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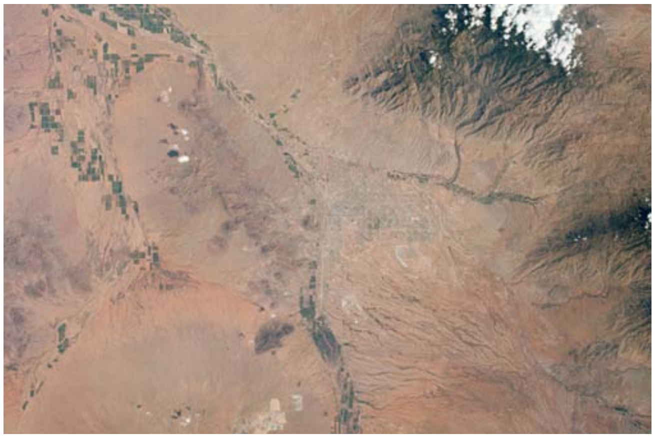
Deliverable 1.1

Relative effect of Land Use - Land Cover change and Climate Change on Extreme precipitation events in the Tucson-Phoenix urban corridor and associated Watersheds



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Cover picture captions:

Top picture: Satellite image of Tucson, Arizona in 1965
Source: http://eoimages.gsfc.nasa.gov/

Bottom picture: Satellite image of Tucson, Arizona in 2011
Source: http://eoimages.gsfc.nasa.gov/

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1. INTRODUCTION

Humans have profoundly altered their environment. Nearly one-third of the global land cover has been modified (Lyon et al. 2008) while at the same time, the composition of the atmosphere has been dramatically altered by anthropogenic greenhouse gas emissions (IPCC, 2007). Changes in extreme events are expected to be one of the most dramatic consequences of our changing environment (NRC, 2011), and could pose huge pressures on the health, economy, and overall wellbeing of at-risk communities. In this work we will focus on the effects of climate and land cover change on urban environments, with a particular emphasis on extreme rainfall events. Urban regions compose only a small fraction of the land surface (roughly 3%) but the percent of the population living in cities has increased dramatically and is likely to increase in the coming decades (see Figure 1). Projections show that by 2030, 3 out of 5 people will live in urban regions (UN, 2007). As a result of the number of people in urban areas, as much as 35 percent of human induced CO2 emissions originate from cities (Hutyra et al., 2011). At the same time, urban areas are characterized by high density of population and civil infrastructure, and serve as social, economic and political hubs. Consequently, urban areas are more vulnerable to extreme precipitation and flooding events (Rosenzweig et al., 2010). In fact, many of the major weather disasters in the last 30 years have been in urban areas, ranging from major ice and snow events, to floods, and hurricanes - these billion dollar weather events have had huge social and economic cost (NRC, 2012). Our area of study will be the Phoenix-Tucson area of the semiarid southwestern United States, as this region has experienced some of the most rapid urban development in the United States in the past six decades.

Climate change and land use/land cover change (LULCC) will affect the surface hydrologic response of urban regions and their associated watersheds. We will look at the changes in hydrologic response using the concept of “Ecosystem Services”. Ecosystem services are the contributions of ecosystem structure and function - in combination with other inputs - to human well being (Burkhard et al., 2012a). The additional note ‘in combination with other inputs’ refers to the ways human activities modify ecosystems for fulfilling the needs of the society. This definition has been promoted by the ’Salzau Message’ on Sustaining Ecosystem Services and Natural Capital (2010). Still according to the same document, ecosystems, ecosystem functioning, and ecosystem services are being threatened and degraded by human activities, and the situation will be exaggerated by climate change and biodiversity loss.

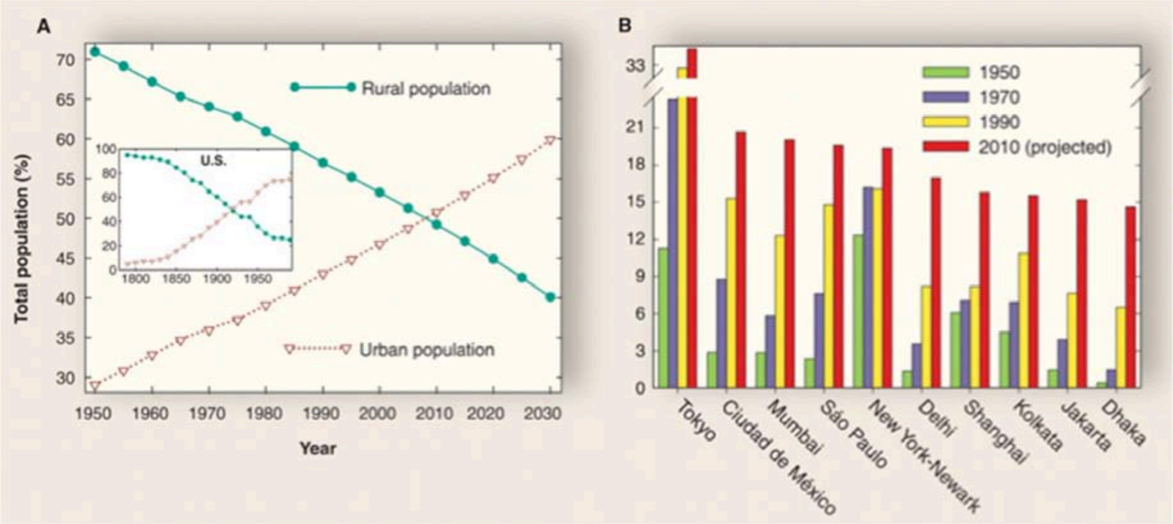


Figure 1. (A) Change in world urban and rural population (%) from 1950 to 2030 (projected). Inset shows comparable data for the United States from 1790 to 1990. (B) Change in population of the 10 largest urban agglomerations from 1950 to 2010 (projected), ranked from left (largest) to right by their projected population size in 2010: Tokyo, Japan; Ciudad de México, Mexico; Mumbai, India; Sáo Paulo, Brazil; New York–Newark, USA; Delhi, India; Shanghai, China; Kolkata, India;

The ecosystem services approach studies the human-environmental systems in a manner that provides qualitative and quantitative data that is crucial for the better understanding of the consequences of human activities on nature and society. Its analysis methods are developed in a way that provides more efficient and comprehensive data that helps to identify and quantify the ecological and socio-economic trade-offs and synergies on which decision-making should be based ('Salzau Message'). Climate change has the potential to substantially alter the provisioning of essential ecosystem services (MEA, 2005; Naidoo et al., 2008), with individual ecoregions and ecosystem services projected to exhibit different degrees of vulnerability (Gonzalez et al., 2010; Beaumont et al., 2011) (in Cheelkin et al., 2013). Climate change is expected to be one of the main factors affecting human health and well being over the coming decades (Thomas et al. 2004; ME Assessment 2005; Schröter et al. 2005; Pimm 2009). Ecosystem services can also be altered by land use change. A method for assessing the vulnerability of ecosystem services to land use change is presented by Metzger et al., 2006. 'Vulnerability' is defined as the degree to which a system is susceptible to, or unable to cope with, adverse natural or anthropogenic changes.

