Arnold Schwarzenegger
Governor

HYDROLOGICAL TRENDS OVER THE WESTERN UNITED STATES: PATTERNS AND POTENTIAL CAUSES

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Scripps Institution of Oceanography,
United States Geological Survey,
Lawrence Livermore National Laboratory,
Centre for Atmospheric and Oceanic Studies

August 2010
CEC-500-2010-026

Prepared By:
[1] Scripps Institution of Oceanography
[2] United State Geological Survey
[3] Lawrence Livermore National Laboratory
[4] Centre for Atmospheric and Oceanic Sciences
T. Das[1], H.G. Hidalgo[1], M.D. Dettinger[2,1], D.R. Cayan[1,2], D.W. Pierce[1], C. Bonfils[3], T.P. Barnett[1], G. Bala[3,4], A. Mirin[3]
La Jolla, CA 92037[1,2]
Livermore, CA 94550[3]
Bangalore, Karnataka, India[4]
Commission Contract No. 500-02-004
Commission Work Authorization No. UC MR-025

Prepared For:
Public Interest Energy Research (PIER)
California Energy Commission

Guido Franco
Contract Manager

Linda Spiegel
Program Area Lead
Environmental Area

Kenneth Koyama
Office Manager
Energy Systems Research Office

Thom Kelly, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Melissa Jones
Executive Director

Acknowledgments

This work was supported by the Lawrence Livermore National Laboratory through a Laboratory Directed Research and Development grant to the Scripps Institution of Oceanography (SIO) via the San Diego Supercomputer Center for the Lawrence Livermore / University of California Scientific Data management (LUSciD) project. The U.S. Geological Survey and SIO provided partial salary support for Dan Cayan and Michael Dettinger; and the California Energy Commission Public Interest Energy Research Program, through the California Climate Change Center, provided partial salary support for Dan Cayan, David Pierce, and Hugo Hidalgo and the National Oceanic and Atmospheric Administration Regional Integrated Sciences and Assessments Program provided partial salary support for Dan Cayan, Mary Tyree, and Jennifer Johns at SIO. The Program of Climate Model Diagnosis and Intercomparison (PCMDI) supported Céline Bonfils and Govindswamy Bala (the former via a Department of Energy Distinguished Scientist Fellowship awarded to B. Santer). The Variable Capacity Infiltration (VIC) model calibrated soil parameters were generously provided by Andrew W. Wood at the 3 Tier Group, Seattle, WA 98121. The authors thank Mary Tyree for her support in processing some of the data. The authors thank Jennifer Johns for her comments on the initial version of the manuscript.

Cite as:

Das, T., H.G. Hidalgo, M.D. Dettinger, D.R. Cayan, D.W. Pierce, C. Bonfils, T.P. Barnett, G. Bala, A. Mirin. 2010. *Structure and Origins of Trends in Hydrological Measures Over the Western United States*. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2010-026.

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Structure and Origins of Trends in Hydrological Measures Over the Western United States is the final report for the Continuing Climatic Data Collection, Analyses, and Modeling project (Contract Number 500-02-004, Work Authorization Number UC MR-025) conducted by Scripps Institution of Oceanography, United State Geological Survey, Lawrence Livermore National Laboratory, and the Centre for Atmospheric and Oceanic Sciences. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

Table of Contents

List of Figures

List of Tables

Abstract

Estimation of climate change impacts at local levels in important river basins in California are needed because changes of temperature and flows affect hydropower generation, water supply, and may have important ecological implications. This study examines, at about 7.5 miles spatial resolution, the geographic structure of observed trends in key hydrologically relevant variables (e..g, late winter and spring temperature, total number of snowy days during the winter as a fraction of total number of wet days during the winter) across California and the western United States over the period 1950-1999 and investigates whether these trends are significantly different from trends associated with natural climate variations. The observed changes were compared to natural internal climate variability simulated by global and regional climate models. The authors find that the observed winter temperature and each of the hydrologic parameters have experienced significant changes over considerable parts of the snow-dominated western United States. These trends are not likely to have resulted from natural variability alone but by warming of regions where mean spring temperature is close to freezing.

These findings are important for California because it suggests that climate change is already affecting water resources in the State and, therefore, California must start preparing for these changes.

Keywords: Climate change, detection, regional climate, downscaling, variable infiltration capacity (VIC)

Executive Summary

Introduction

A large number of studies have investigated recent trends in observed and simulated hydro-meteorological variables (e.g., snowpack levels) across the western United States. In regions with complex topography, such as the western United States, there are wide variations in temperature. Some of these studies have inferred that such changes are partially caused by rising greenhouse gas concentrations, which alter temperature and thus affect the snow pack distribution in the western United States, and partially by decades-long (decadal) natural climatic fluctuations over the North Pacific Ocean. A recent study by Scripps Institution of Oceanography and Lawrence Livermore National Laboratory applied different methods to distinguish whether these recent changes occurred as the result of internal natural variations within the climate system or as the result of human influence. Computer runs of climate models were used to characterize long-term climatic variations that could arise solely from internal climate fluctuations. The overall study showed that recent trends in snowpack, winter temperatures, and streamflow timing across the western United States have been outside the bounds of natural variability (that is, they are detectably unnatural) and that they have been so similar to trends projected by combinations of climate models and hydrologic models forced with human-caused greenhouse-gas increases that they may be confidently attributed (in part) to human influence on the global climate.

Purpose

The overall study described above focused on subregional-scale summaries of conditions across the western United States. This study determined whether detectable climate changes can be identified over the western United States' complex topographic setting (including California) at high spatial resolution (about 7.5 miles). The authors used simulations using regional climate models assuming that increases in greenhouse gas concentration in the atmosphere have not taken place and simulations (control simulations) and simulations with greenhouse gas concentrations going up as seen in the historical record. The researchers also used a well tested hydrologic model known as the Variable Infiltration Capacity (VIC) model to estimate locations where changes in hydrological variables are unlikely to have been due to natural variability inherent to the system.

Project Objectives

The objective of this report is to identify the fraction of the regions of the western United States where detectably unnatural trends should be expected. The authors focus on some simple indices that are of immediate interest to California's water resources, including late winter and spring temperature; total number of wintertime snowy days as a fraction of all wet winter days; first April snow water equivalent as a fraction of October through March precipitation total; and January-February-March runoff as fraction of water-year (October to September) total.

Project Outcomes

The following were the major outcomes for this project:

- Using key hydrologic measures, including January-February-March temperature; fraction of days with snow; first April snow water equivalent as a fraction of October through March precipitation total; and January-February-March runoff fractions, the researchers find that that the observed winter temperature and each of the hydrologic measures have undergone significant trends over considerable parts (37–89 percent) of the snow-dominated western United States.
- These trends are not likely to have resulted from natural variability alone, as gauged from the distribution of trends produced from the long control (without increasing greenhouse gases) simulation. In a relatively large portion of the Columbia River basin, and to a lesser extent in the California Sierra Nevada and in the Colorado River basin, trends in snow accumulation and runoff timing are unlikely to have been caused by natural variations alone. These trends are caused by warming of regions with mean spring temperature close to freezing.
- In all cases, the significant changes occurred in a direction consistent with the sign of the changes associated with warming, for example, January-February-March average temperature increases, days with snowfall decreases, snowpack decreases, and January-February-March runoff increases.
- The authors also analyzed the fine-scale data in snow-influenced catchments across the western United States. To find a detectable trend (at 95 percent confidence level) at the catchment scale, at least 25 percent of the total catchment area must have trended significantly for snowy days as a fraction of wet days and snowpack water content, but at least 45 percent area for January-February-March runoff fractions.

Conclusions

The present study yields results, on a fine-scale grid, that indicate a positive detection of changes in hydrologic variables that could not be expected from natural variability in many areas within the western United States. The authors used long model control (no increased in greenhouse gases in the atmosphere) simulations to quantify the trends in the variables likely to arise from natural internal climate variability and compared the observed trends to those variables. If this warming continues into future decades as projected by climate models, there will be serious implications for the hydrological cycle and water supplies in California and the rest of the western United States. The present study brings the results down to scales needed for water management, studies of ecosystem diversity, and anticipation of wildfires.

Recommendations

This study shows that the hydroclimatic measures explored here are sensitive and useful monitors of the early effects of climate change (in particular of regional warming) at the scales of small to large river basins. The observed changes are spatially complex and depend on altitude as well as location within the region. Continued monitoring of the changes already underway needs to be supported and, indeed, expanded to even broader areas. Notably, the middle elevation zones of the West are probably under monitored.

Benefits to California

Previous work examining climate change impacts on a global scale has led to an understanding that the effects of climate change are likely to be significant. However, there is a mismatch between the spatial resolution of information such global studies provide (typically approximately 125 miles) and the resolution needed to understand how climate change will affect California's water supply and ecosystems. California's varied and complex topography will ultimately benefit from information at even finer scales than the about 7 miles considered here, but this work is nonetheless a significant step in the direction needed to understand climate change's effects on the state's hydrology. The changes in the physical environment quantified in this work can help form the basis for policies and management practices that are informed by an understanding of how the environment is likely to change in coming decades.

1.0 Introduction

A growing number of studies investigating recent trends in the observed (and simulated) hydro-meteorological variables across the western United States can be found in the literature. The main changes observed in this region include a large increase of winter and spring temperatures (Dettinger and Cayan 1995; Karoly et al. 2003; Bonfils et al. 2008a; 2008b), a substantial decline in the volume of snow pack in low and middle altitudes (Lettenmaier and Gan 1990; Dettinger et al. 2004, Knowles and Cayan, 2004; Hamlet et al. 2005), a significant decline in April 1st Snow Water Equivalent (SWE; Mote 2003; Mote et al. 2005; Mote 2006; Mote et al. 2008; Pierce et al. 2008), and a reduction in March snow cover extent (Groisman et al. 2004). A reduction of the proportion of precipitation falling as snow instead of rain has also been observed (Knowles et al. 2006), as well as an earlier streamflow from snow dominated basins (Dettinger and Cayan 1995; Cayan et al. 2001; Stewart et al. 2005; Regonda et al. 2005), and a sizeable increase of winter streamflow fraction (Dettinger and Cayan 1995; Stewart et al. 2005). These recent changes threaten to have important impacts on western United States water resources management and distribution if the changes continue into future decades (e.g., as in projections of greenhouse-forced warming trends) (Barnett et al. 2004; Christensen et al. 2004; 2007). This is because much of the water in the western United States is stored as snow in winter, which starts to melt during late spring and early summer. Due to earlier snowmelt and more precipitation falling as liquid instead of stored as snow, there could be new stresses on the existing water resources management structures in the western United States in coming decades.

In some of these studies, it has been indicated that such changes are partially linked with rising greenhouse gas concentrations, which alter temperature patterns and thus affect the snow pack distribution in the western United States, and partly from natural climatic decadal fluctuations over the North Pacific Ocean (Dettinger and Cayan 1995). Pacific Decadal Oscillation (PDO; Mantua et al. 1997) fluctuations, the dominant decadal natural variability in this region, however can only partially explain the magnitude of the recent changes in snowfall fractions (Knowles et al. 2006), spring snow pack (Mote et al. 2005) and center timing from snow-dominated basins (Stewart et al. 2005). Knowles et al. (2006), Mote et al. (2005) and Stewart et al. (2005) argued that the remaining parts of the variability might be due to large-scale anthropogenic warming.

