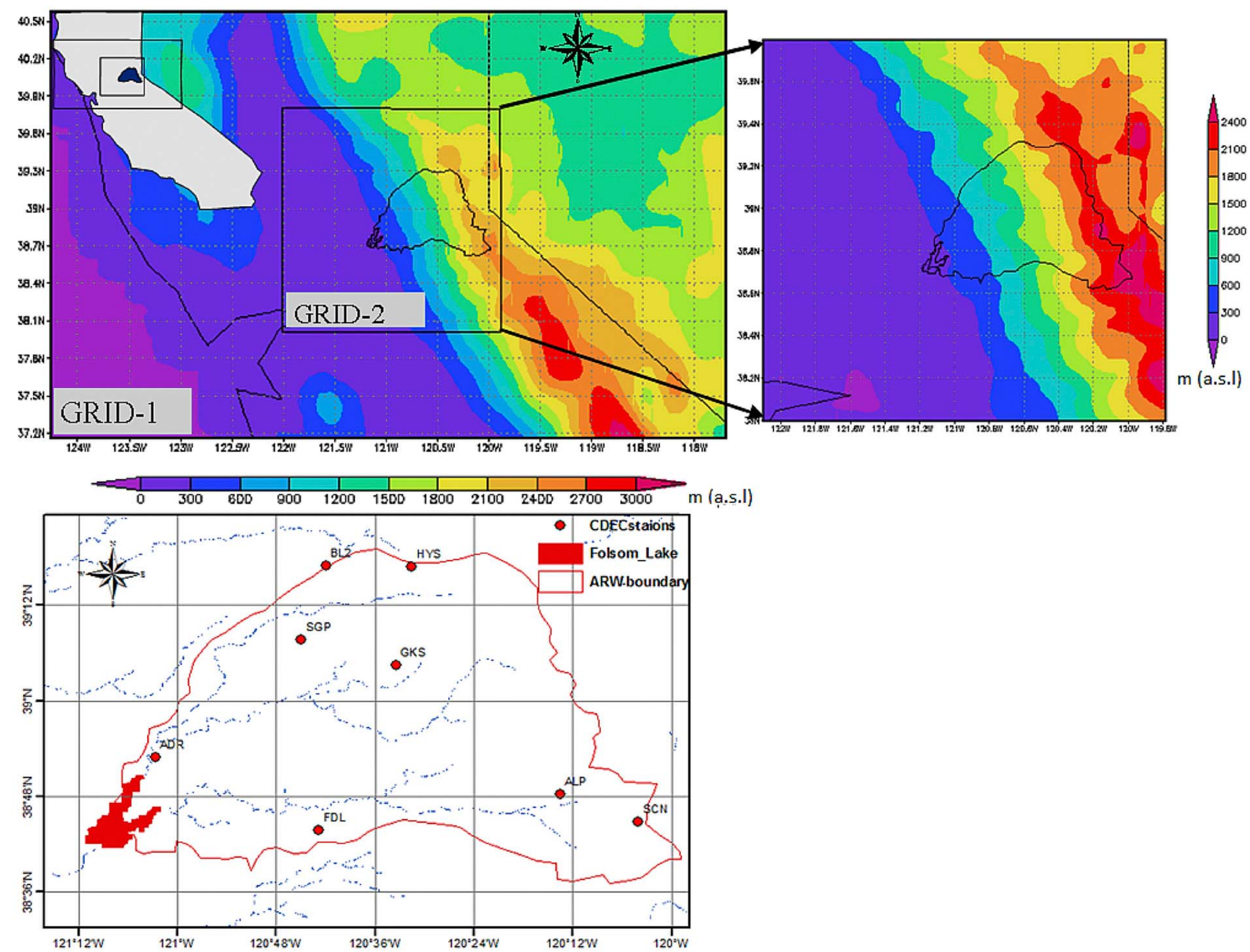

Figure 1. (top) Topography of the American River Watershed (ARW) for the two grids considered. (bottom) The locations of the eight CDEC stations around ARW.

during winter season originate in the Pacific Ocean. When assisted with strong wind, the moisture is transported and eventually precipitates inland as soon as it encounters the Sierra Nevada barrier. However, the likely effects of Folsom dam-triggered LULC changes on the modification of such damaging ARs have not yet been studied to the best of our knowledge. We therefore selected the 1996–1997 damaging storm event over the ARW as an ideal candidate for our study.

3. Data and Methodology

[16] The numerical model used for this study was the Regional Atmospheric Modeling System (RAMS version 6.0 [*Pielke et al.*, 1992]). RAMS is a three-dimensional, non-hydrostatic model developed based on the fundamental equations of motion, heat and moisture [*Pielke*, 2001]. It was developed with the intention of fostering research over mesoscale and regional, cloud as well as land-atmosphere interactions and regional level atmospheric phenomena [*Tripoli and Cotton*, 1982; *Tremback et al.*, 1985]. RAMS has demonstrated its capability in a range of applications that also involve mesoscale simulations of precipitation and precipitation forcings [*Abbs*, 1999; *Cotton et al.*, 2003; *Nicolini et al.*, 2002].

[17] Since ARW region is predominantly orographic with elevation differences between the highest and lowest points in the range of 2500–3000 m, the computational dimension required should suffice for steep topography and presence of orographic precipitation. This study utilized a nested grid configuration and all simulations were performed on the horizontal grid domain as shown in Figure 1. The coarser grid (Grid 1) consisted of 60 $\times$ 40 grid points at 10 km interval spacing and it covered much of the northern California, part of western Nevada and a small portion of the eastern Pacific Ocean. The nested grid (Grid 2) had 62 $\times$ 62 grid points spaced at 3.305 km interval and covered all of the ARW. Thirty vertical levels were assigned for both grids. A vertical grid spacing of 100 m at the ground was used with a vertical grid stretch ratio of 1.15 up to 1.5 km and kept constant from here on up to model top. A 20 s time step was used on course grid and a 5 s in the inner grid.

[18] The boundary values at the ground surface are provided by LEAF-3 land surface model. Accordingly, 11 soil layers have been used to represent surface fluxes of heat and moisture interaction of land with the atmosphere [*Walko et al.*, 2000]. The level 3 bulk microphysics parameterization was activated for mixing ratio and precipitation concentration prognosis. For the lateral boundary condition

parameterization, the Klemp and Wilhelmson scheme was used [*Walko and Tremback*, 2002]. The short- and long-wave radiative transfer parameterization was furnished through Harrington scheme [*Harrington*, 1997]. It is based on analysis of effects of radiative cooling or heating on the initiation of water and ice crystals in clouds. For cumulus-convective parameterization, the Kuo scheme has been adopted [*Kuo*, 1974]. Based on a nonsteady deep cumulus model, the scheme utilizes temperature gradient and large-scale moisture convergence as indicators for convective initiation. A more recent Kain-Fritsch (KF) scheme [*Kain and Fritsch*, 1993] uses a Lagrangian parcel method to detect occurrence of atmospheric instability that leads to the growth of cloud and initiation of convective precipitation. The reason for using the relatively older Kuo scheme for this study is based on the extensive work of *Castro* [2005] over North America which suggested that the KF scheme generally overestimated precipitation in steep topography regions even when nudging is not activated.

