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Gondola would create 1 of largest US ski areas near Tahoe

April 13, 2015

RENO, Nev. (AP) — A resort operator announced plans Monday to build a high-speed gondola connecting two Lake Tahoe slopes and creating one of the largest ski areas in the country.

The gondola will link Alpine Meadows with Squaw Valley, which hosted the 1960 Winter Olympics and later slipped in positions after the development of major resorts in Colorado, Utah and elsewhere. The move follows a similar effort in Utah by another company to create a gondola connection between two major resorts.

Conservationists who have been fighting a larger expansion plan at the ski resort said they have concerns about the proposed gondola but will reserve judgment on the idea until they see more details. Environmentalists are already fighting with businesses over a plan to build 10-story high rises and a large indoor water park that they believe could mar the picturesque mountain landscape surrounding Lake Tahoe.

The gondola would make it easier for skiers and snowboarders to experience the different terrain of the adjoining Sierra Nevada resorts in California while reducing vehicle traffic between them, said Andy Wirth, president and CEO of Squaw Valley Ski Holdings LLC.

"We are quite confident that this connection and providing one experience will return us to being one of the pre-eminent destinations in all of North America," Wirth told The Associated Press. "Now, you basically have this incredible pairing of mountains, this easy to get back and forth, and it makes it one experience."

The project is pending review by U.S. Forest Service and Placer County, California.

"Today's announcement raises a wide range of questions about the future of Squaw Valley, Alpine Meadows and Lake Tahoe," said Tom Mooers, executive director of the nonprofit Sierra Watch.

"We look forward to seeing the specifics in an actual proposal so we can address important issues — ranging from threats to the neighboring Granite Chief Wilderness Area to potential changes to the Tahoe skiing experience," he said.

Connecting the two mountains has been a vision of the resorts' founders and skiers for six decades, Wirth said, and the combined 6,000 acres of skiable terrain would make it among the nation's largest.

Last month, Vail Resorts Inc. received approval from Park City, Utah, planning officials to build a high-speed gondola that would connect two ski resorts it owns there. The company said the lift linking Park City Mountain Resort and Canyons Resort would offer a combined 7,300 acres of skiable terrain and make it the largest ski area in the United States.

The 1997 merger of the Whistler and Blackcomb resorts north of Vancouver, British Columbia, formed the largest ski resort in North America, with some 8,000 acres of skiable terrain.

Wirth said a major stumbling block was recently removed when his company reached an agreement with Troy Caldwell, who owns property located between the two resorts, to create the base-to-base gondola connection.

Alpine Meadows is known for more family-friendly terrain while Squaw Valley offers some of the world's most challenging slopes.

Wirth declined comment on the cost of the project, saying the company is still in negotiations with the lift manufacturer.

The company has designed the project to reduce its aesthetic and environmental impacts, and plans to submit its plans to the governmental agencies within two months, Wirth said.

"We think the project is very approvable," he said, adding the gondola will be located in such a way that it won't be visible from the adjoining Granite Chief Wilderness.

Squaw Valley has scaled back separate expansion plans for its village after environmentalists voiced concerns that mountain views, traffic and water supplies would be adversely affected. Placer County is expected to release a draft environmental impact report on the plans later this spring, Wirth said.

Mooers said that while the latest version of the expansion plan is an improvement, it still would result in the construction of up to 750 new hotel-condominium units and about 1,500 new hotel bedrooms.

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Tahoe Sierra IRWM

Please submit by 17 January 2014 to AraceliCazarez@KennedyJenks.com

Project Template

Please provide information in the tables below:

I. Project Proponent Information

Agency/ Organization	Squaw Valley Public Service District
Name of Primary Contact	Mike Geary
Name of Secondary Contact	Cindy Herbert
Mailing Address	P.O. Box 2026, Olympic Valley, CA 96146
E-mail	cherbert@svpsd.org
Phone (###)###-####	530-583-4692
Other Cooperating Agencies/Organizations/Stakeholders	TDPUD, NCSD, Placer County Water Agency, Placer County, Alpine Springs CWD, SV Mutual Water Co., SW Gas, SuddenLink, Liberty Energy, ATT
Is your agency/organization committed to the project through completion? If not, please explain	Yes