In this work we will investigate the combined effects of climate change and land use / cover change (LULCC) on extreme precipitation in the Tucson-Phoenix corridor and their associated watersheds. We will evaluate how the ecosystem services provided by the watersheds might be affected in the future. We address this question through the use of historical observations and numerical modeling. The work is divided in two objectives:

Objective 1) We will investigate the relative effect of projected LULCC and projected climate change on extreme precipitation events in the Tucson-Phoenix urban corridor using the Weather Research Forecast (WRF) regional climate model coupled to a state-of-the-art land surface model with detailed characterization of urban regions. Our hypothesis is that these two different anthropogenic forcings act synergistically to magnify extremes.

Objective 2) We will quantify how climate change and LULCC can result in changes in ecosystem services provided by the Verde Basin Watershed. We focus primarily on the flood mitigation role of the watershed.

2. BACKGROUND

2.1. Effects of Climate Change on the Hydrology of Arizona

Arizona is located in the subtropical latitudes of the Southwestern US and is characterized by hot summers and mild winters. The climate in the region is highly variable, as it is affected by the complex interplay between the mountains, proximity to the Gulf of California, Gulf of Mexico and Pacific Oceans. During the winter, the mid-latitude storm track brings moisture and precipitation to the region. Variability in winter precipitation is strongly controlled by El Nino Southern Oscillation (ENSO), which brings wetter than average and cooler than average conditions to the region (Dettinger et al. 1998). The North American Monsoon (NAM) is the primary driver of summer precipitation. However, the NAM exhibits strong interannual variability that has also been linked to the Pacific Ocean (Castro et al. 2007).

Global climate models (GCMs) are the primary tools used to understand how anthropogenic greenhouse gas emissions could affect future climate throughout the globe. Many studies have analyzed projected climate changes in the Southwestern US using ensembles of different GCMs with several different possible pathways of greenhouse gas emissions. Some common conclusions that emerge from these studies are summarized as part of the National Climate Assessment (Garfin et al. 2013). The broad conclusions of the studies are that mean temperature is projected to increase substantially, particularly in the summer and fall. Mean precipitation is projected to decrease in southern Arizona, while precipitation extremes are projected to increase. The average higher temperatures will likely bring less mountain snowpack accumulation and reductions in streamflow.

2.2. Possible Changes in Ecosystem Services associated to Climate Change and LULCC

The concept of ecosystem services is based on the assumption that the ecosystem’s structure and functions provide goods and services, which contribute to human well being. This concept has become a very popular scientific topic during the last two decades as it provides an appropriate methodological framework for linking both physical and socio-economic sciences with decision making. Ecosystem services are usually classified into four major groups: provisioning, regulating, cultural and supporting (Costanza et al. 1997; de Groot et al. 2002; MA, 2005). However, the supporting services are omitted by some researchers (Burkhard et al. 2009) as they do not contribute directly to the human well-being. Various ecosystem functions contribute to hydrological processes; therefore they can be defined as water related ecosystem services. They include: 1) freshwater (provisioning) – use of water for drinking, domestic use, irrigation, industry etc.; 2) water flow regulation (regulating) – maintaining of water cycle features such as water storage and buffer, natural drainage, flood regulation etc.; 3) water purification (regulating) - the capacity of ecosystems to purify water from sediments pesticides, disease-causing microbes etc. (Kandziora et al. 2013). In this work we will focus on water flow regulation ecosystem service. Flood regulating services are based on the water flows regulation functions of ecosystems that reduce the amount of surface runoff and consequently the flood hazard. The flood regulating services can have preventive or mitigating functions. In the first case, the ecosystems (i.e. forests) redirect or absorb parts of the incoming water (from rainfall), reducing the surface runoff and consequently the amount of river discharge. The mitigation function is related to ecosystems (i.e. flood plains and wetlands) which provide retention space for the water surplus to spill, thus reducing the flood's destructive power. The water retention function can be quantified using watershed based hydrological models and GIS spatial analyses (Nedkov and Burkhard, 2012).

In 2008 the Committee on Ecological Impacts of Climate Change, National Research Council, published a report on 'Ecological Impact of Climate Change', making a profound analysis of the topic. Climate change can impact ecosystems in many ways. A few of many possible examples are discussed below.

Climate change is linked to a number of other changes that already can be seen around the world. These include earlier spring snowmelt and peak stream flow, melting mountain glaciers, a dramatic decrease in sea ice during the arctic summer, and increasing frequency of extreme weather events, including the most intense hurricanes (IPCC 2007b). Changes in average annual precipitation have varied from place to place in the United States.

Climate dynamics and the cycling of water between land, rivers and lakes, and clouds and oceans are closely connected. Climate change to date has produced complicated effects on water balances, supply, demand, and quality. When winter precipitation falls as rain instead of snow and as mountain snowpacks melt earlier, less water is "stored" in the form of snow for slow release throughout the summer (Mote 2003), when it is needed by the wildlife in and around streams and rivers and for agriculture and domestic uses. Even if the amount of precipitation does not change, warmer temperatures mean that moisture evaporates more quickly, so that the amount of moisture available to plants declines. The complex interaction between temperature and water demand and availability means that climate change can have many different kinds of effects on ecosystems.

The character of extreme weather and climate events is also changing on a global scale. The number of frost days in midlatitude regions is decreasing, while the number of days with extreme warm temperatures is increasing. Many land regions have experienced an increase in days with very heavy rain, but the recent CCSP report on climate extremes concluded that “there are recent regional tendencies toward more severe droughts in the southwestern U.S., parts of Canada and Alaska, and Mexico” (Kunkel et al. 2008, Dai et al. 2004; Seager et al., 2007).

These seemingly contradictory changes are consistent with a climate in which a greater input of heat energy is leading to a more active water cycle. In addition, warmer ocean temperatures are associated with the recent increase in the fraction of hurricanes that grow to the most destructive categories 4 and 5 (Emanuel 2005; Webster et al. 2005).

2.2.1. Changes in Extreme Precipitation

Our interest in extreme precipitation events stems in part from a previous study published by the group (Dominguez et al. 2012). In this study, we analyze an ensemble of dynamically downscaled climate model projections for the Western US. Dynamical downscaling is a method used to bring the coarse scale GCM projections (that are on the order of 200 km) to the regional scale using regional climate models. By analyzing this ensemble, we find a consistent and statistically significant increase in the intensity of future extreme winter precipitation events over the western United States (Figure 2). We define extreme precipitation as events that have a probability of occurring once every 20 or 50 years. All eight simulations analyzed in our work consistently show an increase in the intensity of extreme winter precipitation with the multi-model mean projecting an approximate 6% increase in 20-year return period and 7% increase in 50-year return period daily precipitation for the southwestern US. In contrast with extreme precipitation, the multi-model ensemble shows a decrease in mean winter precipitation of approximately 7.5% in the southwestern US.