[19] RAMS requires two sets of data as an input: the first set represents the three-dimensional atmospheric variables for initial and boundary conditions as well as nudging, the other represents the surface characteristics data sets for land-atmosphere interaction. The main data source for the atmospheric variables was the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data [*Kalnay et al.*, 1996]. Surface characteristic data sets including the 30 s terrain height data, soil moisture at various levels from Food and Agricultural Organization (FAO), the Normalized Difference Vegetation Index (NDVI), sea surface temperature (SST) and LULC were obtained from the RAMS model distributers-Atmospheric, Meteorological and Environmental Technologies (ATMET) data archive (also available at http://www.atmet.com). Spatially distributed ground-based interpolated precipitation was obtained from PRISM (Parameter-elevation Regressions on Independent Slope Model) climate group's data archive (also available at http://www.prism.oregonstate.edu/). PRISM uses point measurements of precipitation and produces spatial estimates of monthly, yearly and event-based estimates of precipitation through a unique set of expert knowledge of complex climate extremes [*Daly et al.*, 1994]. Since the PRISM data sets are available at 4 km spatial resolution, which is close to the inner grid resolution considered for this study (3.305 km), it was used as reference for calibration and validation of the RAMS simulations. Point-based measurements of precipitation were obtained from the California Data Exchange Center (CDEC) daily rainfall gauges found within the ARW (Figure 1, bottom).

[20] Two land data archives have been used to reconstruct the reservoir as well as the various LULC scenarios. The first is the Historical Database of the Global Environment (HYDE; available at http://themasites.pbl.nl/en/themasites/hyde/index.html). HYDE presents gridded time series of land use for the last 12,000 years [*Klein Goldewijk et al.*, 2011]. Thus, these land data were useful in reconstructing the predam (1950s) land use scenario for RAMS domain. However, the HYDE data set contains uncertainties that urge it be used cautiously. Some of the uncertainties are that (1) good historic data (with sufficient temporal and spatial resolution) are difficult to find, (2) data are often only available in hard copies and hence requiring intensive digitizing, (3) frequently data are missing in time series that required an interpolation techniques that might have introduced more error and (4) there is a lack of representation of urban areas in the HYDE database. The other land data source was the MODIS-Land cover type-2 products with 14 class University of Maryland (UMD) classification (available at http://glcf.umiacs.umd.edu/). To make the LULC scenarios ready for RAMS ingestion, both land data sets (HYDE and MODIS-UMD) were reclassified to the Olson's Global Ecosystem (OGE) LULC classes, which is default for land use preparation in RAMS. The OGE reclassified classes for the various LULC considered scenarios are shown on Figure 2.

[21] Two broader categories were established in setting up LULC scenarios in ARW. The first category represented the *predam* condition which is assumed to represent the natural landscape before construction of the Folsom dam (Figure 2a). The second category represented the *postdam* conditions observed in the region. Since much of the anthropogenic changes are assumed to occur in the postdam period, this category is further divided into *control* (the existing LULC condition as of 2003 based on MODIS-UMD; Figure 2b); *reservoir double* (a case where the reservoir size is doubled from the control; Figure 2c); *nonirrigation* (representing a condition where all the observed irrigated landscape in control amounting to 11,291 km^2 in the inner grid is transformed to the nearby predam land use type; Figure 2d). The percentage coverage for each case and each LULC type is also provided in Table 1.

[22] The evaluation and comparison of LULC-driven feedbacks was carried out to test the following three scenarios. First, the *predam/postdam* scenario aimed at identifying the impact on precipitation pattern as a dam becomes functional. Because the storm pertained to 1996–1997 (by which time both Sacramento and irrigation experienced an increase in areal extent), this part of the analysis helped in understanding the combined effects of the presence of the reservoir, irrigation and enhanced downstream urbanization. Second, the *reservoir-atmosphere* feedback scenario aimed at identifying the effect of a changing reservoir size on the precipitation. Last, the *land-atmosphere* feedback scenario was investigated to identify the exclusive effect of downstream irrigation on extreme precipitation near dams.

[23] The modes of simulation were carried out in the following fashion: first, a two month simulation (December 1996 to January 1997) was performed on a single grid for the purpose of calibration and validation with the selected configuration. Second, an hourly simulation that involved both the *normal* conditions as well as *moisture-maximized* cases was performed for all the selected LULC scenarios. Here, the normal simulations represent the existing condition where the atmospheric variables are unperturbed, whereas the moisture-maximized systematically perturbs the relative humidity term to represent the maximum moisture in the planetary boundary layer to a value of 100%. The purpose of moisture maximization was to generate the maximum possible precipitation that is commonly called PMP in engineering design protocols since the intended goal of our study is to investigate the implications on dam design and operations. Hereafter, it should be stressed that the subsequent results of model simulation will use the term Extreme

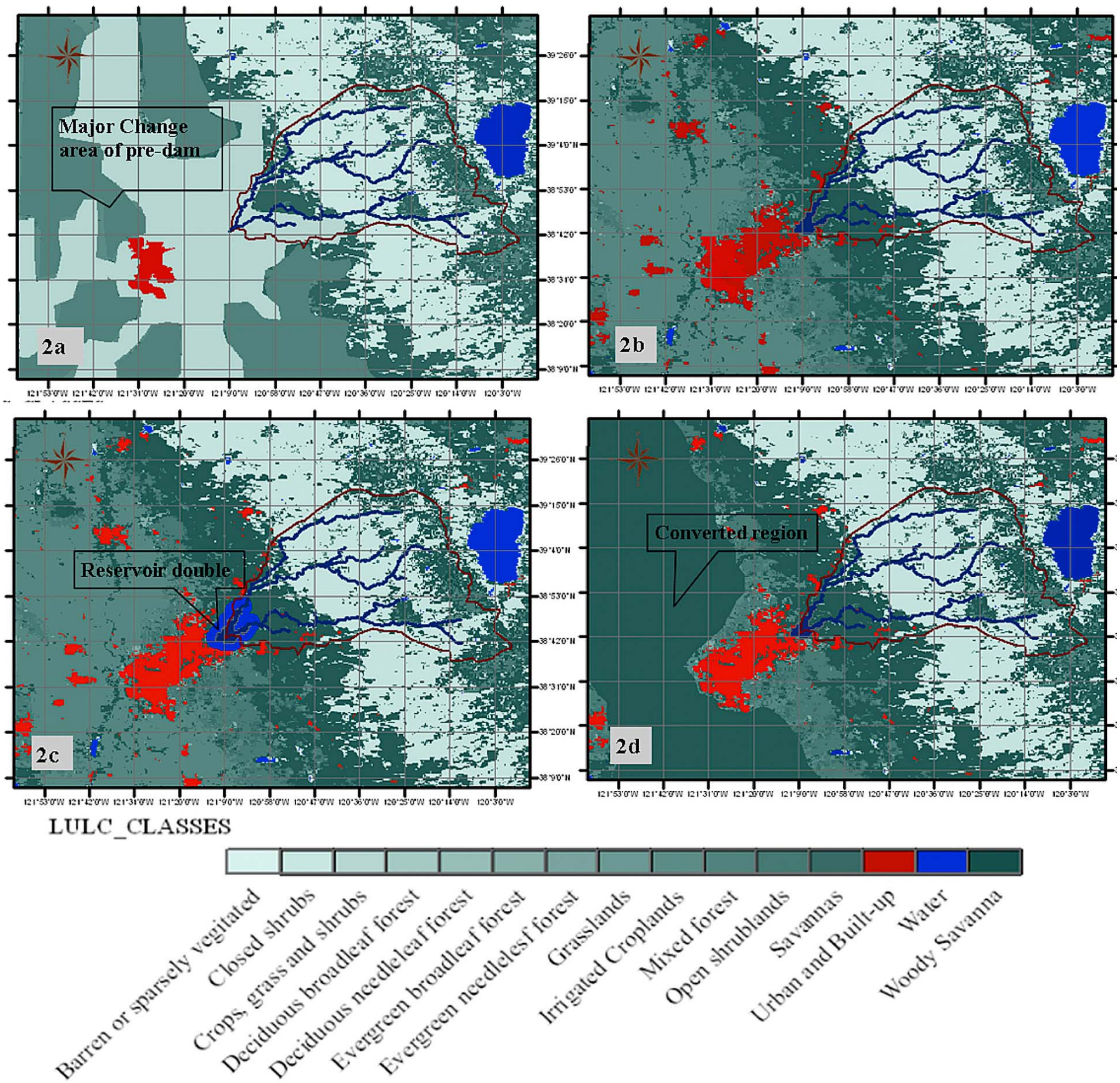

Figure 2. The OGE reclassified classes for the considered scenarios: (a) for predam, (b) for the control, (c) for reservoir double, and (d) for the nonirrigation cases.