II. General Project Information

Project Title	Redundant Water Supply
Project Category	☐ **Restoration** ☐ **Storm Water/Flood Control** ☑ **Waste Water/ Water Supply**
Project Description (Briefly describe the project, in 300 words or less)	The Squaw Valley Public Service District (District) is actively pursuing a project to procure redundant and supplemental water supplies for future reliability and beneficial uses of our constituents. In September 2009, the District completed the Alternative/Supplemental Water Supply and Enhanced Utilities Feasibility Study. The purpose of the study was to determine potential project "fatal flaws" and it investigated the feasibility of importing water supplies from outside District boundaries. The Study concluded that the feasibility of the project was apparent based on the available water supply from the Martis Valley; desire of local water purveyors to work with the District on the project; potential transmission main corridors within the Highway 89 corridor and USFS rights of way; there being no major environmental fatal flaws; and interest from natural gas and communications providers in the area partnering with the District to create a utility corridor to provide these services to the Valley and others along the alignment.Phase II of the project titled the Preferred Alternative Analysis is currently moving forward in concert with Placer County's Truckee River Access and Bike Trail Project. Phase II will consist of an alternatives analysis, preliminary design, and updated feasibility study to include cost estimates and a public outreach program. Phase III of the project, the subject of this project description, is the environmental compliance and permitting stage of the project with construction of the terminal tank. The terminal tank will, in the short term, provide system balancing to mitigate the 3 mile distance from the West Tank and enhance fire flows in eastern Olympic Valley. The installation of a utility corridor along the Truckee

	River would require compliance with CEQA, Clean Water Act Section 401 and 404, Federal and California Endangered Species Act and California Fish and Game Code Section 1600A.	
Project Prioritization:	**Total number of projects submitted by your Agency:**	6
	Agency Prioritization of this project (e.g., 3 of 5)	1
Does this project contribute to a larger Project (e.g., TMDL, EIP, Phase 2 of 3) ? If so provide description.	Yes, feasibility phase completed, preferred alternative study and preliminary design funded and underway. This is the environmental and 1st construction phase of a large regional project that may include another project for public access to an aquatic resource (Truckee River Access and Bikeway Project)	
Political Support – List related MOUs, agreements or TACs currently in place.	Olympic Valley Groundwater Management Plan	
Project Location:		
Latitude:	39.20511	
Longitude:	-120.20595	
Project Location Description (e.g., along the south bank of stream/river between river miles or miles from Towns/intersection and/or address):	The project consists of up to 8.5 miles of utility corridor to be installed in concert with the Truckee River Access and Bike Path Project adjacent to the Truckee River between Truckee and Olympic Valley, a supply source, booster station, and terminal tank	

III. Plan Objectives Addressed

For each of the objectives addressed by the project, provide a one to two sentence description of how the project contributes to attaining the objective and how the project will be quantified. If the project does not address any of the draft IRWM plan objectives, provide a one to two sentence description of how the project relates to a challenge or opportunity of the Region (see the bottom of page 4).

Objectives:	**Will the project address the objective?**	**Brief explanation of project linkage to selected Objective**	**Quantification** (e.g. acres of streams/wetlands restored or enhanced)
WQ1 - Meet approved TMDL standards in accordance with the attainment date, and participate in the development of future TMDLs.	☑ Yes ☐ N/A	A redundant water supply will result in reduced pumping of the Squaw Valley aquifer thus increasing surface flows in Squaw Creek, a direct impact on TMDL's	Presently unknown

Objectives:	**Will the project address the objective?**	**Brief explanation of project linkage to selected Objective**	**Quantification** (e.g. acres of streams/wetlands restored or enhanced)
WQ2 – Reduce pollutant loads by implementing measures such as stormwater LID retrofits, erosion control/restoration to meet Water Quality Objectives (WQOs) for receiving water bodies established in the Basin Plan within the planning horizon.	☐ Yes ☑ N/A	--	--
WQ3 - Implement water quality monitoring programs through planning horizon, and coordinate annually throughout the Region.	☐ Yes ☑ N/A	--	--
WQ4 - Ensure that drinking water supplied by public water systems continues to meet Federal and State standards.	☑ Yes ☐ N/A	A redundant water supply will help to ensure the continued quality of the Squaw Valley aquifer by reducing reliance on the already limited resource	Presently unknown
WQ5 - Restore degraded streams, wetlands, riparian and upland areas to re-establish natural water filtering processes.	☑ Yes ☐ N/A	Reduced pumping on the Squaw Valley aquifer will help to increase in stream flows and restore riparian habitat	Presently unknown
WQ6 -Operate and maintain, build, or replace infrastructure for reliable collection, treatment and disposal of wastewater.	☐ Yes ☑ N/A	--	--
WS1 - Provide water supply to meet projected demands for a 20-year planning horizon.	☑ Yes ☐ N/A	A redundant and supplemental water supply will provide water for build out demand for 20 years and beyond	A WSA is being prepared to update quantity necessary. Assume 1,210 Acre Feet
WS2 - Operate and maintain, build, or replace infrastructure to reliably supply water.	☑ Yes ☐ N/A	Project builds infrastructure for long term redundancy and reliability of water supply	1,210 Acre-Feet