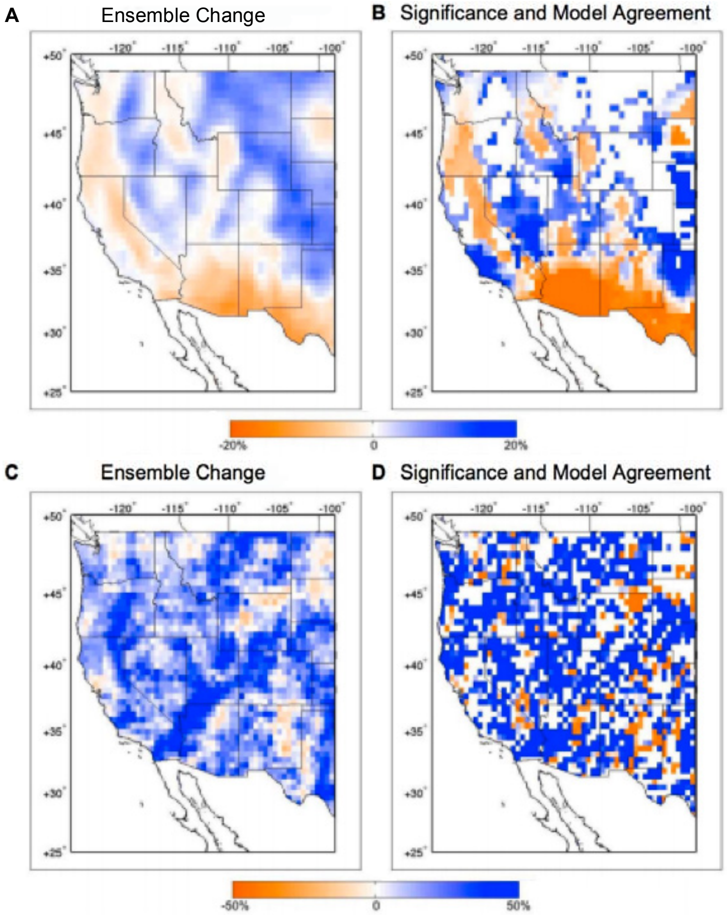


Figure 2. (A) Ensemble average percent change in mean winter precipitation between the historical (1968–1999) and future (2038–2070) periods for all simulations. (B) Ensemble average percent change in mean winter precipitation for only those models with statistically significant changes and only where more than 4 models agree on the sign of the change. (C) Ensemble average percent change in 50-year return period winter precipitation between the historical (1968–1999) and future (2038–2070) periods for all simulations. (D) Ensemble average percent change in 50-year return period winter precipitation for only those models with statistically significant changes and only where more than 4 models agree on the sign of the change.

2.2.2. Projected changes in Streamflow in the Verde Basin due to Climate Change

Our group has also explored how future climate change could potentially affect the hydrology of the Verde River Basin (Rajagopal et al., 2012, 2013). The Verde River Basin and the adjacent Salt Watershed are part of the larger Colorado River basin, and are the main source of water supply for approximately 4 million people living in the Phoenix metropolitan area.

In this study, we use the Variable Infiltration Capacity (VIC) model for the Salt and the Verde watersheds in central Arizona, drive the model with climate data from five statistically downscaled global climate models for the historical period and the future period. We then assess the physical hydrologic processes giving rise to changes in streamflow in the basin. While previous studies have covered the larger Colorado River basin, these studies are largely not beneficial in terms of actionable data for the management of these watersheds in the lower basin.

We find that declines may be expected in streamflow for both the Salt and the Verde River basins (Figure 3). Because snowmelt is currently 70% of total streamflow, the declines can be attributed primarily to increases in mean temperature, small decreases in mean winter precipitation and declines in snowmelt.

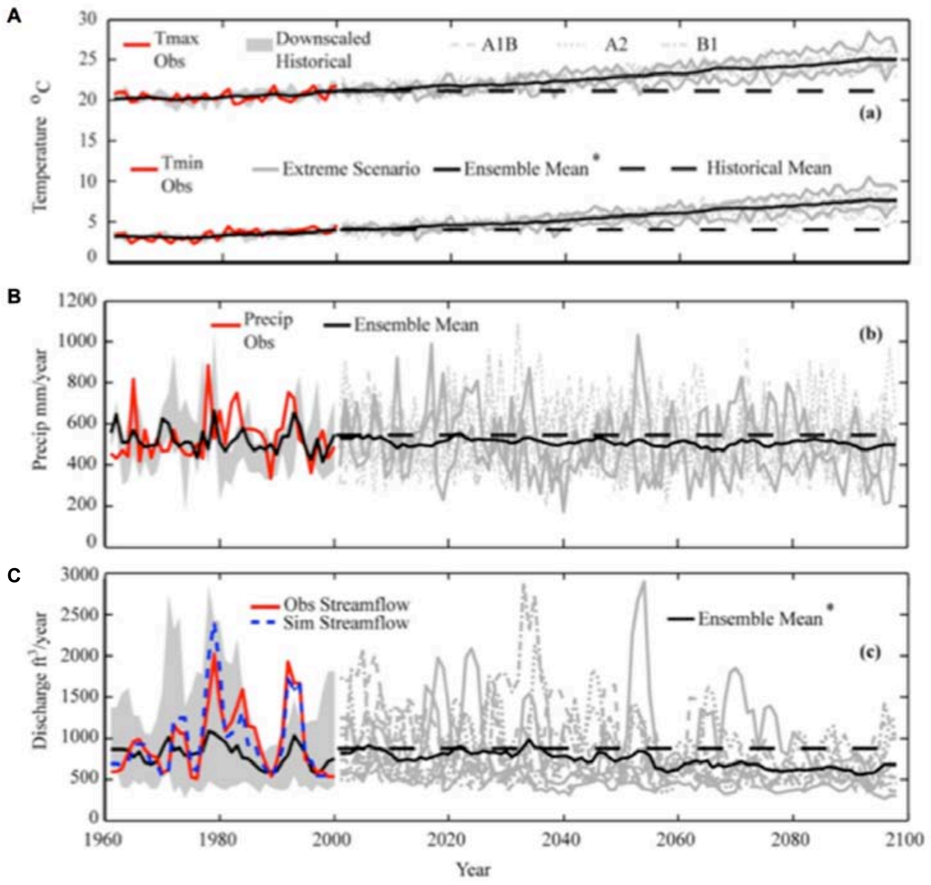


Figure 3: Historical and Future change to (A) temperature, (B) precipitation and (C) streamflow in the Salt River Basin. The * indicate that the ensemble mean had a significant trend using a non parametric test at the p-value 0.05. (Taken from Rajagopal et al., 2013)

2.2.3. Effects of Urbanization on the Hydrometeorology of Arizona

While a great deal of attention has been focused on the effects of changes in atmospheric composition on precipitation, less attention has been given to LULCC on precipitation patterns (Pielke et al., 2011). Urban regions in particular affect the overlying atmosphere in several ways. Perhaps the most well known mechanism is through the urban heat island (UHI). Changes in nighttime temperatures associated with UHI have been found to be up to 10K in Phoenix (Grossman-Clarke et al., 2010). As natural surfaces are replaced by surfaces with different heat capacity, thermal inertia and albedo, urban regions tend to store more energy and convert it to sensible heat (Shepherd et al., 2005). In addition to the UHI, urban regions are can alter precipitation patterns through 1) changes in convergence patterns due to increased surface roughness; 2) destabilization of the boundary layer due to increased surface sensible heat flux, and in some cases due to irrigation; and 3) enhanced aerosols for cloud concentration nuclei (CCN) (Shepherd et al., 2005; Changnon et al., 1981; Shepherd et al., 2002; Diem and Brown, 2003).