Precipitation (EP) as a distinction from PMP obtained from the standard engineering methods.

4. Results and Discussion

4.1. RAMS Calibration and Validation

[24] Based on the configurations mentioned in section 3, a run was initiated for the whole period of December 1996 to January 1997. Monthly averaged values of precipitation were computed for the purpose of comparison with the PRISM gridded precipitation values. Figure 3 shows the spatial distribution of the RAMS simulated versus the PRISM precipitation fields for both months. Figure 3 shows that RAMS is capable of capturing the important features of precipitation characteristics (i.e., orographic precipitation) in ARW. Figure 4 shows the point-based results of RAMS-simulated and observed precipitation values from seven CDEC in situ gages. It is evident that even at the point scale, RAMS is able to simulate the trends in precipitation fairly consistently at various locations within the ARW and greater model domain.

[25] To test the robustness of RAMS simulation, a perturbation sensitivity experiment was performed for a 5% change (both increase and decrease) in the wind speed and absolute humidity during initial conditions. The goal was to identify if the inherent “precision” or “noise” level of RAMS simulated precipitation could be larger than the signal due to each

Table 1. Percentage Coverage of the LULC Classes in Each of the Considered Scenarios

LULC Class Name	Percent Area (%)			
	Predam	Control	Reservoir Double	Nonirrigation
Urban and built up	1.18	3.83	3.71	3.73
Evergreen neddleleaf forest	26.75	27.69	27.67	27.44
Deciduous neddleleaf forest	0.79	0.84	0.84	0.81
Deciduous broadleaf forest	0.002	0.002	0.002	0.002
Evergreen broadleaf forest	0.002	0.002	0.002	0.002
Closed shrubs	0.27	0.892	0.855	0.71
Water	0.26	1.79	2.55	1.69
Mixed forest	1.43	0.81	0.81	0.77
Irrigated Croplands	0.68	21.42	21.37	2.77
Grasslands	25.16	8.23	8.22	7.34
Savannas	2.56	1.91	1.90	1.73
Barren or sparsely vegetated	0.33	0.06	0.06	0.04
Woody savanna	17.94	31.80	31.31	52.28
Open shrublands	0.65	0.68	0.68	0.67
Crops, grass and shrubs	22.12	-	-	0.001

LULC scenario. We found that sensitivity experiments generated similar values of precipitation as that of the unperturbed simulations shown in Figure 4.

4.2. Evaluation of RAMS Simulation for LULC Feedback Scenarios

[26] This section presents the simulation results of precipitation for the various feedback scenarios outlined in section 3. According to U.S. Army Corps of Engineers, a 72 h precipitation magnitude is considered the standard period for determination of a flood magnitude in ARW [*USACE*, 2005]. Given our broader goal of understanding implications on dam design and operations, we chose to analyze rainfall patterns as 72 h totals.

[27] Historically, extreme storm events and floods were observed in the ARW as far back as in the 1850s [*Ohara et al.*, 2011]. In the 19th century, the maximum 72 h precipitation totals were estimated in the range of 323 mm to 373 mm [*Roos*, 2003]. There were also estimates of the 72 h totals for ARW during the 1996–1997 storm episode. *USACE* [2005] estimated this value to be 285 mm while *Roos* [2003] estimated it to be 328 mm. *Ohara et al.* [2011] also found a value of 330 mm by using the Fifth Generation Mesoscale Model (MM5) for the same region and storm episode. The 72 h accumulated CDEC estimate also yielded a value of 255 mm. Since all these estimates were made based on ground observations, the variability in the estimates can be attributed to the areal averaging technique used as well as the selection of rain gauges [*Ohara et al.*, 2011]. Records of standard PMP estimates over ARW were also available from these sources. The first 72 h PMP value for the basin was published in HMR-36 in 1961, and its estimate was 800 mm [*U.S. Weather Bureau* (*USWB*), 1961]. A recent study done by *USACE* [2001] with consideration of orographic effects "improved" this value to be 752 mm. These values were found to be more than double of that of the historical 72 h maximum values area averaged over the AR watershed domain.

[28] All simulations for this study were started on 15 December 1996 at 00:00 UTC and ended on 5 January 1997 at 00:00 UTC. The atmospheric fields were updated every 6 h based on NCEP/NCAR and a four-dimensional data assimilation (4DDA) was activated to nudge the simulated values to the observed ones and avoid undesirable model noise and drift. The accumulated precipitation amount for the control case and the 72 h moving totals both for the normal and moisture-maximized were computed as shown in Figure 5. The maximum 72 h precipitation total was found to be ∼264 mm and it occurred on 1/2/97 at 17:00 UTC. This value is close to the USACE and CDEC estimates but is smaller than the estimate reported by *Roos* [2003]. The 72 h EP (as a distinction to the PMP of the standard methods) obtained by the moisture maximization procedure was ∼354 mm (a 34% increase from the normal case). Sections 4.2.1–4.2.3 present the evaluation of the various LULC feedback scenarios with respect to control (current scenario of the Folsom dam) for normal and moisture-maximized simulations. It is also important to note that unless otherwise specified, all computations of the maximum 72 h moving sums have been performed over the ARW domain (inner Grid).

4.2.1. The Predam/Postdam Hypothesis

[29] Most anthropogenic changes around dams are prominent once the dam becomes functional. Hence, it is essential to investigate the conditions after the dam (the postdam represented by the control case) and compare it to the initial undisturbed conditions before (predam) in terms of LULC changes. According to the HYDE classification, the 1950s land use indicates the predominance of croplands and sparse vegetation on the downstream area of the Folsom dam (Figure 2d), while much of the upstream areas remained unaffected due to steep terrain near the Sierra Nevada. The urban and built-up area that is evident from Figure 2a is absent in the predam era. Figure 6 shows the accumulated precipitation and the 72 h moving totals for both normal and moisture-maximized of the predam. The maximum 72 h total for the predam is found to be about 257 mm; while the EP, after moisture maximization is found to be around 346 mm. These values show a 7.0 mm (∼3%) and a 7.7 mm (∼2%) decrease in the 72 h precipitation total from the control for both the normal and maximized runs, respectively.

[30] Generally, the decrease in the precipitation amount agrees with the conclusions drawn by *Yusuf and Salami* [2009]. These decreases, however, are bounded within the basin since the initial objective was to analyze modifications on the extreme precipitation (EP) within the ARW. Since atmospheric models do not necessarily acknowledge watershed boundaries, there perhaps are changes observed in the nearby areas of the watershed that need further inspection even though they do not reflect on the EP estimation. Figure 7 shows the difference between precipitation of the control and the predam for the normal cases of simulation. Wind vectors overlain on the precipitation difference of the coarser grid show that the predominant wind is seen to originate from the southwest on the windward side of the Sierra Nevada. From Figure 7, the lower elevation areas around the dam and on the downstream seem to experience an increase in precipitation from the predam within a range of 10–50 mm in small isolated pockets. Along the Sierra Nevada on the leeward side of the mountain, a decrease in the range of 20–50 mm is observed. It is also noted that there is a large decrease in the control relative to the predam on the windward side of the mountain.