Objectives:	**Will the project address the objective?**	**Brief explanation of project linkage to selected Objective**	**Quantification** (e.g. acres of streams/wetlands restored or enhanced)
WS3 - Implement and promote water conservation measures and practices to meet state goals.	☐ Yes ☑ N/A	--	--
GWM1 - Maintain and monitor groundwater supply to assure future reliability.	☑ Yes ☐ N/A	Project maintains redundancy and supplements water supply	1,210 Acre-Feet
GWM2 - Promote groundwater protection activities for high quality groundwater, and advocate for improvements to impacted groundwater quality through public education.	☑ Yes ☐ N/A	Project includes public education and outreach program	Unknown
GWM3 - Manage groundwater for multiple uses (e.g. municipal/industrial/agricultural supply and environmental use).	☑ Yes ☐ N/A	Project provides supplemental supply for future users. Positive environment impact by reduced pumping of Squaw Valley aquifer	Increase existing supply by 1,210 Acre Feet
ER1 - Enhance and restore water bodies, wetlands, riparian areas and associated uplands to support healthy watersheds, viable native fish, wildlife and plant habitats.	☑ Yes ☐ N/A	Project promotes reduced pumping on existing aquifer which in turn increases surface flows improving habitat during low flow periods	Unknown
ER2 - Develop and implement programs to prevent the spread of existing invasive species and colonization of potential future invasive species.	☐ Yes ☑ N/A	--	--
ER3 - Implement, in coordination with public and private landowners, activities to manage forest health and wildfire risks.	☑ Yes ☐ N/A	Project provides fire protection to private landowners along 8 mile corridor adjacent to Truckee River where none presently exists	Unknown

Objectives:	**Will the project address the objective?**	**Brief explanation of project linkage to selected Objective**	**Quantification** (e.g. acres of streams/wetlands restored or enhanced)
ER4 - Minimize ecosystem impacts caused by existing and new development.	☐ Yes ☑ N/A	--	--
IWM1 - Conduct local and regional water-related planning activities within the planning horizon as supported by current and future watershed science.	☐ Yes ☑ N/A	--	--
IWM2 - Ensure collaboration among multiple jurisdictions within the Region for information exchange.	☑ Yes ☐ N/A	Project will be a coordinated effort between water purveyors, county parks department, communications, and gas company	Presently Unknown
IWM3 - Increase public education and awareness of watershed functions, protection and restoration needs to encourage stewardship by the public.	☑ Yes ☐ N/A	Projects promotes goals of the Squaw Valley Groundwater Management Plan, includes public outreach and education program	Unknown
IWM4 - Promote activities that reduce flood risk.	☐ Yes ☑ N/A	--	--
IWM5 - Address climate change (e.g. water quality, water supply, groundwater recharge, flood management) in local and regional planning efforts and support efforts to continue improving the science.	☑ Yes ☐ N/A	A long term reliable water supply is needed to offset impacts of global warming, may become critical infrastructure in future supply scenario. Meets Groundwater Management Plan Goals.	Unknown
IWM6 - Monitor water storage, release and exchange activities in order to improve coordination with regional planning.	☐ Yes ☑ N/A	--	--

If no objectives are addressed; describe how the project relates to a challenge or opportunity of the Region:

--

Project Impacts and Benefits

Please provide a summary of the expected project benefits and impacts in the table below or check N/A if not applicable; **do not leave a blank cell**.