Only recently have formal efforts been undertaken (Knutson et al. 1999; Karoly et al. 2003; Bonfils et al. 2008a and Maurer et al. 2007) to distinguish whether the recent changes occurred due to internal natural variations of the climate system or human influence using rigorous detection-and-attribution procedures (Hegerl et al. 1996; 1997; Barnett et al. 2001; Zwiers and Zhang 2003; The International Ad Hoc Detection and Attribution Group 2005; Zhang et al. 2007; Santer et al. 2007). In formal terms, detection is the determination that a particular climate change or sequence is unlikely to have occurred solely due to natural causes. In the present study, climate from a long control run of a climate model is used to characterize the kinds of long-term variations that can arise solely from the internal fluctuations of the global climate system. Other external but natural, forcings of the climate system, like solar-irradiance changes and volcanic emissions, cannot be tested with available control runs of sufficient length (although Barnett et al. (2008) tested hydroclimatic trends from a simulation with climate forced only by historical solar and volcanic influences and found that observed trends could not be attributed to those influences). Attribution (not undertaken here) is a later step in which the particular causes of the "unnatural" parts of observed trends are rigorously identified. Detection studies are important because if the recent changes are found to be due to internal natural variations alone, one can reasonably anticipate that the climate system will return to its past states after some time has passed.

Karoly et al. (2003) carried out a comparison of temperature trends in observations and three model simulations at the scale of Northern America. They found that the temperature changes from 1950 to 1999 were unlikely to be due to natural climate variation alone, while most of the observed warming from 1900 to 1949 was naturally driven. Accounting for uncertainties in the observational datasets, Bonfils et al. (2008a) observed noticeable increases in California-averaged annual mean temperature for the time periods 1915-2000 and 1950-1999. These warmings are too large and too prolonged to have likely been caused by natural variations alone. In this study, natural variations were characterized using a long control (no change in greenhouse-gas concentrations) simulation by global climate models to develop multi-model 86-year and 50-year trend distributions. The authors also indicated that the recent warming in California is particularly fast in winter and spring and is likely associated with human-induced changes in large-scale atmospheric circulation pattern occurring over the North Pacific Ocean. The hypothesis that human activities have influenced the circulation over the North Pacific Ocean is strengthened by a recent study (Meehl et al. 2008) that has identified an anthropogenic component in the phase shifts of the PDO mode.

More recently, a series of three formal fingerprint-based detection and attribution studies have been performed for the western United States region. These studies have focused on various late winter/early spring hydrologically-relevant temperature variables (Bonfils et al. 2008b) and SWE as a fraction of precipitation (SWE/P; Pierce et al. 2008) over nine mountainous regions, and on center timing of stream flow (CT; defined as the day when half of the water year flow has passed a given point) in three major tributaries areas of the western United States (California region represented by the Sacramento and San Joaquin rivers, Colorado at the Lees Ferry and Columbia at The Dalles; Hidalgo et al. 2008b). Bonfils et al. 2008b showed that the changes in the observed temperature-based indices across the mountainous regions are unlikely, at a high statistical confidence, to have occurred due to natural variations. They concluded that changes in the climate due to anthropogenic greenhouse gasses (GHGs), ozone, and aerosols are causing part of the recent changes. Similarly, Pierce et al. (2008) and Hidalgo et al. (2008b) showed that the observed changes in SWE/P and in CT are unlikely to have arisen exclusively from natural internal climate variability. Barnett et al. (2008) performed a multiple variable detection and attribution study and showed how the changes in minimum temperature

(Tmin), SWE/P and CT for the period 1950-1999 co-vary. They concluded, with a high statistical significance, that up to 60% of the climatic trends in those variables are human-related.

In regions with complex topography such as the western United States, there are strong gradients in temperature and associated hydrologic structure. These strong gradients provide a strong incentive to investigate responses to climate variability and climate change at high resolution (e.g., ~12 km) scales that are much finer than are provided by global climate models. However, the detection of climate change at fine scales may be challenging because the signal-to-noise ratio decreases with increasing resolution (Karoly and Wu 2005). Consequently, the majority of the previous works on detection study have been performed on global, continental or sub-continental scale. On the other hand, when a variety of elevational settings are lumped together, the response to warming may be diluted because of the strong variations that are mixed together. For example, Hidalgo et al. (2008b) were able to detect fractional runoff changes that were different from background natural variability at a high level of confidence in the Columbia basin, changes aggregated over the California Sierra Nevada and in the Colorado basins were only marginally significant or not at all. Maurer et al. (2007) examined whether the decreases in CT, at four river points in the Sierra Nevada, are statistically significantly different from changes associated with internal natural variability. Maurer et al. (2007) concluded that the recent observed trends in streamflow timing at the four river points analyzed are still within the trends obtained from the simulated natural variations. This suggests that, in settings that contain high topographic variation, it may be useful to evaluate climate responses at finer, rather than coarser spatial units.

Thus, based on coarser regional results, the present study investigates the hypothesis that there are detectable climate changes that can be delineated over a complex topographic setting using a high resolution 1/8 degree (~ 12 km resolution) spatial network over the western United States (Fig. 1a). Because of the increased signal to noise issues that plague evaluations at this scale, the present study does not attempt to formally attribute the causes of the unnatural trends at every grid cell. Rather, the present study will use fine resolution simulations to investigate the spatial structure of detectable trends across the snow-dominated western United States. The motivation of the present study is to find the fraction of the regions of the western United States where detectably unnatural trends should be expected. The researchers focus on some simple indices, which are hydrologically relevant in the area of interest, including late winter and spring temperature, winter-total snowy days as a fraction of winter-total wet days, 1st April Snow Water Equivalent as a fraction of October through March precipitation total, and seasonal runoff fraction. Although global climate changes have been well described in the literature, and even some regional ones, for many applications, such as regional water management, studies of ecosystem diversity, and anticipation of wildfires, finer spatial detail is needed. The researchers also extend the analysis to investigate the fraction of grid cells within a catchment that are required to exhibit detectable changes in order to achieve detectability from the catchment-aggregated runoff and other measures. This would provide a useful rule of thumb for many practical purposes, such as designing monitoring networks or helping to decide whether there should even be (detectable) trends in a catchment of interest.

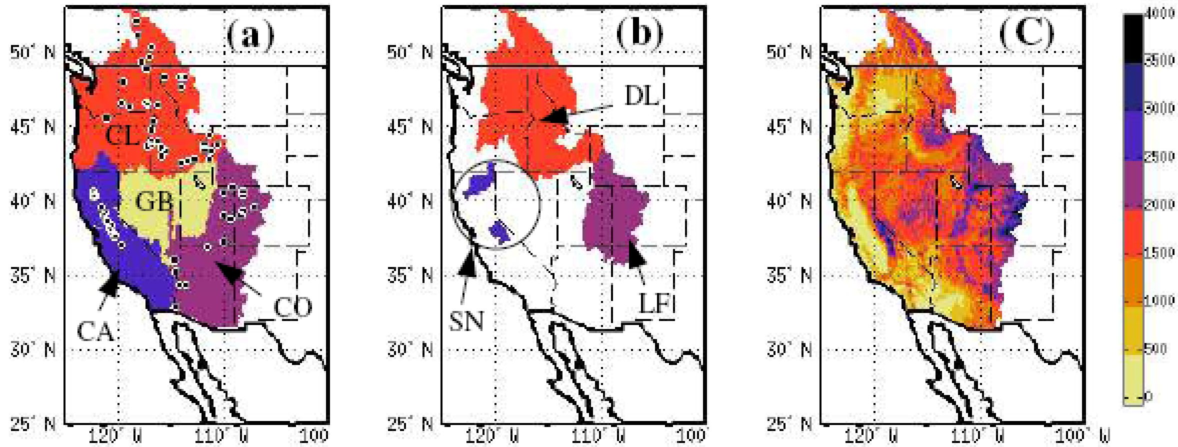

Figure 1(a). Simulation domain showing four major basins/region in the western United States; CA: California region (mostly the Sacramento and San Joaquin River basins), GB: Great Basin, CO: Colorado River basin, CL: Columbia River basin; dots represent the outlet of selected catchments. (b) Selected tributaries areas in the western United States; SN: Sacramento at Bend Bridge and San Joaquin tributaries, LF: Colorado at the Lees Ferry, DL: Columbia at The Dalles. (c) elevation (in meters above sea level).

Source: Authors

This article is organized as follows. Section 2 presents the data sets and models used in this study. A description on the methodology and definitions of various climate indices analyzed in this study are given in Section 3. Section 4 presents results obtained for the different indices analyzed. The relationship between total significant area and detectability at catchment scale is also presented in Section 4. A summary and conclusions are given in Section 5.

2.0 Data Sets and Models

2.1. Observed Data and Global Climate Model Results

Gridded meteorological observations were used to characterize observed climate changes occurring across the western United States over the period 1950-1999. Daily gridded precipitation, maximum and minimum temperature observations at 1/8 degree spatial resolution were obtained from the Surface Water Modeling Group at the University of Washington (http://www.hydro.washington.edu; Hamlet and Lettenmaier 2005). In order to investigate the sensitivity of the results to the meteorological observational datasets (used to drive a hydrological model), the authors have repeated the entire analysis using a different version, the Maurer et al. (2002) dataset, which did not include any form of adjustment for temporal inhomogeneities. The conclusions remained insensitive to the choice of the observational dataset used. In the following sections, only the results using the Hamlet and Lettenmaier (2005) dataset are presented, because this dataset was produced with attention to accounting for station and instrument changes that would otherwise add non-climatic noise to the long-term trend signal (Hamlet and Lettenmaier 2005).

Internal climate variability in western United States in the absence of any anthropogenic effects is characterized using precipitation and temperature data from an 850-year pre-industrial control simulation of the NCAR/DOE Community Climate System Model (CCSM3; Collins et al. 2007). The simulation was performed at Lawrence Livermore National Laboratory and used the Finite Volume (FV) dynamical methods for the atmospheric transport (CCSM3-FV; Bala et al. 2008a; 2008b). The horizontal spatial resolution of the atmospheric model was 1 × 1.25 degree with 26 vertical levels. This pre-industrial control simulation used constant 1870-level atmospheric composition to force the model. Bala et al. (2008a) have evaluated the fidelity of a 400-year present day control climate simulation that used this FV configuration for CCSM3. They found significant improvement in the simulation of surface wind stress, sea surface temperature and sea ice when compared to a spectral version of CCSM3.

2.2. Downscaling of the Control Run

Daily precipitation total (P) and daily maximum and minimum temperatures (Tmax, Tmin) from the CCSM3-FV model were downscaled to 1/8 degree resolution using the Constructed Analogues (CANA; Hidalgo et al. 2008a) statistical downscaling method. The CANA procedure starts with a simple variance correction to ensure the same variability of the GCM data as observations. Then, the bias-corrected global model fields are downscaled using a linear combination of previously observed patterns[1] (Maurer and Hidalgo 2008; Hidalgo et al. 2008a). The 30 most similar previously observed patterns are used in a linear regression to obtain an estimate that best matches, on the coarse grid, the GCM pattern to be downscaled. The downscaled values of precipitation and temperatures are estimated by applying the linear

[1] The coarsened gridded meteorological observations of Maurer et al. (2002) from the period 1950 to 1976 and their corresponding high resolution patterns were used as the library.

regression coefficients to the fine scale versions of the previously observed patterns. Results using CANA and those obtained with another statistical downscaling methodology (bias correction and spatial downscaling; Wood et al. 2004), are qualitatively similar (Maurer and Hidalgo 2008). An advantage of the CANA method over the bias correction and spatial downscaling method is that CANA can capture changes in the diurnal cycle of temperatures; the downside is that to do this it requires daily observations rather than monthly. Details of the CANA method can be found in Hidalgo et al. (2008a).