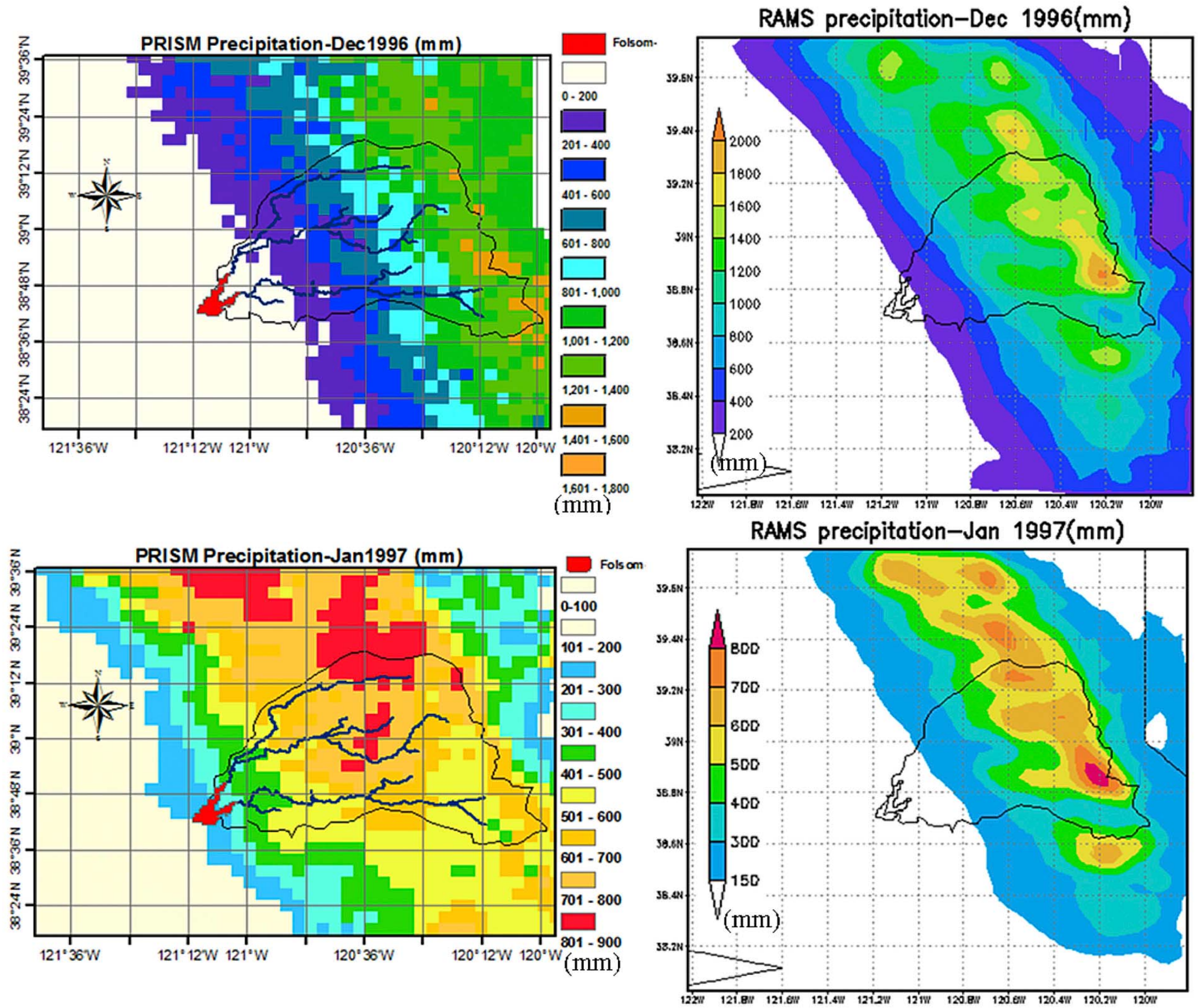

Figure 3. Comparison of simulated RAMS monthly basin-averaged precipitation fields in mm and PRISM data over the simulation domain covering larger area than ARW (top) for December 1996 and (bottom) for January 1997.

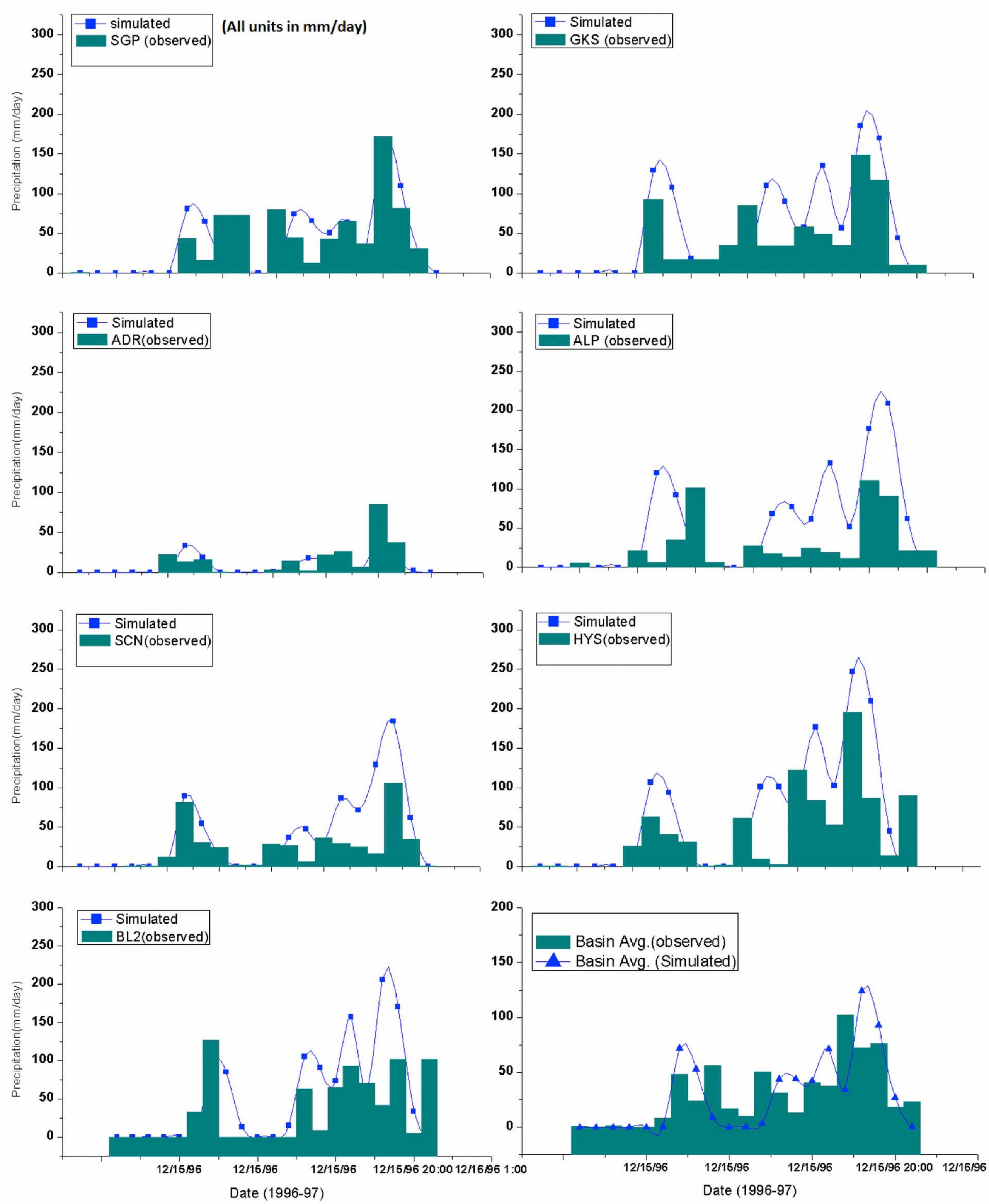

Figure 4. Comparison of observed and simulated daily precipitation (mm/d) at the CDEC stations and the daily basin-averaged precipitation over ARW extent during 1996–1997 storm event.