Increased precipitation downwind of urban regions has been documented by Changnon et al. (1991) and Braham et al. (1981). Diem and Brown (2003) argue that increases in summer precipitation totals over the Lower Verde basin, located downwind of Phoenix AZ, could be due to urbanization and irrigation in the Phoenix area. The authors hypothesize that convergence and contribution of water vapor resulting from irrigation are the dominant mechanisms for this downwind effect (CCN concentration changes play a secondary role). Shepherd et al. (2006) used a 108-year precipitation historical record and found that the convective monsoon thunderstorms that form east of Phoenix propagate west, and interact with urban dynamic circulation to form precipitation over the metropolitan area. Changes in intensity and frequency of precipitation associated with urbanization have also been documented in the Phoenix area. The rapid growth of the city of Phoenix has been related to an increase in the frequency and intensity of late afternoon and evening monsoonal storms, with declines in events between midnight and noon (Balling and Brazel, 1987). The frequency of intense summer convective storms over Phoenix has also increased in recent decades (Selover, 1997). More recently, detailed regional climate model studies have evaluated the effect of LULCC on energy and precipitation in the Greater Phoenix area (Georgescu et al., 2009a; b). Using detailed land cover descriptions of the area for 1973, 1992 and 2001 as boundary conditions for the RAMS regional climate model, the authors find that mesoscale circulations were stronger for the 2001 than the 1973 period. They also found enhanced precipitation and argue that the physical mechanisms are a complex interplay of micro-meso and large-scale circulation during the monsoon season. However, precipitation recycling seems to play an important role in precipitation enhancement as well (Georgescu et al., 2009b).

3. METHODOLOGY

The primary tool we use to investigate the combined effects of climate change and LULCC on extreme precipitation in the Tucson-Phoenix corridor and their associated watersheds is numerical modeling. Numerical models will allow us to perform experiments and sensitivity analyses to test the relative effect of these different forcing mechanisms. Furthermore, numerical models allow us to incorporate future scenarios of land use and large-scale climate, and evaluate the regional response. The numerical model that we use to simulate the regional climate of the historical period 1990-2000 and the future period 2030-2040 is the WRF-Noah-UCM model This coupled land surface and urban modeling system for the community weather research and forecasting (WRF) regional climate model is an international collaborative research and development effort aim to addressing emerging issues arising in the urban areas (Chen et al., 2011). Our region of interest encompasses the Tucson-Phoenix corridor, which encompasses the urban regions, and the Salt, Verde, Santa Cruz and Gila River basins. The primary (highest resolution) domain of the WRF-Noah-UCM will cover approximately the entire state of Arizona.

3.1. Models

3.1.1. Weather Research Forecast (WRF) Model

Global Climate Models (GCM) usually fail to represent urban areas due to their coarse resolution (usually ~200 km) and the relative small size of urban areas. One of the most important advances in urban meteorological forecasting has been the development of urban canopy models (UCM) for Numerical Prediction Models (NWP, e.g. WRF) with increasing resolution to few kilometers. This allows a better representation of urban areas and also as major improvement compared to former tools. We intend to implement the single layer urban canopy model (UCM) coupled in WRF Version 3.4.1 to investigate the effect of LULCC (including urbanization) and climate change on regional climate, especially precipitation extremes which can potentially cause extensive damage and are important for urban flood infrastructure planning.

The regional climate model we use is the Advanced Research version of Weather Research and Forecasting Model (WRF) (Skamarock et al., 2005). It was collaborative effort principally among the National Center for Atmospheric Research, the National Center for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), THE Naval Research Laboratory, the University of Oklahoma and the Federal Aviation Administration

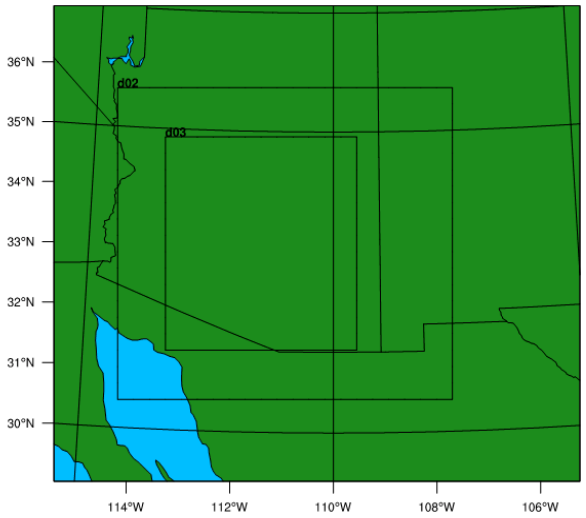


Figure 4. Domain configuration, outer domain resolution is 30km, intermediate 10km and inner domain 2.5 km.

(FAA). The Advanced Research WRF (ARW) modeling system is designed to be flexible, portable and efficient on parallel computing platforms, and suitable for use in a broad range of applications across scales ranging from meter to kilometers. The WRF model features nonhydrostatic, compressible with a mass coordinate (Chen et al., 2011, Skamarock et al., 2005). The physical parameterizations that will be used in the initial runs includes: Morrison double-moment scheme for all nests, CAM scheme which allows for aerosols and trace gases for longwave and shortwave radiation, Eta similarity which based on Monin-Obukhov with Zilitinkevich thermal roughness length and standard similarity function for the surface layer parameterization and land surface use the unified NCEP/NCAR/AFWA scheme, Mellor-Yamada-Janjin scheme for the planetary boundary layer physics, for the outer two domains turn on the cumulous parameterization using Kain-Fritsch scheme. Twoway interaction is used to communicate information between model run and large scale observation data.

In our numerical experiments, the coupled WRF/Noah/UCM model is integrated over the southwestern United States, with latitude 28N to 36N, and longitude 115W to 105W. The domain mainly encompasses the state of Arizona. It has 3 nested domains with outer grid size 30 km, intermediate domain grid spacing 10 km and most inner domain grid spacing 2.5 km. The graphical representation is shown in Figure 4.

3.1.2. Urban Canopy Model

Chen et al, 2004 developed a coupled Noah/Urban-canopy model (UCM) based on Kusaka et al. 2001. The Noah-UCM is coupled to the regional climate model WRF Version 3.4.1. The Noah LSM has single vegetation canopy layer and the following prognostic variables: soil moisture and temperature in the soil layers, water stored on the canopy and snow stored on the ground (Chen et al., 2004). In our experiment, we use the Noah LSM as our land surface model (Chen et al., 1996) to provide surface energy fluxes and surface skin temperature which serve as the boundary conditions for the atmospheric model. The Noah LSM has a bulk parameterization for urban land use (Liu et al. 2004, Tewari et al. 2004). However, we are using a single layer urban canopy model (UCM) to better represent the energy and temperature fluxes in the urban region. This single-layer urban canopy model was first developed by Kusaka et al. 2001 and further modified by Kusaka and Kimura, 2004. It consists of 2-dimensional symmetrical street canyons with infinite length, and treats radiation in 3 dimensions - which consider the canyon orientation and the diurnal variation of azimuth angle (Tewari et al. 2007). The UCM model estimates temperature and sensible and latent heat fluxes at roof, wall, and roads - which later serve as lower boundary conditions for atmospheric model.

Chen et al, 2004 show the difference of urban temperature by comparing simulation result of traditional parameterization and the UCM models. The result show that traditional approach fails to capture the UHI effect over Houston area.