2.3. Hydrological Model

Runoff and SWE, major variables of interest to hydrological studies, have not been readily observed at the temporal and spatial scales required for this study. Likewise, they cannot be obtained by downscaling global model results, since no library of observed fine-resolution daily fields exist to use in the downscaling scheme. Accordingly, to produce both the "observed" and climate model driven SWE and runoff fields on the fine spatial scale, the authors use the Variable Infiltration Capacity (VIC; Liang et al. 1994; 1996) model (version 4.0.5 Beta release 1). To estimate the "observed" trends, the authors drove VIC with observed daily P, Tmin, and Tmax fields on the 1/8 degree grid; to estimate the downscaled climate model trends, the authors drive VIC with the downscaled model daily P, Tmin, and Tmax fields on the 1/8 degree grid. VIC uses a tiled representation of the land surface within each model grid cell and allows sub-grid variability in topography, infiltration and land surface vegetation classes (Maurer et al. 2002). The sub-surfaces are modeled using three soil layers with different thickness. Surface runoff uses an infiltration formulation based on the Xinanjiang model (Wood et al. 1992), while baseflow follows the ARNO model (Liang et al. 1994). Sub-grid variability in soil moisture storage capacity is represented through the use of a spatial probability distribution function, and a nonlinear recession function is used to model the base flow component from the lowest soil layer (Liang et al. 1994; Sheffield et al. 2004). VIC has been successfully applied at spatial scales ranging from regional to global (Hamlet et al. 1999; Maurer et al. 2002; Wood et al. 2004; Christensen et al. 2004; Christensen and Lettenmaier 2007; Hamlet et al. 2007; Maurer 2007; Barnett et al. 2008; Pierce et al. 2008; Hidalgo et al. 2008b; Nijssen et al. 2001; Sheffield and Wood 2007).

The calibrated soil parameters for VIC were obtained from Andrew W. Wood at the University of Washington, presently at 3 Tier Group, Seattle (personal communication, 2007). The vegetation cover was obtained from the North American Land Data Assimilation System (NLDAS). The VIC model was run at a daily time step with the settings of 1-hour snow model time step, and five snow elevation bands. The first 9 months of the simulations were used for model initializations and were not considered for further analysis, as suggested by Hamlet et al. (2007). A number of variables, including runoff, baseflow, soil moisture at three soil layers and SWE were produced from the VIC model using the gridded observed and model control run meteorologies along with the physiographic characteristics of the catchment (for example soil and vegetation). The ability of the model to simulate monthly streamflow at some of the calibration points across the study domain is satisfactory when compared with the naturalized streamflow (Maurer et al. 2002; Hamlet et al. 2007; and see Fig. 3 Hidalgo et al. 2008b).

Additionally, Mote et al. 2005 found reasonable agreement between the spatial pattern of observed SWE and the VIC simulated values.

2.4. Definition of Climate Variables

This study focused on five hydrologically relevant detection variables:

- Monthly and seasonal precipitation as a fraction of total precipitation over the water year (October through September).
- Monthly and seasonally averaged temperatures.
- Seasonal (January-February-March) accumulated runoff (as simulated by VIC), calculated as the fraction of accumulated runoff over the water year.
- 1st April SWE as a fraction of October through March precipitation total (SWE/P_{ONDJFM}), chosen to reduce the influence of precipitation on snowpack and produce a snow-based climate index that is more directly sensitive to temperature changes (Pierce et al. 2008).
- The fraction of winter days with precipitation occurring as snow to the total number of winter days with precipitation. A given wet day (day with precipitation amount is above 0.1 mm), in the period November through March, was classified as a snowy day if the amount of snowfall (*S*) is greater than 0.1 mm. *S* was calculated using the same equation as in VIC according to the formula:

$$S = \begin{cases} 0 & \text{for } T \geq T_{rain} \\ P \cdot \left(\dfrac{T - T_{rain}}{T_{snow} - T_{rain}} \right) & \text{for } T_{snow} < T < T_{rain} \\ P & \text{for } T \leq T_{snow} \end{cases} \quad (1)$$

Where, *T* is the daily average temperature, T_{snow} is the maximum temperature at which snow can fall and T_{rain} is the minimum temperature at which rain can fall. To be consistent with the VIC model simulations, the values of T_{snow} and T_{rain} were set to -0.5°C and 0.5°C respectively.

2.5. Natural Variability in the Control Run

The strength of the conclusions of any detection analysis rely on the ability of the control model to represent the strength and key features of the natural internal climate variability in the absence of anthropogenic effects. In particular, the ability to simulate decadal variability is crucial for the identification of slow-evolving climate responses to slow-evolving external forcings. To compare the low-frequency variability in the model control run simulation to observations, the authors have computed standard deviations in each grid cell for each index after application of a 5-year low-pass filter. The observations were linearly detrended before the calculation in an attempt to remove the linear part of possible anthropogenic influence. The low-frequency variability in the control simulation is reasonably well represented with no evidence that the model systematically under- or over-estimate the observed variability for all climate indices (Fig. 2). Thus, the authors concluded that the CCSM3-FV model used here provide an adequate representation of natural internal climate variability for the detection work. Barnett et al. (2008), Pierce et al. (2008) and Bonfils et al. (2008b) have also tackled this issue using the CCSM3-FV data (i.e., Barnett et al. 2008 Fig. S3) and found similar conclusions.

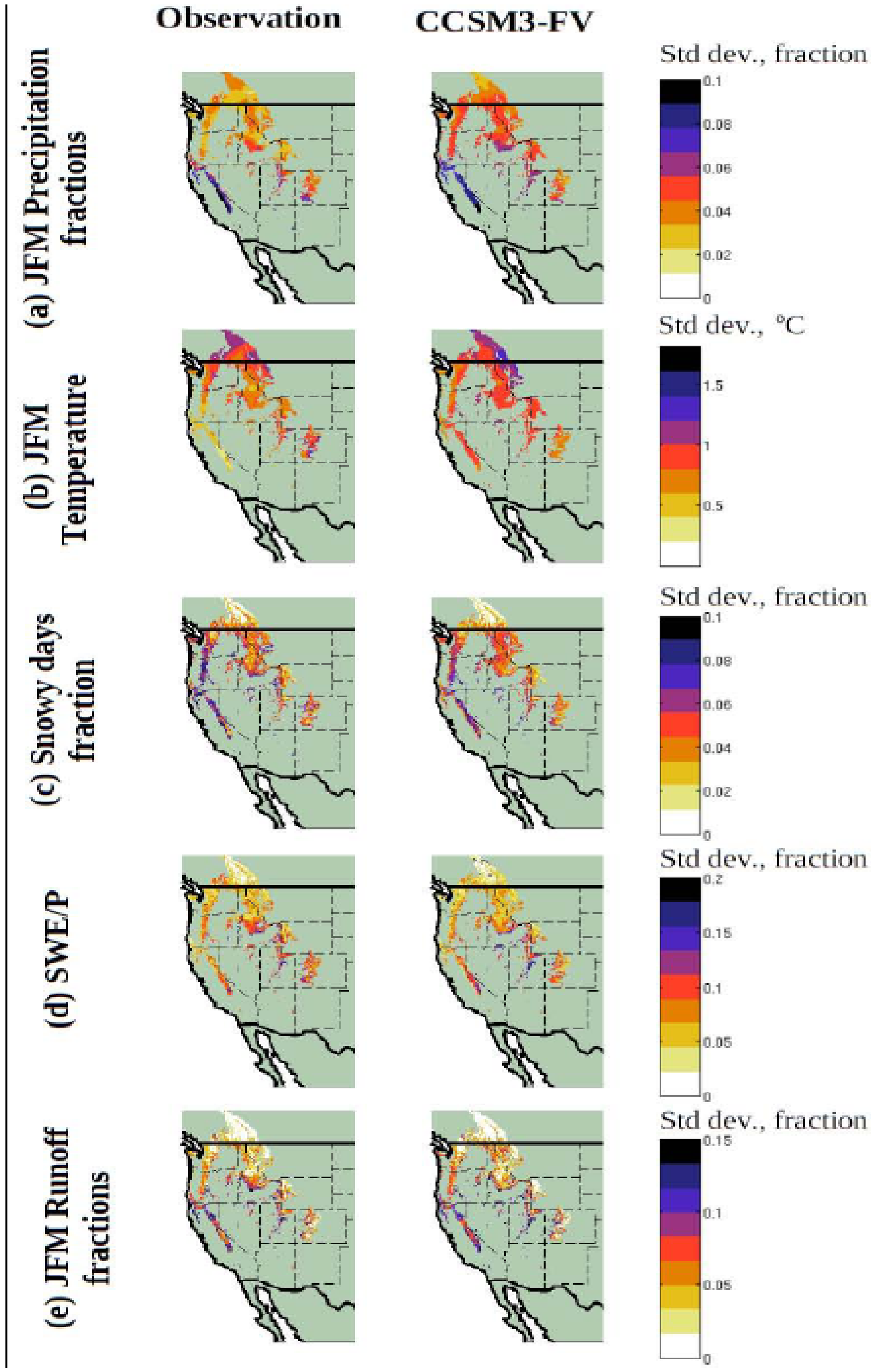

Figure 2. Standard deviations of 5-year low pass filtered climate indices obtained using downscaled CCSM3-FV run and gridded observation (for VIC grid cells with at least 50 mm mean value of SWE on 1st April). The observations were linearly detrended before the calculation of standard deviation to remove the part of the possible anthropogenic influence. (a) JFM total precipitation as a fraction of water year total precipitation, (b) JFM

average temperature, (c) Snowy days as a fraction of wet days, (d) SWE/P_{ONDJFM} and (e) JFM total runoff as a fraction of water year total runoff.

Source: Authors

3.0 Method

At each grid cell and for each variable, the linear trend over 50-year segments (with the start of each segment offset by 10 years from the previous segment's start) was calculated from the 850-year control run. This produced 80 partially overlapping estimates of what the 50-year trend could be in the absence of anthropogenic forcing. An Anderson-Darling test[2] (Anderson and Darling, 1952) showed that the distribution of control run trends was Gaussian in the great majority of the grid cells, except for some grid cells of the JFM runoff fractions. Accordingly, the authors used the mean and standard deviation from the control run to fit a Gaussian distribution at each grid cell.

The authors evaluated the observed trends mainly over the interval of water years 1950-1999 and later over different starting and ending years within this period. The probability of finding the observed trend in the estimated Gaussian distribution of unforced trends is computed using a two-tailed test. The authors used a two-tailed test because the authors did not make any *a priori* assumption on the direction of the trends of the indices analyzed, since the authors wanted to evaluate, for example, a significant lack of negative temperature trends as well as a significant surplus of positive temperature trends. Fig. 3 shows the schematic diagram of the methodology the authors employed to compute the probability. The bars represent the distribution of the 50-year unforced trends in the model control run. If an observed trend (arrow) falls within the shaded region (showing the two-tailed p=0.05 level), which indicates the amplitude of naturally-driven trends that occur only in 5% of the time, the researchers can conclude that this trend is unlikely to be the result of internal natural variations. Probability maps for each variable were obtained by applying this procedure to all model grid cells across the western United States.

The researchers also examined the effect of spatial coherence on the results using a Monte Carlo simulation as in Livezey and Chen (1982) and Karoly and Wu (2005). Since there is a high spatial coherence of the hydro-meteorological variables, this can lead to spurious detection, as described in those references. The Monte Carlo approach used accounts for the effects of this spatial coherence.

---

2 Anderson-Darling test is a modification of Kolmogorov-Smirnov test in which a test statistic (p) was calculated to The assess whether the distribution of the trends in the climate indexes computed using the control run data were drawn from a population with a normal distribution. The null hypothesis that the data (trends in the climate indexes computed using the control run) came from a normal distribution was rejected when the calculated p-value was less than a chosen alpha (0.05).