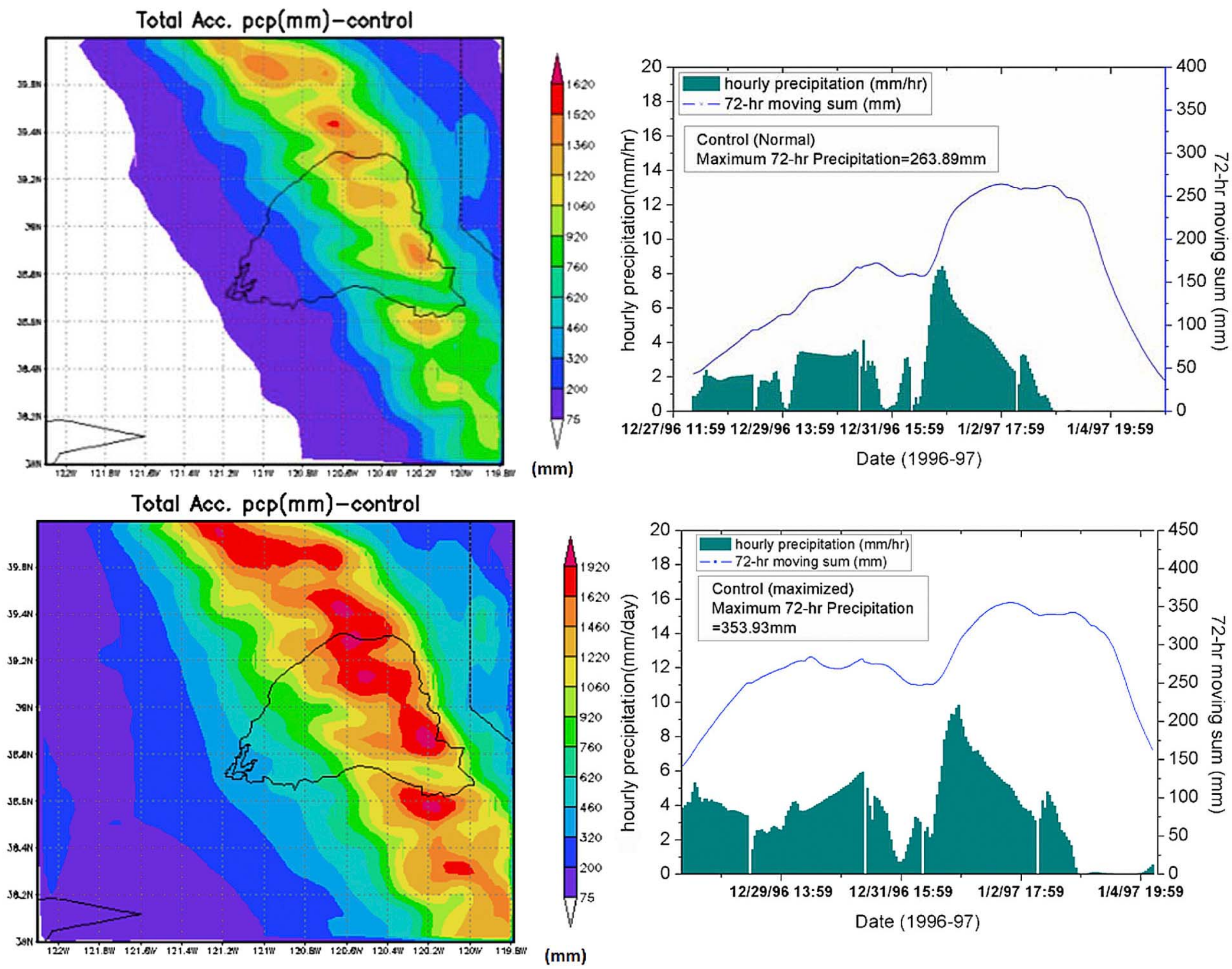

Figure 5. (left) Total accumulated precipitation (mm) for the control case and (right) hourly precipitation and the 72 h moving sum over the ARW and for both (top) normal and (bottom) moisture-maximized cases. Simulation period spans from 15 December 1996 to 5 January 1997.

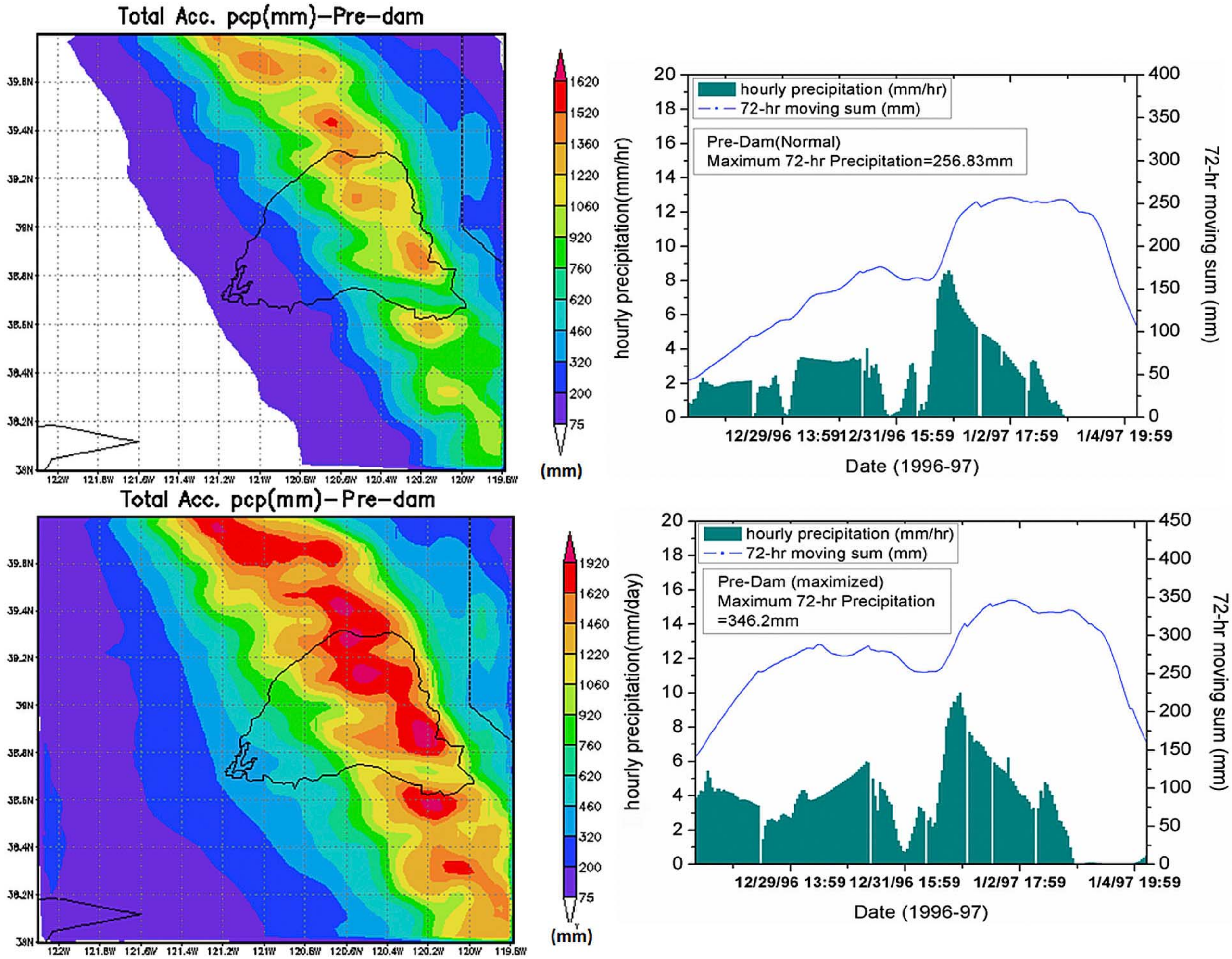

Figure 6. (left) Total accumulated precipitation (mm) for the predam case and (right) hourly precipitation and the 72 h moving sum over the ARW and for both (top) normal and (bottom) moisture-maximized cases. Simulation period spans from 15 December 1996 to 5 January 1997.