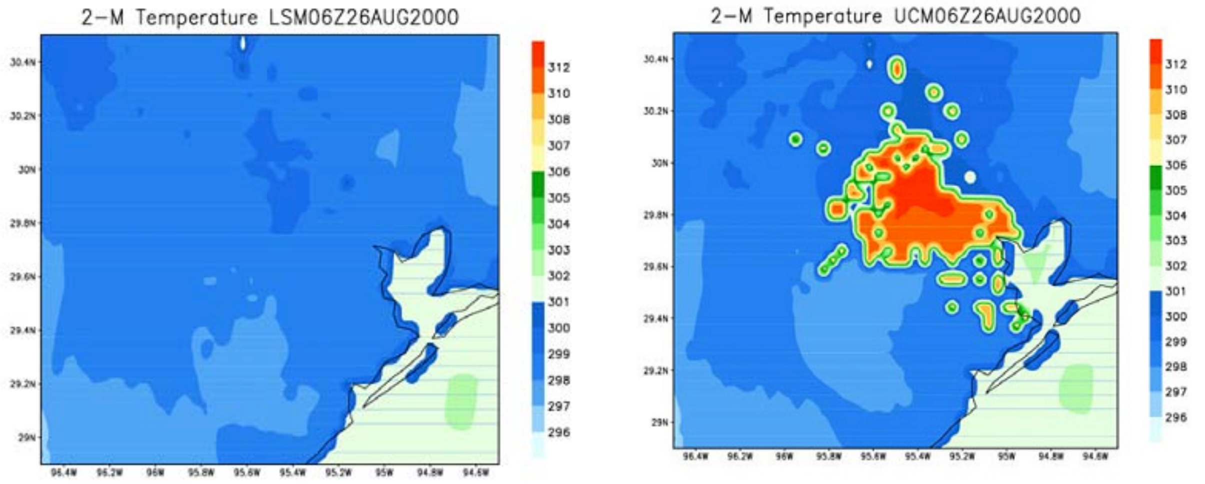


Figure 5. WRF simulation results of temperature without UCM (left figure) and with UCM (right figure) of Houston area

3.1.3. Projections of Future Land Use

The land use map we use to evaluate the effects past land use change on climate obtained through the North America Land Cover (NALC) data (year 2005, shown in Figure 6 below). The NALC dataset was produced by Canada Centre for Remote Sensing from observations acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS/Terra), at a 250-meter spatial and

10-day temporal resolution. In addition to the map of land use for the year 2005, we also have projections of land use for the future (year 2050, shown in Figure 6 below) to simulate future scenarios. The future land use projection is obtained by merging the North America Land Cover data (NALC, 2005) with projection data. For the most part of Arizona, we use the State of Arizona's land use projection that was generated by Maricopa Association of Governments (MAG) using the Red Dot Algorithm (RDA). The algorithm could be simply stated as follows: 1) dividing the land-use extent and pattern according to land ownership of Arizona, 2) exclude areas that are unlikely to develop or likely to develop relative slowly into urban areas, e.g., military base, natural parks, forests, native American lands, Bureau of Land Management (BLM) lands, flood plains and steep slopes, 3) the rest of which are State Trust lands and private lands that are places where future development would possibly occur. For the areas around and south of Tucson, an urban developing model named SLEUTH model was used to simulate future condition (Norman et al., 2012).

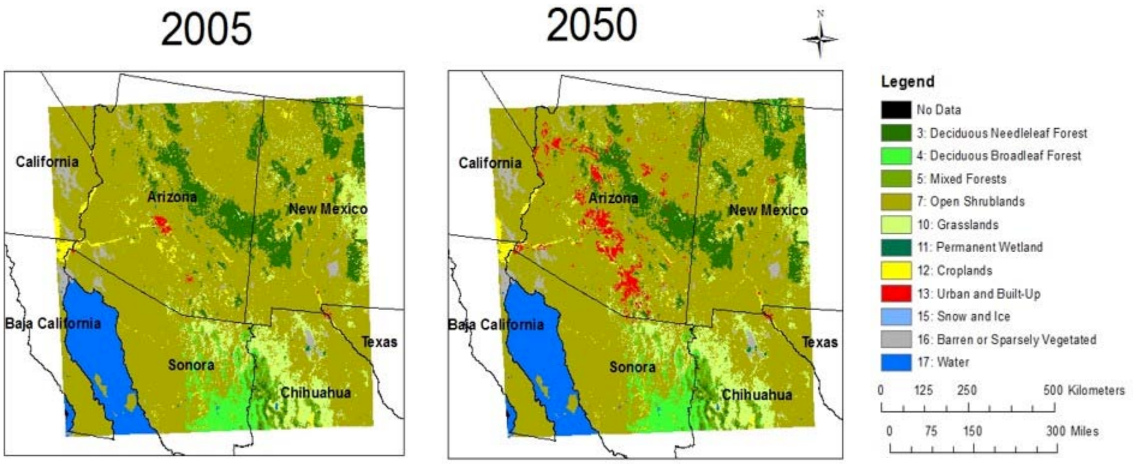


Figure 6. Land use map for year 2005 representing current condition and land use projection for year 2050 representing future scenario.

The model was initially developed by Clarke et al, 1997, later verified and validated by Clarke and Gaydos 1998. The name of the model is an acronym for its input layer names: slope, land use, exclusion, urban extent, transportation, and hill shade (Norman et al., 2012). The SLEUTH simulates four types of urban land-use changes: spontaneous growth, new spreading center growth, edge growth and road-influenced growth (Jantz et al., 2010).The SLEUTH model characterize with five parameters: dispersion, breed, spread, road gravity and slope to simulate the aforementioned land-use change types. All parameters have to be calibrated with historical land use data and are use to predict future land use and land cover scenarios. The aforementioned projected land cover data aggregated together and adapted to MODIS 20-level classification scheme to be consistent. Urban areas are assumed to be high intensity residential area in WRF, however, we modified the corresponding urban parameterization in WRF to make it more realistically reflect the urban condition in this experiment.

3.1.4. Variable Infiltration Capacity (VIC) Model

The land surface model used to analyze the hydrologic impacts of climate change in the Verde River Basin is the Variable Infiltration Capacity (VIC) macroscale energy and water balance model (Liang et al., 1994; Cherkauer et al., 2003; and Andreadis et al., 2007). As compared to other land surface schemes, VIC’s distinguishing hydrologic features are its representation of sub grid variability in soil storage capacity as a spatial probability distribution, to which surface runoff is related (Zhao et al., 1980), and its parameterization of base flow, which occurs from a lower soil moisture zone as a nonlinear recession (Dumenil and Todini, 1992). Sub grid-scale variability in soil properties is represented in VIC by a spatially varying infiltration capacity. Movement of moisture between the soil layers is modeled as gravity drainage, with the unsaturated hydraulic conductivity a function of the degree of saturation of the soil (Campbell, 1974). The deepest soil layer produces base flow according a nonlinear base flow formulation Liang et al (1994). In this way, the model separates subsurface flow from quick storm response. Horizontally, the land surface is described by a given number of tiled land cover classes. The subsurface is characterized vertically by an arbitrary number of soil layers. For most applications two or three soil layers have been used, with the top layer relatively thin (usually 5-10 cm). The land cover (vegetation) classes are specified by the fraction of the grid cell which they occupy, with their leaf area index (LAI), canopy resistance, and relative fraction of roots in each of the soil layers. The VIC model has been tested and applied at a range of scales, from large river basins to continental and global scales. These studies have been reported in Abdulla et al. (1996); Nijssen et al. (1997); Wood et al. (1997); Wood et al. (1998); Dubayah et al., (2000); O'Donnell et al , (1999); and Nijssen et al. (2001).