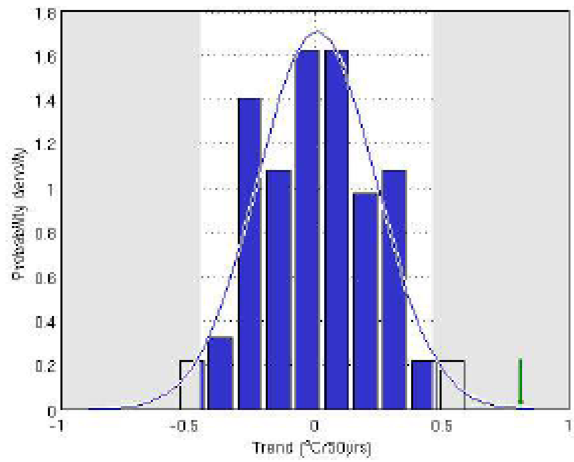

Figure 3. Schematic showing method used to calculate the probability of the JFM average temperature trend being exceeded in the control run. Bars show the distribution of the trends from the control run and the arrow indicates the observed trend. Note if the trend from observation fall within the shaded region indicate the observed trend can be found from the control run simulation at only 5% of the times.

Source: Authors

Because the main focus is to investigate the changes in hydrology, the analysis begins by focusing on the mountainous western United States, where warming-related impacts are particularly important (Mote et al. 2005) and for which hydrological changes may have large implications for the water supply, ecology, or likelihood of wildfire in the region. As in Hamlet et al. (2007), locations where mean April 1st SWE is greater than 50 mm are included.

In a last section, the analysis is extended using the data on the selected catchments across the western United States to identify relationships, for each of the climate variables, between the fraction of catchment area within which significant changes have occurred and the significance of detectability at the whole-catchment scale. Trends in 66 catchments across the western United States were analyzed (Fig. 1a). The areas of the catchments range between 720 km^2 and 679,248 km^2, with a median value of 19,008 km^2. The average elevations of the catchments range between 359 m and 2900 m, with a median value of 1763 m. The catchment-average spring (March-April-May) temperatures range between -2°C and 14°C, with a median value of 3°C.

4.0 Results and Discussions

4.1. Spatial Pattern of Observed Trends

The authors analyzed observed monthly precipitation (for January through March) as a fraction of water year total precipitation, and monthly average temperatures, for the period 1950 through 1999. The trends found in monthly precipitation fraction were well within the distribution of natural variability as estimated from the control model run (not shown). This agrees with the results of Barnett et al. (2008), who also found that natural variability could account for changes in water year total precipitation for the mountainous western United States during this period.

Observations show warming temperatures since 1950 over the western United States during the months of January, February, and March (Fig. 4a). Among these months, March average temperature shows the strongest widespread upward trend, with larger warming trend in the interior west than the region along the coast. Notable warming in January is concentrated along the coast of California region and Columbia River basin, and February average temperature shows widespread but only mild warming trends; see Knowles et al. 2006, for more detail on these cool-season warming patterns.

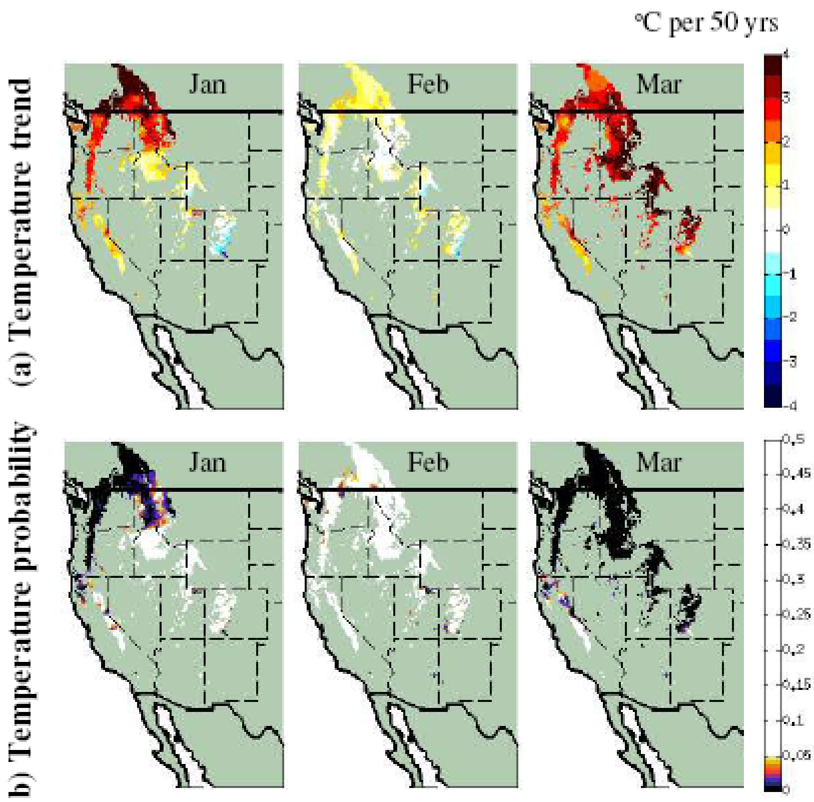

Figure 4(a). Observed trends in monthly average temperature and (b) probabilities of observed trends in monthly average temperature being exceeded in control run trend distribution.

Source: Authors

In view of the considerable warming trends for the study domain during January and March, changes in observed JFM (January-February-March) average temperature were investigated. A linear trend calculation using the JFM average temperature shows a considerable upward trend across most parts of the snow-dominated western United States, with notably larger warming trends across the high mountains of the Columbia River basin (Fig. 5a).

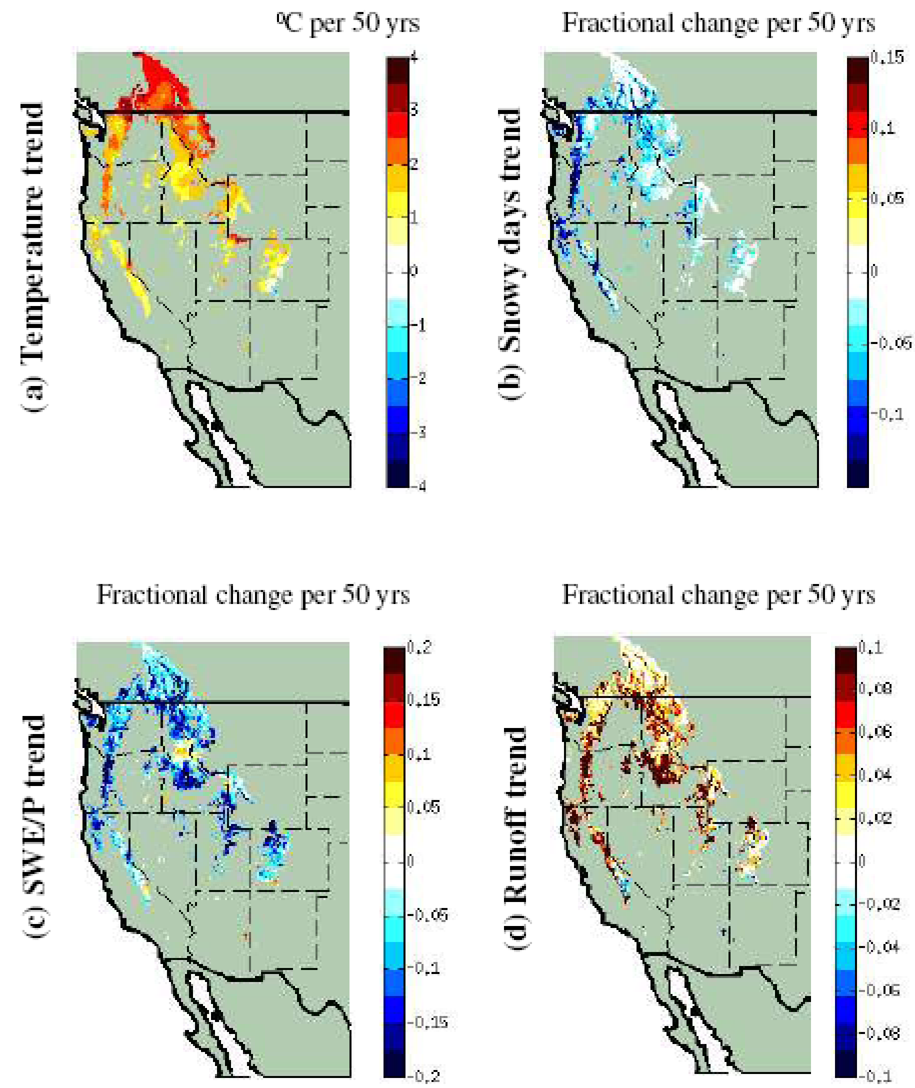

Figure 5. Observational trends for the period 1950-1999. (a) JFM average temperature, (b) Snowy days as a fraction of wet days, (c) SWE/P$_{ONDJFM}$ and (d) JFM accumulated runoff as a fraction of water year accumulated runoff.

Source: Authors

A chain of hydrologic responses to warming was evident in the trends. Downward trends in observed winter-total snowy days as a fraction of winter-total days with precipitation, indicating a decrease in days with snowfall, are also common across many parts of the snow dominated region in the observed simulation, except in regions at the Northern Rockies, which show no trend (Fig. 5b). There are widespread downward trends in observed SWE/P_{ONDJFM} across most parts of the snow dominated western United States, with stronger downward trends in the northern Rockies of the Columbia River basin along with some upward trends at the Southern Sierra and part of Northern Rockies (Fig. 5c). These findings are in agreement with those of Pierce et al. (2008), who described declining fractional SWE/P from snow course data across the nine mountainous regions of the western United States. These trend patterns are also consistent with the results in Mote et al. (2005), who analyzed April 1st SWE from 824 snow stations for the period 1950-1997, and Hamlet et al. (2005), who analyzed VIC simulated April 1st SWE. Using regression analyses, those two studies attributed the widespread downward trend in SWE to a warming trend, and a more regional upward trend in SWE in the southern Sierra (in the California region) to an increase of precipitation over the period. Changes in snowmelt initiation and changes in snow-to-rain ratio should concur with large changes in runoff. Indeed, upward trends in JFM runoff fractions predominate across the snow-dominated western United States, except some weaker downward trends in the Canadian part of the Columbia River basin and Colorado Rockies (Fig. 5d).

4.2. Comparison of Observed Trends With Model Control Run Trends Distribution at the Grid Scale

Figs. 4b and 6 illustrate the probability of the observed trends in Figs. 4a and 5 arising in absence of any external forcings. There are considerable regions over which the observed trends in January and March average temperature are unlikely to have arisen from internal natural variability alone (at 95% significance level) (Fig. 4b). By contrast, the mild warming trends in February are not detectably different from internal natural variability (Fig. 4b).