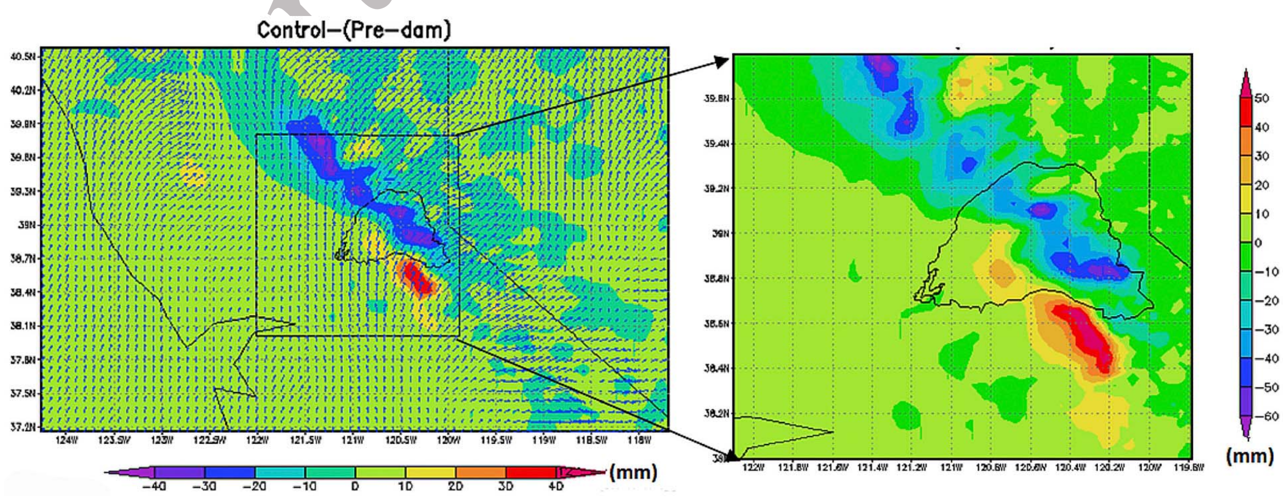

Figure 7. Difference between total accumulated precipitation of the control and the predam for the normal cases of simulation along with the average wind on the 800 mbar level for the coarser grid.

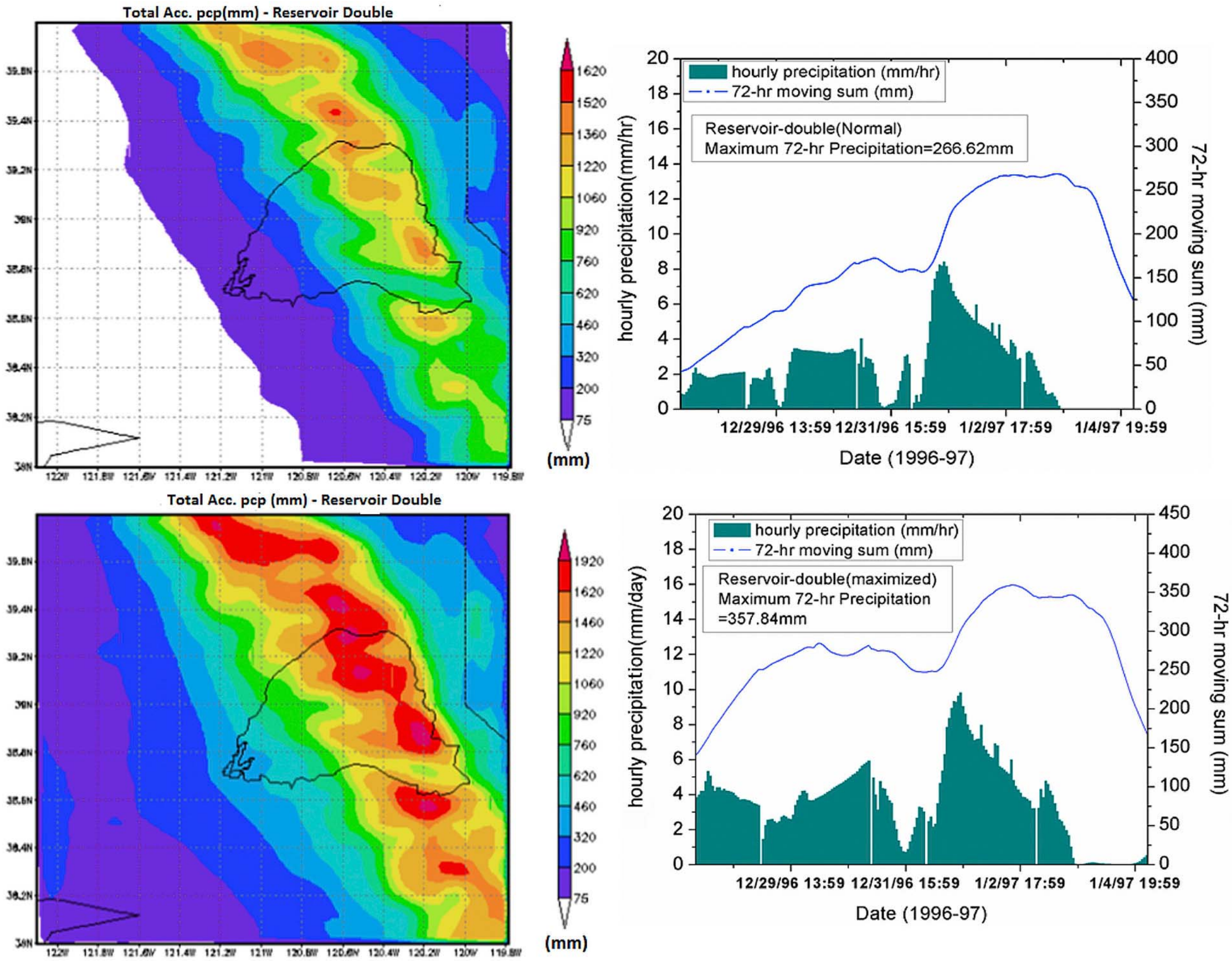

Figure 8. (left) Total accumulated precipitation (mm) for the reservoir double case and (right) hourly precipitation and the 72 h moving sum over the ARW and for both (top) normal and (bottom) moisture-maximized cases. Simulation period spans from 15 December 1996 to 5 January 1997.