3.2. Data

We use the NCEP-II reanalysis as atmospheric forcing to run the model for the historical period. For diagnosis of the model performance, we will use the NARR reanalysis data with 32 km resolution. NCEP-II is an improved version of the NCEP-NCAR reanalysis. In 1998, the

Reanalysis II project was started at the National Energy Research Supercomputing Center of the Department of Energy. The improvements include an updated model, better physical parameterizations and assorted error fixes (Kanamitsu et al., 2002). The NCEP-II covers the period from 1979-present. The NARR project is an extension of the NCEP Global Reanalysis, which is run over the North American Region. It was suggested by the NECP-NCAR Advisory Committee and completed in 2004 after 6 years of development and production effort. The NARR model uses the high resolution NCEP Eta Model (32km/45 layer) together with the Regional Data Assimilation System (RDAS) (Mesinger et al., 2006). The NARR assimilates precipitation, temperature, winds with more accuracy as compared to NCEP-II. Current output includes 8 times daily temperature, precipitation and other variables.

State of the art future climate projections rely on Global Climate Models (GCMs) driven by different greenhouse gas emission scenarios. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) collects GCM output contributed by leading modeling centers around the world in response to proposed activity of the World Climate Research Program's (WCRPs) Working Group on Coupled Modeling (WGCM). These GCM simulations which included past, present and future climate were archived in 2006 and are the primary data for the phase 3 of the Coupled Model Intercomparison Project (CMIP3) (Covey et al., 2003). Unfortunately, GCMs generally do not realistically represent precipitation or other climate variables that are spatially heterogeneous due to their coarse spatial resolution and physical parameterizations, especially in complex terrain. Consequently, the models must be downscaled using either statistical or dynamical downscaling (see Fowler et al., 2007, for details on the two methods). In this work we present results based on both statistical and dynamical downscaling.

Dynamical downscaling is a physically based method to bring the global scale projections to the regional scale using RCMs. We will use this method to test the sensitivity of LULCC and climate change in the Tucson-Phoenix corridor because the use of RCMs allows us to change the land cover (while this would be impossible when using statistical downscaling). Dynamical downscaling is significantly more computationally expensive than statistical downscaling, and far fewer scenarios can be modeled. However, regional models can simulate changes that have never been observed in the historical period, addressing the issue of non-stationarity (Fowler et al. 2007). In addition, dynamical downscaling generally better captures mean and extreme precipitation at the regional scale as stated by Leung and Quian (2009). We will use two different downscaled datasets to evaluate climate model performance for the historical period, provide an envelope of possible future climate projections, and address the issue of model uncertainty in future climate. The two downscaled simulations were generated at the University of Arizona using the WRF model driven by two different AR4-generation GCMs: 1) the Hadley Centre coupled model, version 3 (HadCM3), and 2) the Max-Planck-Institute for Meteorology coupled model (ECHAM5_MPI-OM, MPI hereafter). The HadCM3 and MPI GCMs have been found to perform well for the historical period compared to observations for both the US Southwest (Dominguez et al., 2009) and the Northern Hemisphere (Gleckler et al., 2008). The simulations encompass the conterminous US and northern Mexico at a spatial resolution of 35km, and a temporal resolution of 6 hours.

As stated before, statistical downscaling is less computationally expensive than dynamical downscaling. While it can’t simulate the bi-directional feedbacks between changes in land use and the atmosphere, statistical downscaling can provide many scenarios of possible future changes in climate due to increased greenhouse gas forcing. We will use statistical downscaled scenarios to evaluate possible future changes in ecosystem services in the Verde River Basin caused by increased GHG forcing. We use different emission scenarios from the IPCC Fourth Assessment Report (B1, A1B and A2) from three GCM’s: HADCM3, MPI and CCSM3. Two additional GCM simulations viz. MIROC and PCM were added to represent the simulated driest and wettest extreme respectively for the 21st century in comparison to historical observed precipitation. A total of 11 different GCM scenarios will be used. Bias correction and spatial downscaling for the models from the WCRP CMIP3 dataset has been performed and archived at the Santa Clara University and the Lawrence Livermore National Laboratory website (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html). This is the source of the GCM data used in this study. The methodology for bias correction and spatial downscaling follows Wood et al., (2002, 2004) and Maurer et al., (2007). Bias correction removes biases in the GCM when its simulations of historical climate conditions tend to be too wet/dry/warm/cold relative to the observations. To correct for such biases a quantile mapping technique was used.

4. RESULTS

We have been working in parallel on the WRF simulations with modified land cover, and on the analysis of the VIC results with statistically downscaled data. The goal is to write two separate manuscripts likely to be submitted to the Journal of Hydrometeorology and to Water Resources Research (respectively). Our results are summarized below.

4.1. Relative effect of LULCC and climate change on extreme precipitation events in the Tucson-Phoenix urban corridor

The first months of this project were dedicated to the analysis of the land use data for the 2005 and 2050 periods. Ingesting this data into WRF involved changing the geographical projections and identifying and modifying land use categories to be consistent with WRF. As and example, all land use classified as urban region were set to “high intensity” urban in the Noah-UCM, we will test the sensitivity of this assumption in the coming months.

We selected the year 2004 to calibrate the WRF model. NCEP/DOE Reanalysis II data for the period of July-August of 2004 is used to run the model at a 30km resolution, and we compare the WRF-generated temperature and precipitation to that of NARR (used as a proxy for observations) (Figure 7). We see that temperature is realistically simulated, with a slight hot bias in the southwestern part of the domain. Precipitation on the other had is significantly overestimated in the eastern part of the domain. Summer season precipitation in the Southwestern United States is particularly difficult to simulate. Summer events are usually strong convective events with a small spatial and temporal resolution (a few kilometers, and one to two hours duration). In previous studies we have found that several factors contribute to the overestimation, including excessive precipitable water, excessive CAPE, and deficiencies in the convective parameterization scheme (Tripathi and Dominguez, Accepted in Journal of Geophysical Research). We test the sensitivity of our simulation to the lateral boundary conditions by using different forcing datasets and find that the lateral boundary conditions significantly affect our representation of precipitation in the region (Figure 7). Forcing the model at its lateral boundaries with the NCEP-NCAR reanalysis results in significant overestimation of precipitation in the eastern part of the domain, while using NARR results in a more realistic representation of the local meteorological variables. For this reason we decided to use NARR as our lateral boundary forcing.