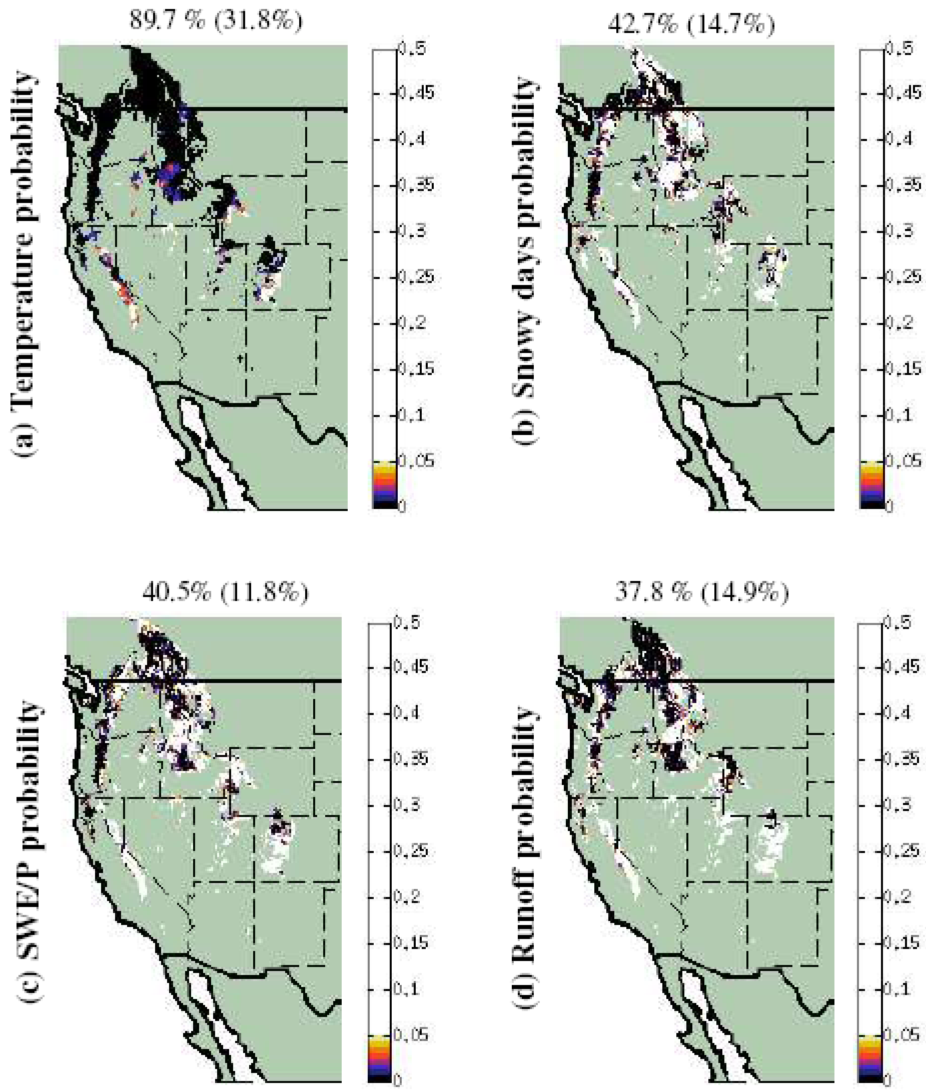

Figure 6. Same as Fig. 5, except for the probabilities of the observational trends (as shown in Fig. 5) being exceeded by trends from the model control run. Percentage in upper right are fractions of VIC grid cells significantly different from the control run at 95% confidence level, and, in parenthesis, the percentage that could occur due to randomness (obtained from the Monte Carlo resampling) (a) JFM average temperature, (b) Snowy days as a fraction of wet days, (c) SWE/P_{ONDJFM} and (d) JFM total runoff as a fraction of water year total runoff.

Source: Authors

The observed trends toward warmer JFM average temperature across nearly all (89%) of the snow-dominated regions of the western United States cannot be explained (at 95% confidence level) by internal natural variability alone, except relatively small areas of the Southern Sierra (California region) and Southern Rockies (lower Colorado River basin) (Fig. 6a). The downward trends of the snow day fraction of wet days (Fig. 6b) also exhibit detectable signals for many grid cells, 42%, over mountainous western United States. The decline in SWE/P_{ONDJFM} found in the observations, 40% of the snow-dominated grid points, is also unlikely to be associated with natural variations alone in many regions (Fig. 6c). However, opposite changes in regions containing upward trends in SWE/P_{ONDJFM} (e.g., Southern Sierra and Utah) cannot be confidently distinguished from internal natural variability. Consistent with the warming and reduction in fraction of snowy days and SWE/P_{ONDJFM} increases in JFM runoff fraction exceed those expected from natural variations alone over substantial mountainous regions, 37% of the snow-dominated grid points, especially in the Columbia River basin, (Fig. 6d). Changes in regions such as the Southern Sierra (California region) and Southern Rockies (Colorado River basin) cannot be distinguished confidently from natural variability.

There is high spatial coherence in the meteorological and hydrological variables, which may overstate how widespread the statistically significant trends are (Livezy and Chen 1982) in Fig. 6. In order to estimate the sampling distribution of the percentage of the grid cells that could simultaneously show a statistically significant trend in the model control run, taking the observed spatial coherence into account, a Monte Carlo experiment was performed based on resampling from the model control run. The authors sequentially selected all 800 possible 50-year segments (i.e., moving 50-year windows with 1-year shifts) of the 850-year control run and computed the probability map from each selection, as done previously with the observations. This resulted in 800 probability maps. The fraction of grid cells exhibiting a apparently detectable signal (at 95% confidence level) was computed from each probability map, giving us 800 values with which to estimate the distribution of the fractions of grid cells that might, by chance, yield a seemingly detectable signal in a 50-year segment from the control run. Although this number would 5% *on average* over the 850-year control run if all grid cells varied independently of each other, the lack of independence between nearby grid cells means that, in any particular 50-year segment, either very few or very many grid cells might show seemingly significant trends. Consequently, the 95th percentile of this rather wide sampling distribution is considerably greater than 5% of the grid cells; the Monte Carlo-derived value is noted for each hydroclimatic variable in parenthesis in the panel titles of Fig. 6. The 95th percentile limits are still much less than the observed fractions of grid cells exhibiting significant trends for each variable, indicating that more grid cells contain significant trends than would be expected by chance, even taking the spatial coherence into account (Fig. 6).

An important property of the changes depicted in Fig. 6 is that they depend on elevation. In order to illustrate the dependence of the changes on elevation, the total number of observed grid cells showing significant trends for each elevation class were computed. Results are shown in Fig. 7, where the grey regions indicate results not significantly different from the control run at the 95% level, based the Monte Carlo resampling. Notably, the grey regions include zero; the wideness of the sampling distribution, noted above, means that even finding *no* grid cells with a significant trend does not indicate a statistically significant *lack* of trends. For example, finding no grid points at all with a statistically significant *decrease* in temperature is still consistent with the control run. Consequently, all significant results presented here arise from a surfeit of trends, not a lack of trends.

In Fig. 7, red points on the left hand panels show the numbers of positive trends, and blue points on the right hand panels show the number of negative trends. The JFM warming (Fig. 7b, left) is detectable at all elevations, but the very small number of downward trends is not inconsistent with natural variability (Fig. 7b, right). The fraction of cells exhibiting significant upward trends decreases monotonically with elevation.

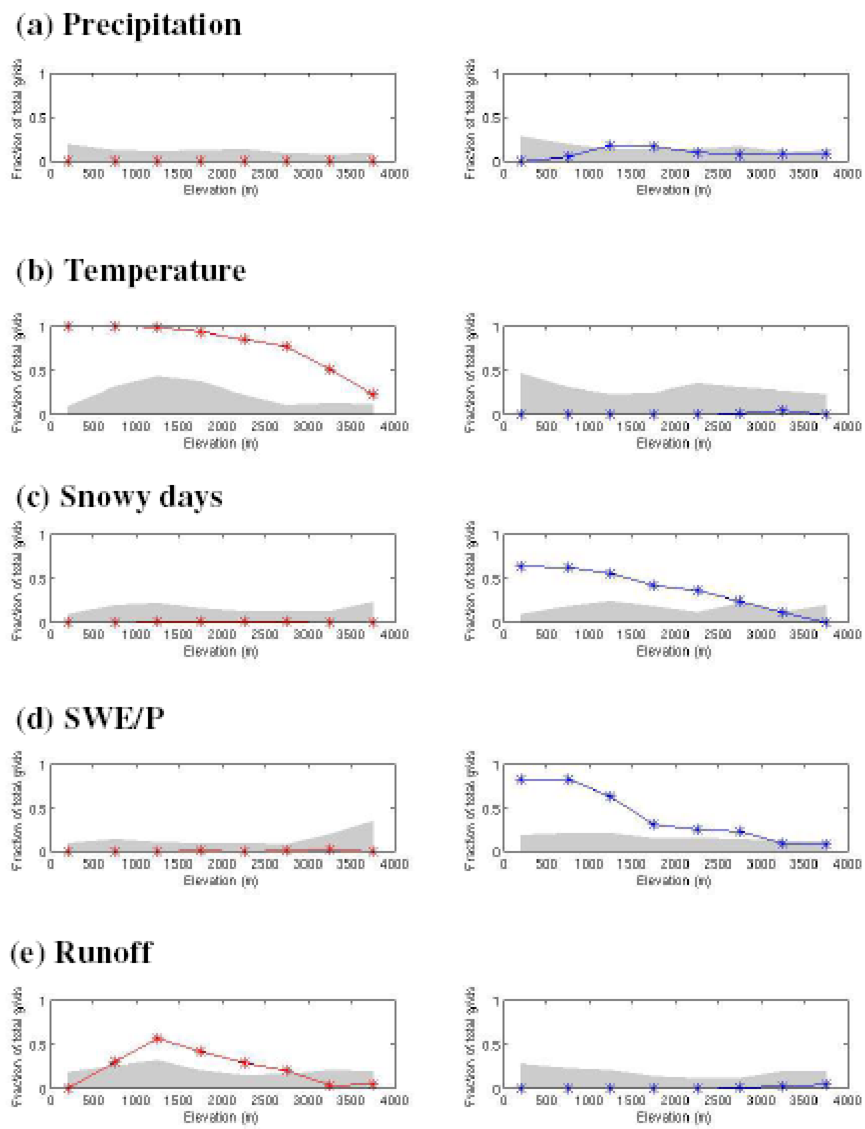

Figure 7. Accumulated number of grid cells as a fraction of total grid cells in each elevation class. On left, red points show the results with positive trends. On right, blue colors show the results with negative trends. Light black regions indicate that results not significant from the control run at the 95% level (using the Monte Carlo resampling method). (a) JFM total precipitation as a fraction of water year total precipitation, (b) JFM average temperature, (c) Snowy days as a fraction of wet days, (d) SWE/P_{ONDJFM} and (e) JFM total runoff as a fraction of water year total runoff.

Source: Authors

The decline of the snowy days as a fraction of wet days from elevations near sea level up to 3000 m also exhibits a high tendency of being statistically significantly different from the distribution of trends from natural variations alone (Fig. 7c, right panel). Conversely the grid cells with increasing trends—which show up mostly in small patches in the Rocky Mountains (e.g., also, Knowles et al. 2006)—are not inconsistent with natural variability (Fig. 7c, left panel). The reduction in SWE/P_{ONDJFM} is particularly detectable at the lower elevations, but it is also detectable at medium altitudes (below 3000 m) (Fig. 7d, right panel). The grid cells with positive trends (Fig. 7d left panel) for all elevation classes, and the highest grid cells with negative trends (more than 3000 m), exhibit trends in numbers that could be expected due to natural variability.

The upward trends in the JFM runoff fractions in the regions with elevation ranging between approximately 750 m to 2500 m tend to be statistically significantly more common than the model estimated natural trends (Fig. 7e, right panel); however, the downward trends for all elevation classes and the upward trends at lower altitudes (lower than 750 m), and higher altitudes (higher than 2750 m) are not statistically significant in numbers than those that would occur due to natural variability (Fig. 7e). Thus JFM runoff fraction trends in the middle elevations--high enough to have significant snowmelt contributions but low enough so that temperatures are close to freezing during critical times—have changed in ways that cannot readily be attributed to natural variability nor to spatial coherence of random occurrences. As noted above, decreasing trends in temperature and runoff, as well as increasing trends in snowy days and SWE/P_{ONDJFM} occur rarely, cannot be shown to be different from natural variability with this data set. However, precipitation trends were not found to be different from natural, except around elevation 1500 m (Fig. 7a). Thus hydrological trends driven by temperatures are the ones most likely to be unnatural. Previous detection and attribution studies of regionally averaged variables (Barnett et al. 2008; Bonfils et al. 2008b; Pierce et al. 2008; and Hidalgo et al. 2008b) have successfully attributed the temperature trends that are detected here at fine scales to forcing from greenhouse gases.