4.2.2. Reservoir-Atmosphere Feedback Hypothesis

[31] Section 4.2.1 indicates that the presence (or absence) of an artificial reservoir can have an impact on the precipitation pattern. A question worthwhile to investigate is how sensitive is this impact to the surface area of the reservoir? The reservoir size was doubled from the control case in terms of surface area (i.e., *reservoir double*) keeping in mind the engineering feasibility of doing so with respect to topographic and hydrological limitations. Our terrain analysis shows that a doubling of the lake area is practical although it may not be economically viable. Figure 8 shows the accumulated precipitation and the 72 h moving totals both for the normal and moisture-maximized cases of the reservoir double. The 72 h maximum precipitation for the normal case was found to be ~267 mm (Table 2), while the EP after moisture maximization was ~358 mm (Table 3). These values show a 2.73 mm (~1%) and a 3.91 mm (~1.1%) increase in the 72 h precipitation amount from the control for both the normal and maximized runs respectively. The spatial difference between the amount of generated precipitation for both the control and reservoir double cases is shown in Figure 9, where the maximum

Table 2. Summary of the 72 h Maximums for the Four Cases (Normal Case)

Run Type	Maximum 72 h Precipitation (mm)	Difference From Control (mm)	Percent Increase/ Decrease From Control
Control	263.89	-	-
Reservoir double	266.62	−2.73	1.035% increase
Nonirrigation	249.72	14.17	5.37% decrease
Predam	256.83	7.06	2.66% decrease

Table 3. Summary of the 72 h Maximums for the Four Cases (Moisture-Maximized Case)

Run Type	Maximum 72 h Precipitation (mm)	Difference From Control (mm)	Percent Increase/ Decrease From Control
Control	353.93	-	-
Reservoir double	357.84	−3.91	1.105% increase
Nonirrigation	343.51	10.42	2.94% decrease
Predam	346.20	7.73	2.18% decrease

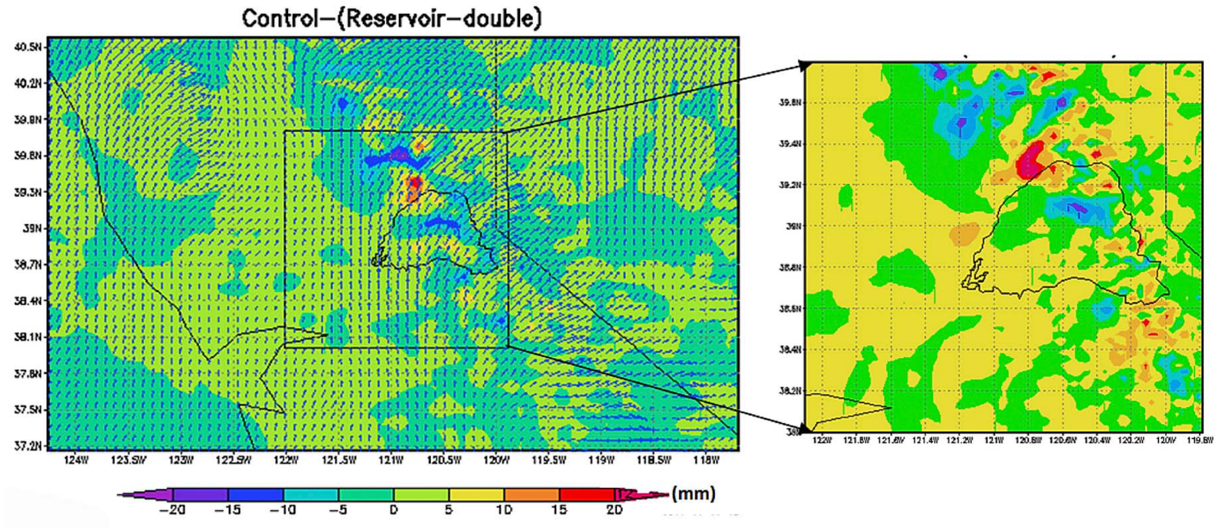

Figure 9. Difference between total accumulated precipitation of the control and the reservoir double for the normal cases of simulation along with the average wind on the 800 mbar level for the coarser grid.

difference is seen to be in the range of 20 mm (increase with reservoir double) at some locations.

[32] In general, it seems that the size of the reservoir surface area does not significantly affect the precipitation modification. This perhaps is due to the fact that the contribution of open water evaporation from reservoirs in the precipitation forming mechanism around ARW is insignificant compared to other moisture sources, such as atmospheric rivers [*Dettinger et al.*, 2012]. However, given that there were differences of up to 20 mm at isolated locations, the hydrologic implication of this scenario should be studied with the aid of a fully distributed hydrologic model.

4.2.3. Land-Atmosphere Feedback Hypothesis

[33] In this section, the irrigation effect as part of the land use change feedback to precipitation modification was investigated. Existing LULC in the nearby regions of ARW already indicated that there is extensive irrigation covering a large area downstream. In order to analyze the irrigation contribution, the already existing irrigated region was replaced by the nearby predominant land cover type (in this case woody savanna) with the assumption that this land cover was transformed to irrigated agriculture with the operation of the Folsom dam. This scenario is hereafter called the nonirrigation case. Results of the accumulated precipitation and the 72 h moving totals for both normal and moisture-maximized cases of the nonirrigation scenario are shown in Figure 10. The 72 h maximum precipitation for the normal case was found to be ~250 mm; while the EP after moisture maximization was ~344 mm. These values reveal a 14.17 mm (~5%) and a 10.42 mm (~3%) decrease in the 72 h precipitation amount from the control for both the normal and maximized runs, respectively. This clearly implies that the presence of irrigation has increased the amount of precipitation generated over ARW.

[34] The spatial difference of the amount of precipitation between the control and the nonirrigation case is also shown in Figure 11. It is evident from Figure 11 that much of the observed change (up to 60 mm increase in accumulated rainfall) is dominant around the downwind regions of the irrigated land similar to the conclusions drawn by *Puma and Cook* [2010]. Hence, our findings point to the possibility of a positive feedback that is established by irrigated landscapes to sustain heavy precipitation patterns further downwind (and upstream) of the dam. For example, dams that are located downstream of orographic rain producing environments with irrigated landscapes located upwind are likely candidates to experience enhanced precipitation and greater reservoir inflow due to irrigation practice downstream of the dam.

5. Conclusion

[35] This study explored the impact of dam-triggered LULC change on the modification of extreme precipitation. The underlying goal was to understand the implications for dam design and operations for the 21st century by leveraging the current know how gained from atmospheric modeling and long-term observational studies. Using the Folsom dam and the American River watershed as an example, various LULC alterations and increased reservoir size scenarios were analyzed and the implication of results on reservoir management discussed. The use of a numerical atmospheric model (RAMS) allowed the simulation of precipitation patterns for the various scenarios considered. More importantly, RAMS was useful in reducing the uncertainties posed by standard methods of PMP estimations used for design of dams, particularly for orographic regions like ARW where terrain induced precipitation predominates.