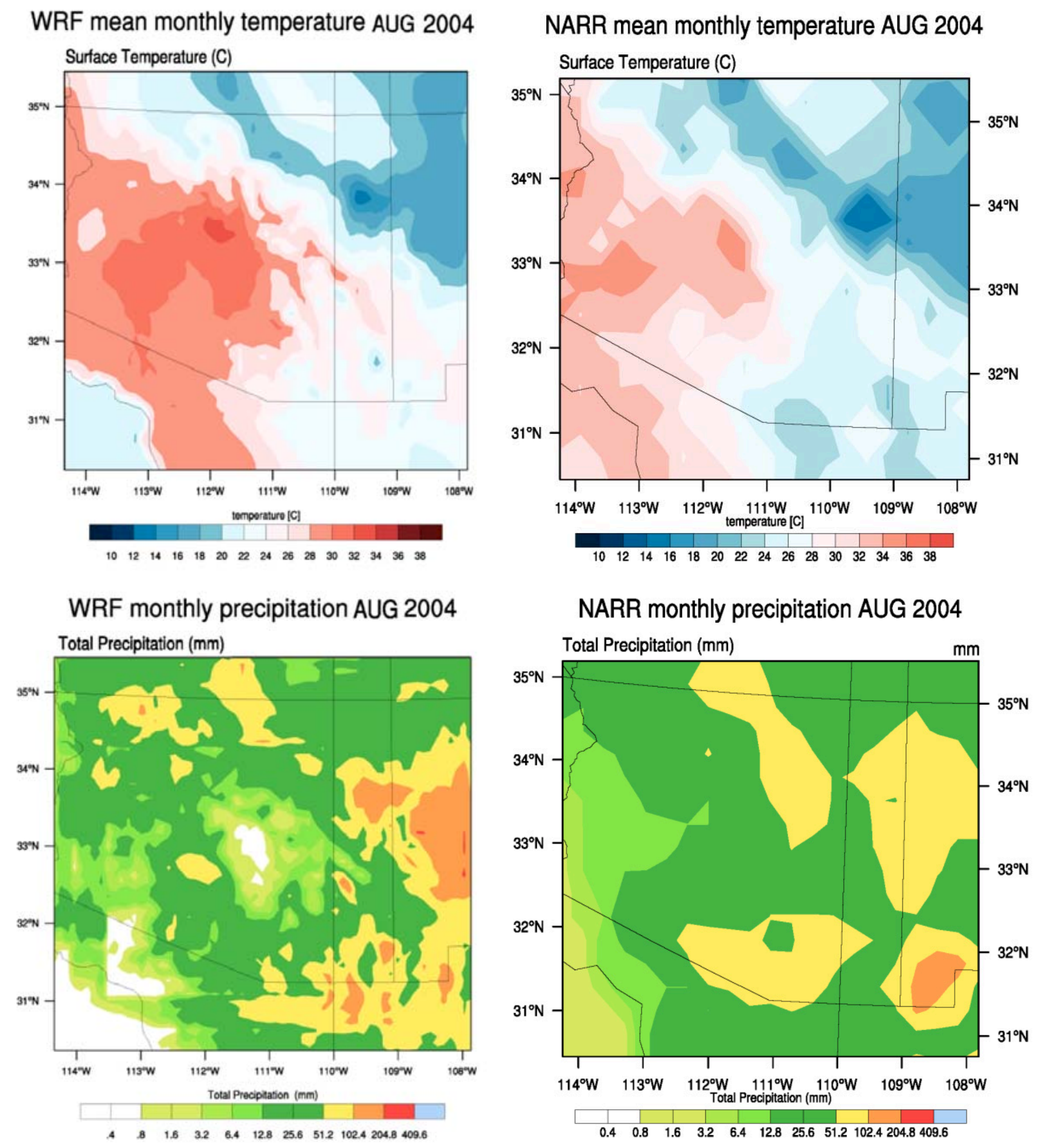


Figure 7. WRF simulations (left) compared to NARR (right) for temperature (top) and precipitation (bottom).

4.2. Effect of climate change on ecosystem services provided by the Verde Basin Watershed

Our group has historical (1949-1985) and future (2010-2100) 3-hourly simulations of the hydrology in the Verde River basin using the VIC hydrologic model (Rajagopal et al. 2012, 2013). We are using this data to evaluate possible future changes in ecosystem services due to climate change.

For the purposes of this paper, we focus only on extreme flooding events. As a first step, we select historical flooding events and analyze the response of the basin to these extreme events. We divide annual cycle into two phases: cold season and warm season, in order to differentiate the effect of snow melting and summer monsoon on extreme streamflow. We define cold season as starting from December 1st to May 31st, warm season as starting from June 1st to November 30th. We evaluate VIC performance by comparing to USGS observation data. In Figure 8 below, blue and red color represents the USGS observation data and VIC model data respectively. Upper three plots are streamflow data for cold season, and lower plots are data for warm season.

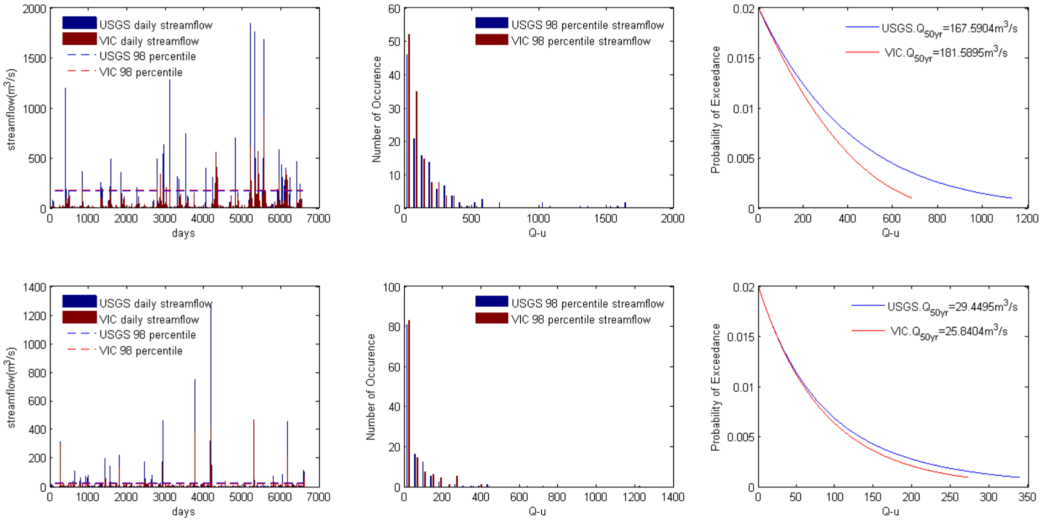


Figure 8. Comparison of streamflow simulated by the VIC hydrologic model and measured at the USGS gauge

We define streamflow events that exceed 98 percentile as extreme events, and we analyze the occurrence and magnitude of such events. Panels a) and d) in Figure 8, show daily streamflow along with the 98 percentile streamflow level represented in dash line. The 98 percentile level in both figures lies relatively close in magnitude. On the other hand, USGS data might suggest more extreme streamflow data in this historical period. In other words, VIC model seems to be underestimating the magnitude of extreme events. Panels b) and e) show histogram for extreme streamflow in cold and warm season where x axis represents the magnitude that streamflow exceeds the threshold value (98 percentile), y axis is the number of occurrence of certain streamflow events. It shows that the VIC model captures the pattern of extreme flow events relatively well. The number of occurrence for each bin is similar to the USGS data. Although the VIC model simulates more low-level extreme streamflow as compared to USGS observation data. This phenomenon is more obvious in figure c) and f) which give probability of exceedance.

Based on the comparison of the VIC streamflow and USGS measurements, we will focus our attention on two flooding events that were realistically captured in the simulation: March 1-6 of 1978 and February 15-24 of 1980.