Fig. 8 demonstrates another aspect of the hydrological changes – the number of grid cells that show significant trends, stratified by 1950-1999 climatological spring average temperature classes (instead of elevation classes). Trends that tested as having significant magnitudes were nearly all found in locations having mean temperatures above -4 ^{o}C. Interestingly, the changes for snowy days, SWE/P_{ONDJFM} and runoff fractions are consistent with natural variability for cells where spring temperatures are below – 4^{o}C. The results support the findings of Knowles et al. (2006) that showed that regions at low to medium elevations with temperature near freezing are more likely to have a decrease in the fraction of precipitation falling as snow, and also consistent with Mote et al 2005 who found these elevations to have incurred unusual reductions in spring snowpack. Figures 7 and 8 also show that changes in the sense *a priori* expected from warming conditions (for example, a decrease of days with snowfall) are more prevalent than those in the opposite sense. Again, the changes in the JFM precipitation fraction at different temperature ranges are not outside what could be expected due to internal natural variability, except at temperature class -4 ^{o}C.

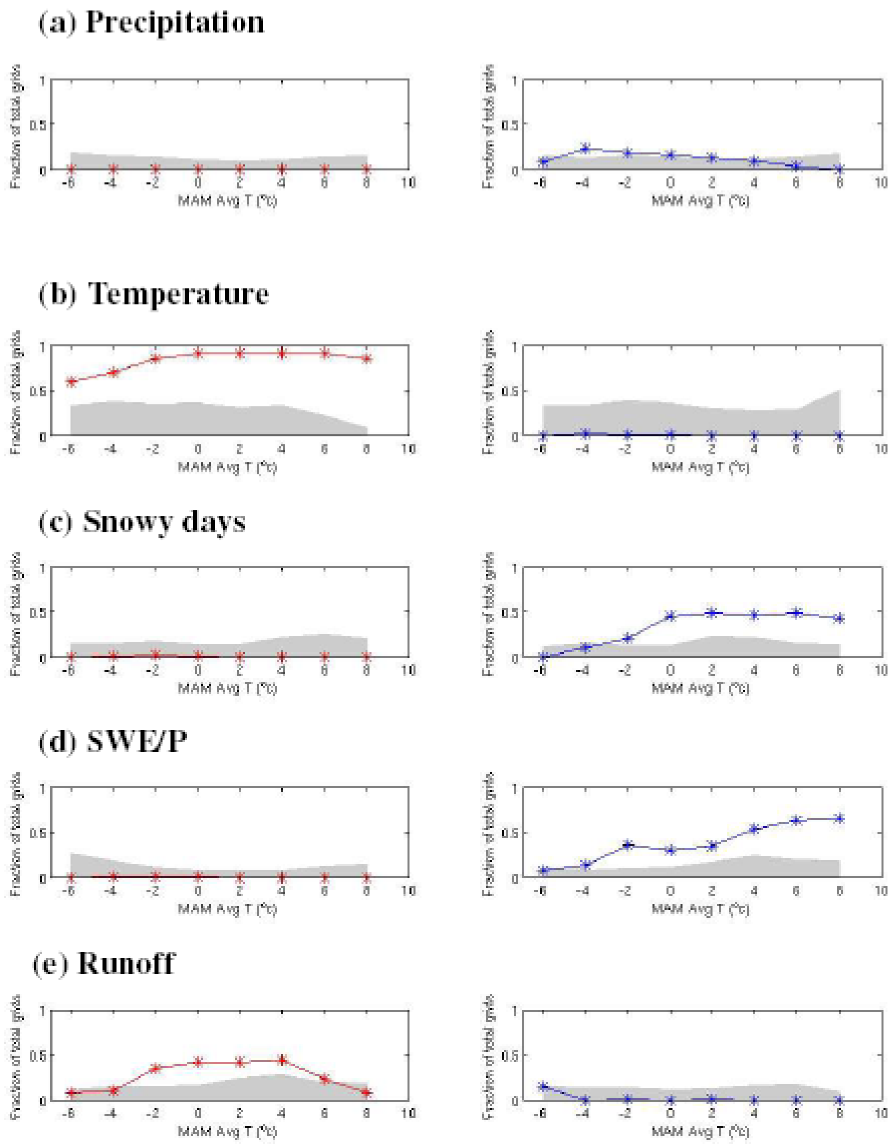

Figure 8. Same as Fig. 7, except the grid cells are categorized according to MAM temperature class. a) JFM total precipitation as a fraction of water year total precipitation, (b) JFM average temperature, (c) Snowy days as a fraction of wet days, (d) SWE/P_{ONDJFM} and (e) JFM total runoff as a fraction of water year total runoff.

Source: Authors

The authors also investigated the sensitivity of these results to the time period analyzed. As an example the results from the JFM average temperature are shown in Fig. 9 (a). In this experiment, three different analysis periods were used, all starting in 1950, to compute the observed trends: 30 years (1950-1979), 40 years (1950-1989), and 50 years (1950-1999). The results show that the longer periods contain more grid cells exhibiting a detectable warming trend (Fig. 9a, left panel). This is different from what is expected for natural variability in an equilibrated climate system, where the period of averaging will make no systematic difference to the fraction of grid cells deemed to have significant trends. Interestingly, the grid cells located at higher elevations (above approximately 1500 m) exhibit more detectable trends as the time period increases in length. Also, the changes at the grid cells located at high elevations are not inconsistent with natural variability for the shorter time period (1959-1979) (Fig. 9a, left panel). Two potential reasons can explain these results: (a) increases in noise when trends are calculated over shorter time periods, or (b) the strength of the trend becomes stronger at the end of the time period (as can occur if the climate respond to the slow-evolving anthropogenic forcing).

To investigate these possibilities, the trends were reanalyzed using a fixed period length of 30 years, but with three different starting years: 1950, 1960 and 1970 (Fig. 9, right panel). Starting in 1950, cells with warming that is greater than would be expected locally from the natural variability are all below 750 m elevation. In contrast, starting in 1960, grid cells with locally detectable warming are above 2250 m, but the Monte Carlo resampling suggests that the numbers of trends seemingly distinguishable from natural variability are not, yet, any larger than might be expected from the spatially coherent natural-variability fields. Starting in 1970, though, cells above 2250 m experienced a detectable warming (Fig. 9a, right panel). Thus the warming trends appear to have begun at lower elevations earlier than at higher elevations. Longer observational records also contributed to researchers' growing ability to detect the long-term trends. Similar patterns were also found in the hydrological variables analyzed in this paper (SWE/P_{ONDJFM} and JFM runoff fractions) (Fig. 9b and Fig. 9c), indicating the crucial role of the very longest time series in analyses such as this.

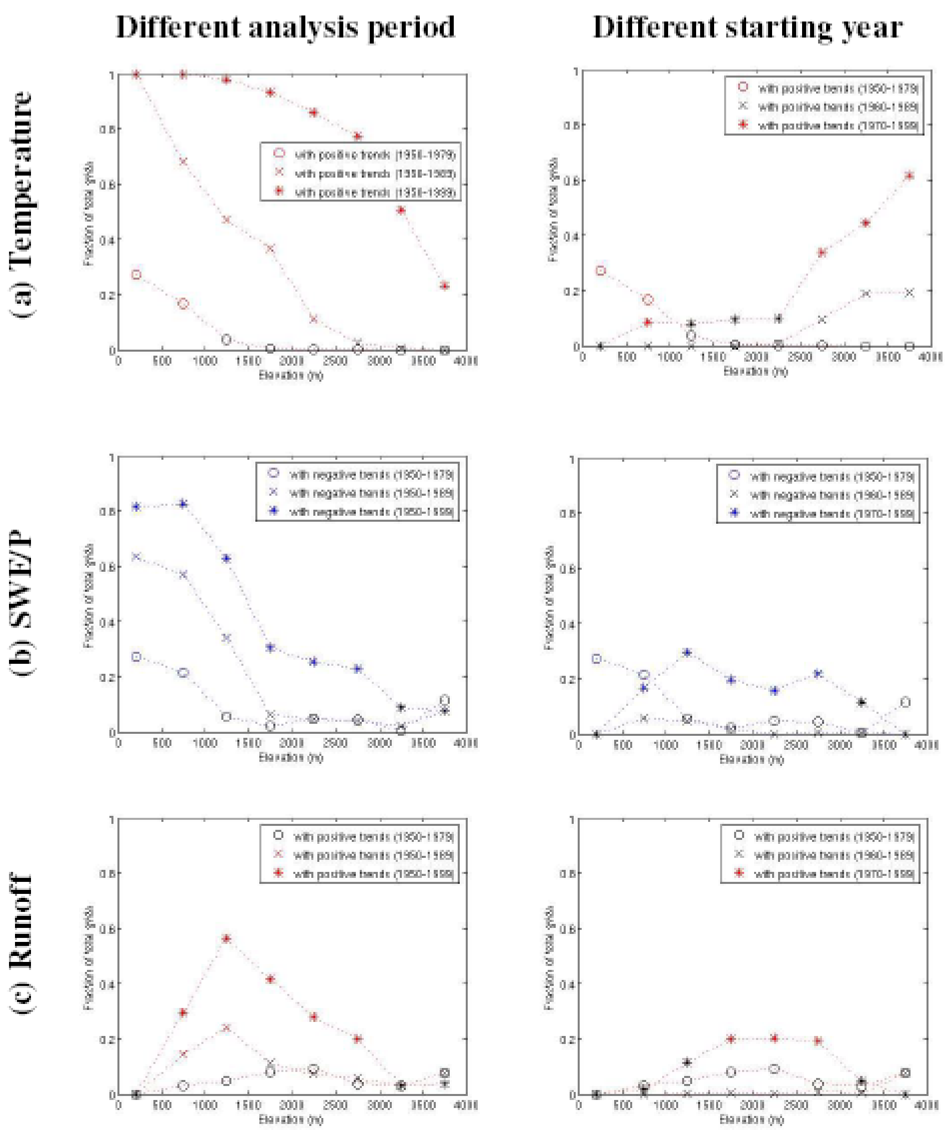

Figure 9. Same as Fig. 7, except the grid cells are accumulated over different time intervals. Left panel shows results when analysis period was 30 years, 40 years, and 50 years, all beginning 1950. Right panel shows results for three different 30 year periods having different staring years, 1950, 1960, and 1970. As before the magnitude of the observed trends are compared to those from an ensemble of segments of the control run having the same record length. Red points show the results with significant (at 95% confidence level) positive trends, blue colors show the results with significant negative trends, and light black colors symbols show results that were not significant from the control run using the Monte Carlo resampling method. (a) JFM average temperature, (b) SWE/P_{ONDJFM} and (c) JFM total runoff as a fraction of water year total runoff.

Source: Authors

4.3. Detection at Catchment Scale

Very often, observations and decisions involving these hydroclimatic trends are addressed to the basin scales, rather than to the individual 12-km grid cells analyzed here. For example, runoff is measured and managed primarily as streamflow accumulated to the river basin scale rather than as a distributed runoff patterns. Thus, in light of the strong elevation dependence of the detectability of trends discussed above, it is natural to ask, "How much of a basin must lie within these critical elevation bands before the observations from the basin as a whole are likely to show detectable trends?" To address this issue and perhaps to develop some rules of thumb for where to expect detectability of unnatural trends thus far, the authors analyze briefly the relations between fractions of catchment areas with detectable trends and corresponding detectability of trends at the whole-catchment scale.