[36] The key goal of our study was to seek answers to two specific science questions: (1) Can a dam (artificial reservoir) and the land use/land cover (LULC) changes triggered by it physically contribute to the modification of extreme precipitation? (2) Among the commonly experienced LULC change due to dams, which type of change leads to the most detectable alteration of extreme precipitation? The answer to our first question is a "yes" while for the second question, we observed that for a dam in which the irrigated land is downstream and upwind, the irrigation impact is much more superior from the two examined impacts in modifying the extreme precipitation patterns. However, the ultimate impact on dam design, operations and operational resilience cannot

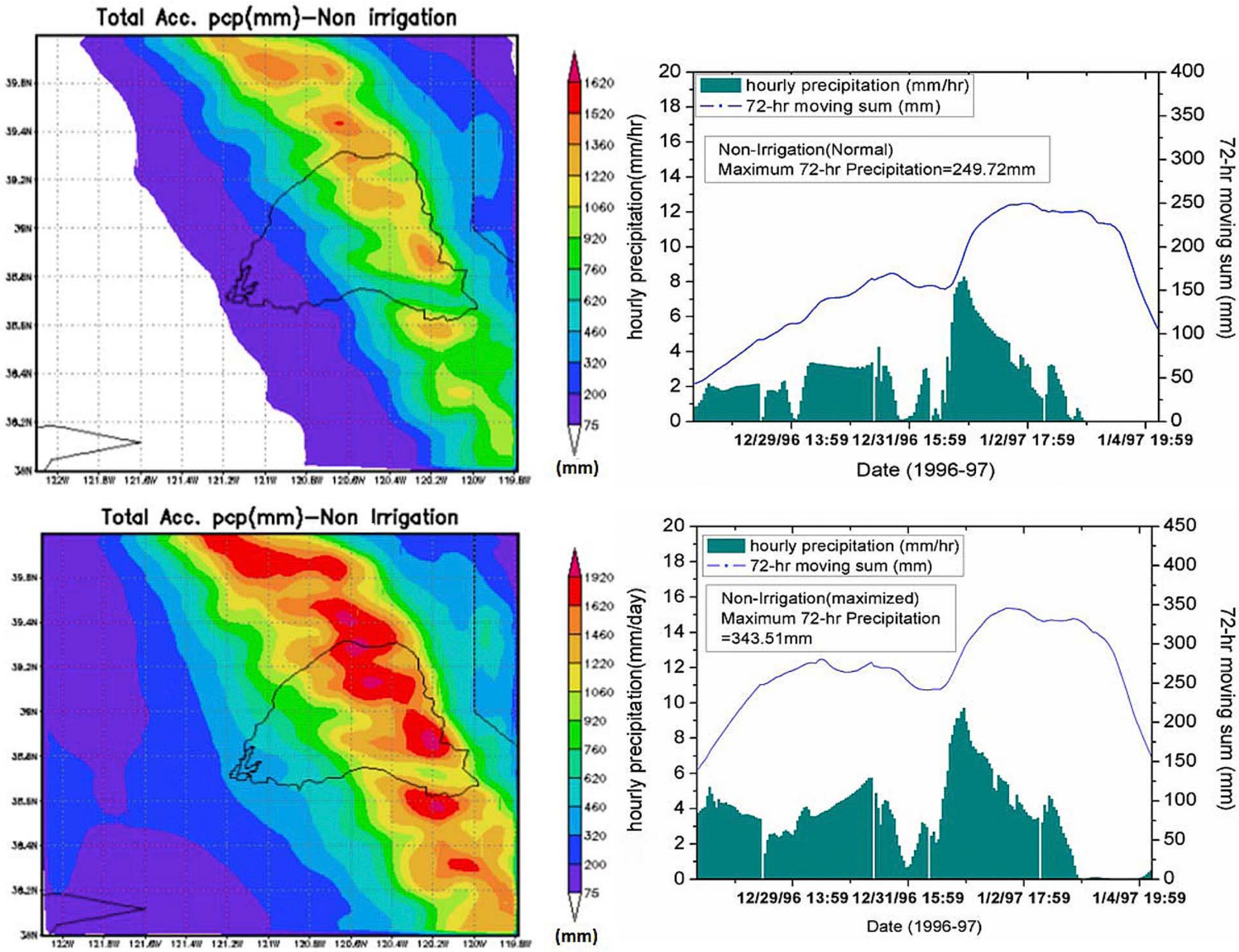

Figure 10. (left) Total accumulated precipitation (mm) for the nonirrigation case and (right) hourly precipitation and the 72 h moving sum over the ARW and for both (top) normal and (bottom) moisture-maximized cases. Simulation period spans from 15 December 1996 to 5 January 1997.

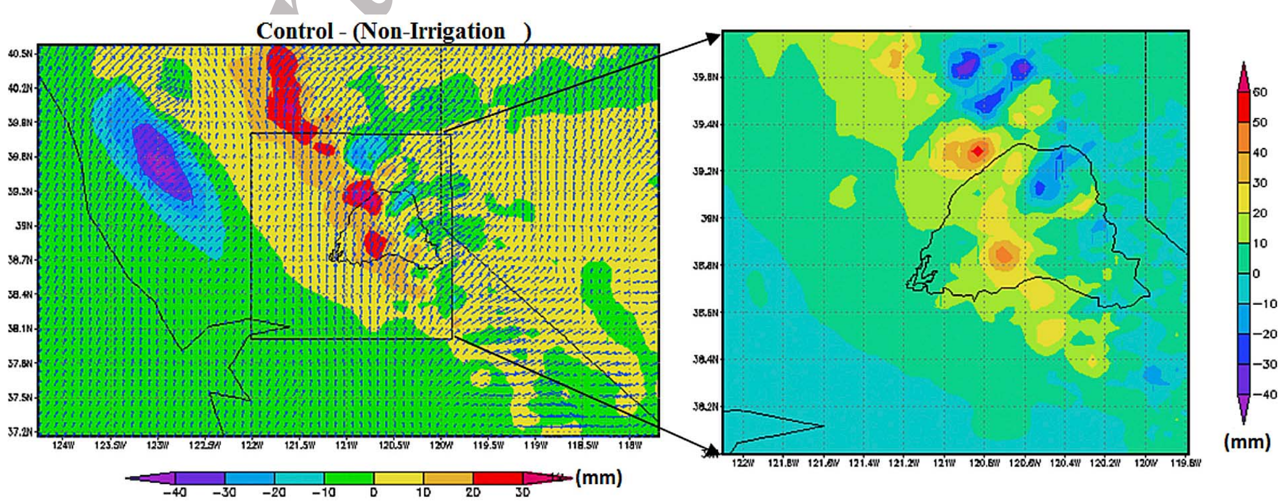

Figure 11. Difference between total accumulated precipitation of the control and the nonirrigation for the normal cases of simulation along with the average wind on the 800 mbar level for the coarser grid.

be obtained from studying a single event or without the use of a distributed hydrologic model. Moreover, it should be noted that such kinds of changes may not prevail for all existing large dams. Land use changes can alter the surface runoff generation mechanism in two ways: (1) through modification of precipitation rates leading to modified infiltration-excess runoff and (2) through enhancement of rainfall partitioning as runoff due to increased imperviousness. The former cause is akin to a "strategic" change that occurs through gradual change in the local climate and hence is not easily apparent as the latter and more instantaneous cause (of increasing imperviousness). Since both causes may be equally important, there is a need to couple the generated PMP-equivalent EP precipitation fields to a spatially distributed hydrologic models for estimation of probable maximum flood (PMF)-equivalent inflows and outflows from a reservoir taking full advantage of the reservoir's stage volume capacity for routing of flows.

[37] Our analysis shows that the considered LULC changes are significant enough to cause a spatial redistribution of heavy rainfall both inside and outside the watershed (Figures 6–11). Because there are always neighboring tributaries to a higher-ordered stream further downstream, it is very important to take a wider view beyond the impounded basin to understand the implications on PMF. For example, for our study region, the American River is a tributary along with two other neighboring rivers (Feather River and Mokelumme River) before merging with the Sacramento River near Sacramento. Thus, it is always plausible that the Folsom dam and its triggered LULC may have detectably impacted the flow in the Sacramento River through these tributary rivers even though the impact within ARW may be found insignificant. Hence, a natural extension of this work that we hope to report in the future is to couple a fully distributed hydrologic model with RAMS and generate PMF-equivalent scenarios for reservoir inflow considering various reservoir sizes and land use change for major cities located downstream. Such a broader study is important for assessing large-scale infrastructure resilience and adaptation in a changing climate considering that there are numerous large cities around the world that depend on impounded surface water from nearby large dams.

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