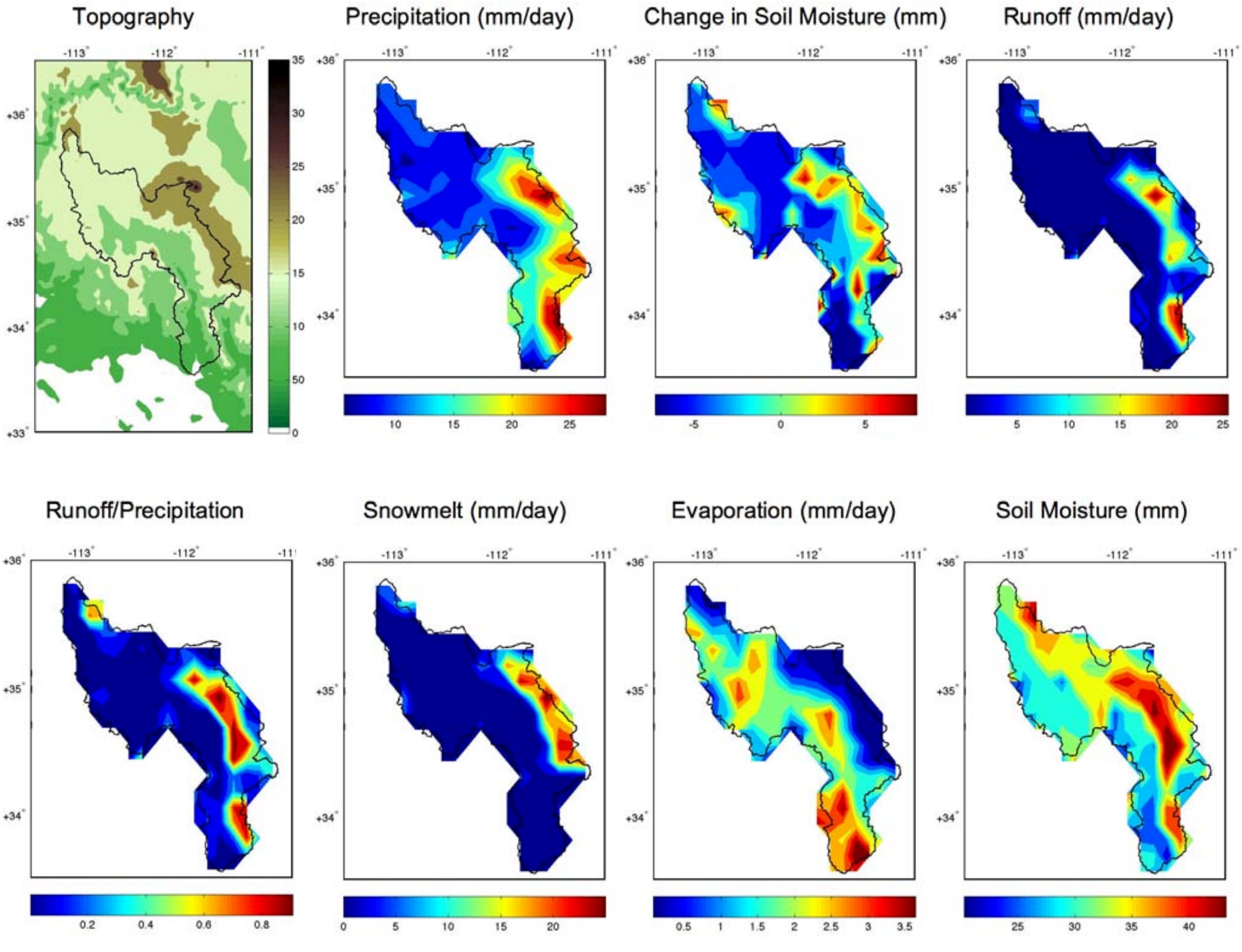


Figure 9. Topography and average hydrologic response of the Verde Basin to the extreme flooding event on March 1-6 of 1978 as simulated by the VIC hydrologic model.

Figure 9 shows different hydrologic variables over the Verde River Basin averaged in time for the March 1-6, 1978 period of intense flooding. We can see that the precipitation focused on the mountainous eastern part of the basin. This part of the basin also experiences significant changes in soil moisture and runoff – while evapotranspiration is concentrated in the warmer lower elevations. Soil moisture changes (March 6 – March 1) are positive in the higher elevations and negative in the valley. From this preliminary analysis it is clear that different locations within the watershed serve a different hydrologic function.

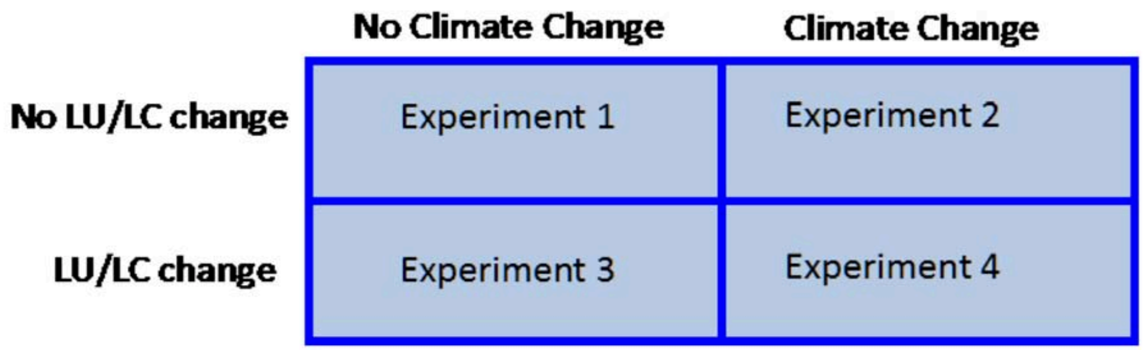
5. CONCLUSIONS AND FUTURE WORK

Understanding how the combined effect of climate change and LULCC could affect climate in the Tucson-Phoenix urban corridor and watersheds is of critical importance in this rapidly developing semiarid region. We address this question through the use of historical observations and numerical modeling. The work is divided in two objectives:

5.1. Relative effect of LULCC and climate change on extreme precipitation events in the Tucson-Phoenix urban corridor

Using the Weather Research Forecast (WRF) regional climate model coupled to a state-of-the-art land surface model with detailed characterization of urban regions, we have begun the process of ingesting modified land cover data into the WRF model and calibrating the model for the year 2004. We find that there is an overestimation of precipitation in the eastern side of the domain, and we are evaluating the effect of anomalous lateral boundary conditions.

When the calibration of the model is finished, we will begin our experiments (see Figure 10 for the experimental design.



	No Climate Change	Climate Change
No LU/LC change	Experiment 1	Experiment 2
LU/LC change	Experiment 3	Experiment 4

Figure 10. Experimental design for WRF-Noah-UCM simulations.

Task 1: Run model for 3 dry and 3 wet historical summer seasons using historical land cover, with NCEP/DOE -RII atmospheric forcing (Experiment 1). We will then modify land cover data to 2050 projected conditions, using the same atmospheric forcing (Experiment 3). These two experiments will show the sensitivity of climate to different land cover conditions.

Task 2: With historical land cover data we will run model using future climate projections 2031 – 2040, and historical climate 1991 – 2000 with UKMO-Hadcm3 forcing (Experiment 2). We will do the same with projected land cover (Experiment 4). These experiments will allow us to quantify relative importance of land cover change with respect to climate change on regional climate.

Task 3: repeat Task 2 with MPI-Echam5 forcing data.

5.2. Effect of climate change on ecosystem services provided by the Verde Basin Watershed

We focus on the flood mitigation role of the Verde watershed, based on previous simulations performed by Rajagopal et al. (2012, 2013). We have compared extreme flooding events, defined as those above the 98th percentile, in both the historical VIC simulations and the USGS data. Based on this analysis we have selected two winter periods and performed a preliminary evaluation of the hydrologic response of the watershed to extreme precipitation.

We will now perform an evaluation of the ecosystem services of the watershed based on an approach that uses hydrologic modeling results to quantify flood regulation functions of different land cover classes which enables the assignment of ecosystem service supply capacities for each of them. The method is based on the assumption that land cover classes presented in areas with high water regulation capacities (as calculated by the hydrologic modeling and the soil type assessment) have high flood regulating capacities. Thus, the results of the capacity assessments performed in the case study areas can be used for ecosystem service mapping in all areas where respective land cover and soil data are available

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