Trends in 66 catchments across the simulation domain of the western United States were analyzed (Fig. 1a). Hydroclimatic variables from all grid cells within a given catchment were averaged for the observed (or simulated using the observed meteorology) and control run data. The probabilities of any resulting trends of the catchment-averaged observed time series were then computed using the same procedure previously applied at the grid-cell scale (described in section 3). The detectability of unnatural trends within each catchment-averaged series was then compared to the fractions of grid cells within that catchment that were locally detectably distinguishable from the control-run natural variability.

This analysis indicates that approximately 25% of the catchment area must have trended significantly (at 95% confidence level) before there are detectable changes (at 95% confidence level) in the catchment level for snowy days as fraction of wet days and SWE/P_{ONDJFM}. Approximately 45% of the catchment area must have trended significantly before there are detectable trends in JFM runoff fractions at the catchment scale (Fig. 10).

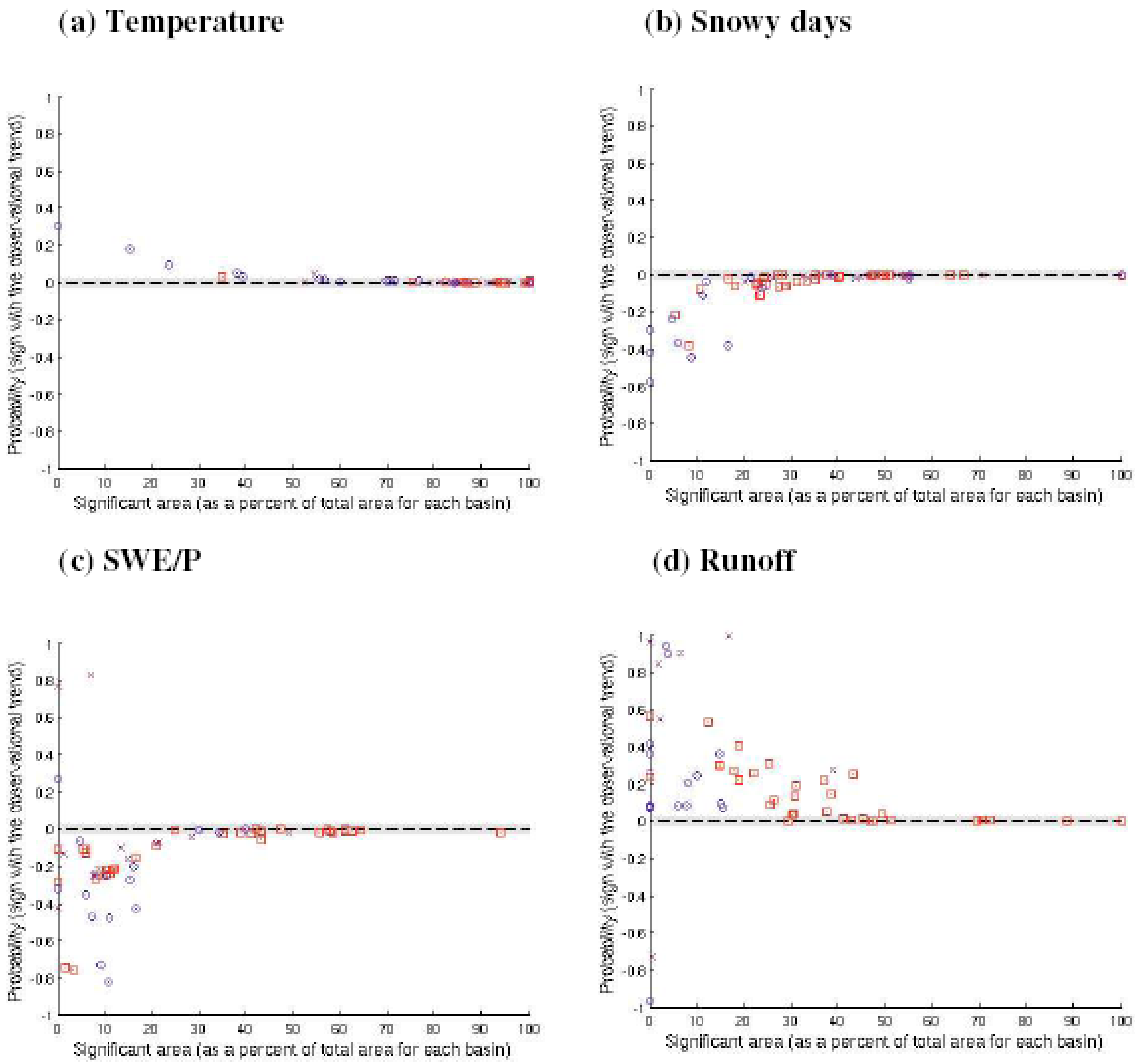

Figure 10. Ordinate shows, for aggregate over a catchment, the probability of that observed trends are different from those from control run, plotted against (abscissa), the percentage of grid points within a catchment having observed trends significantly (at 95% confidence level) greater than those from control run trends. (a) JFM average temperature, (b) Snowy days as a fraction of wet days, (c) SWE/P_{ONDJFM} and (d) JFM total runoff as a fraction of water year total runoff. In the figures "squares", "×" and "circles" symbols show the results for the catchments located in the Columbia River basin, Colorado River basin, and California region (as shown in Fig. 1a), respectively. Symbols within shaded region indicate the observed trends (at the catchment scale) different than the model control run trends distribution at 95% confidence level.

Source: Authors

Since certain elevation zones or average spring temperature bands are most likely to yield detectable trends (thus far), it would be useful to know whether the (known) fraction of a catchment area within these ranges dictates detectability at the catchment scale, better than the area with locally "detectable" trends, which generally is not known *a priori*. Unfortunately, no clearly preferred mean spring temperature ranges or elevation ranges that characterize the significant catchment were found, except with respect to JFM runoff fractions. Catchments with significant trends in JFM runoff fractions all have catchment-average spring temperatures between-2^{o}C and 6^{o}C and those catchments are located at the medium elevation range (approximately ranging between 1400 m and 2500 m). Fractions of catchment areas within such ranges, rather than catchment-average values, did not relate usefully to whole-catchment detectability.

5.0 Summary and Conclusions

This study employs at the fine-scale (1/8 degree × 1/8 degree latitude-longitude) analysis of meteorological and hydrological variables to investigate the structure of observed trends from 1950-1999 in some key hydrologically relevant measures across the western United States. Combined with an 850 year natural variability GCM control simulation, observations were evaluated to determine which elevations and locations have experienced trends that are unlikely to be derived entirely from internal natural climatic variations. The VIC hydrologic model is used to simulate the surface hydrological variables during the observational period and also that arising from the GCM control run. Using key hydrologic measures, including JFM temperature, fraction of days with snow, SWE/P_{ONDJFM} and JFM runoff fractions, the authors find that the observed winter temperature and each of the hydrologic measures have undergone significant trends over considerable parts (37–89%) of the snow dominated western United States (Fig. 6). These trends are not likely to have resulted from natural variability alone, as gauged from the distribution of trends produced from the long control simulation. In a relatively large portion of the Columbia and to a lesser extend in the California Sierra Nevada and in the Colorado River basin, trends in snow accumulation and runoff timing across many middle altitudes are unlikely to have been caused by natural variations alone (Fig. 7). These trends are caused by warming of regions with mean spring temperature close to freezing.

In all cases, the significant changes occurred in a direction consistent with the sign of the changes associated with warming. For example, JFM average temperature increases, days with snowfall decreases, snowpack decreases, and JFM runoff increases. Reinforcing this result is that trends that occurred in the opposite direction are no more frequent than would be expected from natural variability, small and non-significant.

For SWE and JFM runoff fractions that have been evaluated here, good observational datasets do not exist for the spatial scales considered here. The VIC hydrological model forced by observed meteorological conditions was used to simulate these variables, a limitation of this study that should be kept in mind. Though the VIC model performance has been evaluated for the domain of interest for a number of variables (Maurer et al. 2002; Mote et al. 2005), there could be uncertainties arising from several factors, including lack of ability to simulate accurate observed trend, or uncertainties in the preparation of the gridded forcing data set (particularly at the mountains due to fewer stations available for the interpolation). There may be some biases due to specific stations used to construct the gridded data set. There are many localized "point" trends that probably originate at individual stations.

Experiments that considered different start and end points of the 1950-1999 interval suggest that significant warming and associated hydrological trends, not explained by natural variations, have begun earlier at lower elevations than at higher elevations. Longer observational records contribute a growing ability to detect the trends.

The analysis using the data on many snow-influenced catchments across the western United States domain indicated that, to find a detectable trend (at 95% confidence level) at the catchment scale, at least 25% of the total catchment area must have trended significantly for snowy days as a fraction of wet days and SWE/P_{ONDJFM}, but at least 45% area for JFM runoff fractions (at 95% confidence level) (Fig. 10). These thresholds provide a context to understand the behavior observed in the major tributaries areas of the western United States (used in Barnett et al. 2008 and Hidalgo et al. 2008) (California Sierra Nevada, Colorado at the Lees Ferry and Columbia at The Dalles) (as shown in Fig. 1b) as well as many smaller river basins. Among the three major tributaries areas analyzed there, the Columbia contains the largest percentage area with significant trends for April 1 SWE/P_{ONDJFM} (decreasing) and for the fraction of annual runoff in JFM (increasing), as shown in Table 1. While the portion of the Sierra and Colorado with significant trends in these measures is 15%, or less, those in the Columbia exceed 25%. Stronger signatures observed in the Columbia basin are quite clearly a reflection of the greater proportion of low-middle elevations and, in association, a preponderance of late winter and early spring temperatures in the sensitive -2°C to +4°C category. Lower to middle altitudes (near sea level to nearly 3000 m) of California showed the second highest percentage area exhibiting significant trends, but these signals are diluted by the much larger number of grid cells that are located in an elevational environment where warming has not been great enough to produce a significant effect. Warming of even a few degrees in the higher altitudes, above 3000 m, where the temperature is currently much below the freezing point in winter is not sufficient yet to make detectable changes.

Table 1. Areas with significant changes (at 95% confidence level) as a percentage of total area in three major tributaries areas of the western United States (as shown in Fig. 1b) for different climate variables.

	California Sierra Nevada	Colorado at the Lees Ferry	Columbia at The Dalles
JFM average temperature	63.3	85.3	88.7
Snowy days as a fraction of wet days	22.3	48.1	35.6
SWE/PONDJFM	15.2	8.5	24.8
JFM runoff as a fraction water year runoff total	5.5	2.9	25.6

Source: Authors

In addition to conducting climate detection on a very fine scale, the present study differs from most previous trend significance studies, in which a more traditional significance test (parametric or nonparametric) is performed to assess whether or not an observed trend is significantly different from zero. Naturally occurring climate phenomena such as the Pacific Decadal Oscillation can give statistically significant trends over long periods, so the presence of non-zero trends is not necessarily inconsistent with the hypothesis that the trends are caused by natural variability. Instead long model control simulations were used to quantify the trends in variables likely to arise from natural internal climate variability and compared the observed trends to those.

The present study yields results, on a fine-scale grid, that indicate a positive detection of changes in hydrologic variables that could not be expected from natural variability in many sub-areas within the western United States, but experiments were not conducted to attribute these changes to particular external forcings. However, given the conclusions of Barnett et al. (2008), Bonfils et al. (2008b), Pierce et al. (2008), and Hidalgo et al. (2008b) using the same domain but at a much larger spatial scale (nine regions over the western United States), the authors can reasonably predict that the origin of a substantial portion of the trends is anthropogenic warming. If this warming continues into future decades as projected by climate models, there will be serious implications for the hydrological cycle and water supplies of the western United States. The present results usefully bring the results of regional-scale detection-and-attribution down to scales needed for water management, studies of ecosystem diversity, and anticipation of wildfires.

6.0 References

Anderson, T. W. and D.A. Darling, 1952: "Asymptotic Theory of Certain 'Goodness-of-fit' Criteria Based on Stochastic Processes." *Annals of Mathematical Statistics*, 23:193-212.

Barnett, T. P., D. W. Pierce, and R. Schnur, 2001: "Detection of Anthropogenic Climate Change in the World's Oceans." *Science*, 292, 270–274.

Barnett, T.P., R. Malone, W. Pennell, D. Stammer, B. Semtner, and W. Washington, 2004: "The Effects of Climate Change on Water Resources in the West: Introduction and Overview." *Climatic Change*, 62: 1-11.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A.Wood, T. Nazawa, A. Mirin, D. Cayan and M. Dettinger, 2008: "Human-Induced Changes in the Hydrology of the Western U.S." *Science*, doi:10.1126/science.1152538.

Bala, G., R.B. Rood, A. Mirin, J. McClean, K. Achutarao, D. Bader, P. Gleckler, R. Neale and P. Rash, 2008a: "Evaluation of a CCSM3 Simulation With a Finite Volume Dynamical Core for the Atmosphere at 1 deg Latitude x 1.25 deg Longitude Resolution." *J. Climate*, 21, 1467-1486.

Bala, G., R.B. Rood, D. Bader, A. Mirin, D. Ivanova, and C. Drui, 2008b: "Simulated Climate Near Steep Topography: Sensitivity to Numerical Methods for Atmospheric Transport." *Geophysical Research Let.* 35, L14807, doi:10.1029/2008GL033204.

Bonfils, C., P. Duffy, B. Santer, T. Wigley, D.B. Lobell, T.J. Phillips, and C. Doutriaux, 2008a: "Identification of External Influences on Temperatures in California." *Climatic Change*, 87(s1), 43-55.

Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, D.R. Cayan, C. Doutriaux, A.W. Wood, A. Mirin, T. Nozawa, 2008b: "Detection and Attribution of Temperature Changes in the Mountainous Western United States." *J. Climate*, in press.

Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettenmaier, and R.N. Palmer, 2004: "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." *Climatic Change*, 62(1-3), 337-363.

Christensen, N.S. and D.P. Lettenmaier, 2007: "A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin." *Hydrol. Earth Syst. Sci.*, 11, 1417-1434.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D. H. Peterson, 2001: "Changes in the Onset of Spring in the Western United States." *Bull. Amer. Meteor. Soc.*, 82, 399–415.

Cayan, D.R., E.P. Maurer, M.D. Dettinger, M. Tyree and K. Hayhoe, 2008a: "Climate Change Scenarios for the California Region." *Climatic Change,* Vol. 87, Suppl. 1, 21-42 doi: 10.1007/s10584-007-9377-6

Cayan, D.R., A.L. Luers, G. Franco, M. Hanemann, B. Croes and E. Vine, 2008b: "Overview of the California Climate Change Scenarios Project." *Climatic Change*, 87, (Suppl 1):S1-S6, doi:10.1007/s10584-007-9352-2.

Collins, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. McKenna, B.D. Santer, and R.D. Smith. 2007. "The Community Climate System Model: CCSM3." *Journal of Climate* CCSM3 special issue. In press.

Daly, C., R.P. Neilson, and D.L. Phillips, 1994: "A Statistical-Topographic Model for Mapping Climatological Precipitation Over Mountainous Terrain." *Journal of Applied Meteorology* 33: 140-158.

Dettinger, M.D., and D.R. Cayan, 1995: "Large-Scale Atmospheric Forcing of Recent Trends Toward Early Snowmelt Runoff in California." *J. Climate*, 8, 606–623.

Dettinger, M.D., D.R. Cayan, M.K. Meyer, and A.E. Jeton, 2004: "Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099." *Climatic Change*, 62, 283–317.

Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, and J.H. Lawrimore, 2004: "Contemporary Changes of the Hydrological Cycle Over the Contiguous United States: Trends Derived From In Situ Observations." *J. Hydromet*., 5, 64-85.

Hamlet, A.F., and D.P. Lettenmaier, 1999: "Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin." *Journal of the American Water Resources Association*, 35, 1597-1623.

Hamlet A.F. and D.P. Lettenmaier, 2005: "Production of Temporally Consistent Gridded Precipitation and Temperature Fields for the Continental U.S." *J. Hydrometeorology* 6(3), 330-336.

Hamlet A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier, 2007: "20th Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western U.S." *Journal of Climate* 20(8): 1468-1486.

Hegerl, G.C., H. von Storch, K. Hasselmann, B.D. Santer, U. Cubasch, and P.D. Jones, 1996: "Detecting Greenhouse-Gas-Induced Climate Change With an Optimal Fingerprint Method." *J. Climate*, 9, 2281–2306.

Hegerl, G.C., K. Hasselmann, U. Cubasch, J.F.B. Mitchell, E. Roeckner, R. Voss, and J. Waszkewitz, 1997: "Multi-Fingerprint Detection and Attribution of Greenhouse-Gas and Aerosol-Forced Climate Change." *Climate Dyn*., 13, 613–634.

Hidalgo, H.G., M.D. Dettinger, and D.R. Cayan, 2008a: *Downscaling with Constructed Analogues: Daily Precipitation and Temperature Fields Over the United States*. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2007-123. Available on-line: http://www.energy.ca.gov/2007publications/CEC-500-2007-123/CEC-500-2007-123.PDF. 48 pp.

Hidalgo, H.G., T. Das, M.D. Dettinger, D.R. Cayan, D.W. Pierce, T.P. Barnett, G. Bala, A. Mirin., A.W. Wood, C.Bonfils, B.D. Santer, T. Nozawa, 2008b: "Detection and Attribution of Climate Change in Streamflow Timing of the Western United States." *J. Climate*, in review.

Karoly, D.J. and Q. Wu., 2005: "Detection of Regional Surface Temperature Trends." *J. Climate*, 18, 4337-4343.

Karoly, D.J., K. Braganza, P.A. Stott, J.M. Arblaster, G.A. Meehl, A.J. Broccoli, and D.W. Dixon, 2003: "Detection of a Human Influence on North American Climate." *Science*, 302, 1200–1203.

Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006: "Trends in Snowfall Versus Rainfall for the Western United States." *Journal of Climate*, 19(8), 4545-4559.

Knutson, T.R., T.L. Delworth, K.W. Dixon, and R.J. Stouffer, 1999: "Model Assessment of Regional Surface Temperature Trends (1949-1997)." *Journal of Geophysical Research*. 104(D24), 30,981-30.996.

Lettenmaier, D.P. and T.Y. Gan, 1990: "Hydrologic Sensitivities of the Sacramento–San Joaquin River Basin, California, to Global Warming." *Water Resour. Res*., 26, 69–86.

Liang, X., D.P. Lettenmaier, E F. Wood, and S.J. Burges, 1994: "A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs." *J. Geophys. Res*., 99(D7), 14,415-14,428.

Livezey, R.E. and W.Y. Chen, 1983: "Statistical Field Significance and Its Determination by Monte Carlo Techniques." *Mon. Wea. Rev*., 111, 46–59.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: "A Pacific Decadal Climate Oscillation With Impacts on Salmon." *Bulletin of the American Meteorological Society*, Vol. 78, pp 1069-1079.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, 2002: "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *J. Clim*., 15, 3237–3251.

Maurer, E.P., I.T. Stewart, C. Bonfils, P.B. Duffy, D.R. Cayan, 2007: "Detection, Attribution, and Sensitivity of Trends Toward Earlier Streamflow in the Sierra Nevada." *Journal of Geophysical Research-Atmospheres*, 112, D11118.

Maurer, E.P. and H.G. Hidalgo, 2008: "Utility of Daily vs. Monthly Large-Scale Climate Data: An Intercomparison of Two Statistical Downscaling Methods." *Hydrol. Earth Syst. Sci.*

Meehl, G.A., A. Hu., and B.D. Santer: 2008: “The Mid-1970s Climate Shift in the Pacific and the Relative Roles of Forced Versus Inherent Decadal Variability.” *Journal of Climate* (submitted).

Mote, P.W., 2003: “Trends in Snow Water Equivalent in the Pacific Northwest and Their Climatic Causes.” *Geophys. Res. Lett.*, 30, 1601, doi:10.1029/2003GL017258.

Mote, P., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier, 2005: “Declining Mountain Snowpack in Western North America.”, *Bull. Am. Meteorol. Soc*., 86, 39-49.

Mote, P.W., 2006: “Climate-Driven Variability and Trends in Mountain Snowpack in Western North America.” *J. Clim*., 19, 6209-6220.

Mote, P., A.F. Hamlet, and E. Salath, 2008, “Has Spring Snowpack Declined in the Washington Cascades?” *Hydrol. Earth Syst. Sci*., 12, 193–206.

Nijssen, B., G.M. O'Donnell, D.P. Lettenmaier, D. Lohmann, and E.F. Wood, 2001: “Predicting the Discharge of Global Rivers.” *J. Clim*., 14, 3307–3323.

Pierce D.W., T.P. Barnett, H.G. Hidalgo, T. Das, C. Bonfils, B. Sander, G. Bala, M. Dettinger, D. Cayan and A. Mirin, 2008: “Attribution of Declining Western U.S. Snowpack to Human Effects.” *J. Climate*, in press.

Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick, 2005: “Seasonal Cycle Shifts in Hydroclimatology Over the Western United States.” *J. Climate*, 18, 372–384.

Santer, B.D., C. Mears, F.J. Wentz, K.E. Taylor, P.J. Gleckler, T.M.L. Wigley, T.P. Barnett, J.S. Boyle, W. Brüggemann, N.P. Gillett, S.A. Klein, G.A. Meehl, T. Nozawa, D.W. Pierce, P.A. Stott, W.M. Washington, and M.F. Wehner, 2007: “Identification of Human-Induced Changes in Atmospheric Moisture Content.”, *Proc. Nat. Acad. Sc*., 104, 15248-15253.

Sheffield, J., G. Goteti, F. Wen, and E.F. Wood, 2004: “A Simulated Soil Moisture Based Drought Analysis for the United States.” *Journal of Geophysical Research–Atmospheres*, 109, (D24), D24108.

Sheffield, J. and E.F. Wood, 2007: “Characteristics of Global and Regional Drought, 1950-2000: Analysis of Soil Moisture Data From Off-Line Simulation of the Terrestrial Hydrologic Cycle.” *J. Geophys. Res*., 112, D17115, doi:10.1029/2006JD008288.

Stewart, I.T., D.R. Cayan and M.D. Dettinger, 2004: “Changes in Snowmelt Runoff Timing in Western North America Under a ‘Business as Usual’ Climate Change Scenario.” *Climatic Change*, 62, 217-232.

Stewart, I.T., D.R. Cayan and M.D. Dettinger, 2005: “Changes Toward Earlier Streamflow Timing Across Western North America.” *Journal of Climate*, 18, 1136-1155.

The International Ad Hoc Detection and Attribution Group, 2005: “Detecting and Attributing External Influences on the Climate System: A Review of Recent Advances.” *J. Climate*, 18, 1291–1314.

Wood, E.F., D.P. Lettenmaier and V.G. Zartarian, 1992: "A Land-Surface Hydrology Parameterization With Subgrid Variability for General Circulation Models." *Journal of Geophysical Research*, 97(D3): 2717–2728.

Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier, 2004: "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs." *Climatic Change*, 62(1-3), 189-216.

Zhang, X.B., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, T. Nozawa, 2007: "Detection of Human Influence on Twentieth-Century Precipitation Trends." *Nature*, 448 (7152): 461-U4.

Zwiers, F.W. and X. Zhang, 2003: "Toward Regional-Scale Climate Change Detection." *J. Climate*, 16, 793–797.