If applicable describe benefits or impacts of the project with respect to:		
a. Native American Tribal Community considerations.	☑ N/A	--
b. Disadvantaged Community considerations[1].	☑ N/A	--
c. Environmental Justice [2] considerations.	☑ N/A	--
d. Assist the Region in adapting to effects of climate change[3].	☐ N/A	Project mitigates long term impacts of climate change through drought supply planning
e. Generation or reduction of greenhouse gas emissions (e.g. green technology).	☐ N/A	Bringing natural gas to the region will replace heating oil and propane as the energy source thus reducing green house gases
f. Other expected impacts or benefits that are not already mentioned elsewhere.	☐ N/A	Project provides fire protection facilities to residents along Truckee River urban wild-land interface. Bringing natural gas to region will allow the elimination of thousands of propane tanks lowering human risks and reducing fire dangers.

1. A Disadvantaged Community is defined as a community with an annual median household (MHI) income that is less than 80 percent of the Statewide annual MHI. A map has been provided with the Project Template Instruction for reference.
2. Environmental Justice is defined as the fair treatment of people of all races, cultures, and incomes with respect to the development, adoption, implementation and enforcement of environmental laws, regulations and policies. An example of environmental justice benefit would be to improve conditions (e.g. water supply, flooding, sanitation) in an area of racial minorities
3. Climate change effects are likely to include increased flooding, extended drought, and associated secondary effects such as increased wildfire risk, erosion, and sedimentation.

IV. Resource Management Strategies (RMS)

For each resource management strategy employed by the project, provide a one to two sentence description in the table below of how the project incorporates the strategy. A description of the Resource Management Strategies can be found in Volume 2 of the 2009 California Water Plan here: http://www.waterplan.water.ca.gov/cwpu2009/index.cfm

Resource Management Strategy	Will the Project incorporate RMS?	Description, of how RMS to be employed if applicable
Reduce Water Demand		
Agricultural Water Use Efficiency	☐ Yes ☑ No	--
Urban Water Use Efficiency	☐ Yes ☑ No	--
Improve Operational Efficiency and Transfers		
Conveyance - Regional / local	☑ Yes ☐ No	Project reduces reliance on existing supply, provides regional conveyance of resources
System Reoperation	☐ Yes ☑ No	--
Water Transfers	☐ Yes ☑ No	--
Increase Water Supply		
Conjunctive Management & Groundwater	☑ Yes ☐ No	Project promotes regional solution to long term water supply
Desalination	☐ Yes ☑ No	--
Precipitation Enhancement	☐ Yes ☑ No	--
Recycled Municipal Water	☐ Yes ☑ No	--
Surface Storage -- Regional / Local	☑ Yes ☐ No	Project adds 2 million gallon water storage tank to local water system
Improve Water Quality		
Drinking Water Treatment and Distribution	☑ Yes ☐ No	Project reduces or eliminates need to treat future groundwater supply
Groundwater and Aquifer Remediation	☑ Yes ☐ No	Project reduces demand on Squaw Valley aquifer
Matching Water Quality to Use	☐ Yes ☑ No	--
Pollution Prevention	☑ Yes ☐ No	Reduced groundwater pumping minimizes pollutant transport
Salt and Salinity Management	☐ Yes ☑ No	--
Urban Runoff Management	☐ Yes ☑ No	--
Practice Resources Stewardship		
Agricultural Lands Stewardship	☐ Yes ☑ No	--
Economic Incentives (Loans, Grants, and Water Pricing)	☐ Yes ☑ No	--
Ecosystem Restoration	☑ Yes ☐ No	Reduced groundwater pumping will increase in stream flow and help restore riparian habitat
Forest Management	☐ Yes ☑ No	--
Land Use Planning and Management	☐ Yes ☑ No	--
Recharge Areas Protection	☐ Yes ☑ No	--
Water-dependent Recreation	☐ Yes ☑ No	--

Watershed Management	☑ Yes ☐ No	Project implements goals of groundwater management plan
Improve Flood Management		
Flood Risk Management	☐ Yes ☑ No	--

Note: The following RMS have been omitted from the list: Conveyance-Delta and Surface Storage – CALFED.

Other RMS addressed and explanation:

Project provides for redundant and/ or supplemental water supply as mandated by the State of California Water Code section 10610.2 (3) and the Safe Drinking Water Act amendment, the Bio-terrorism Preparedness and Response Act of 2002 (42 U.S.C. 300i-4 (b

V. Project Cost and Financing - Please provide any estimates of project cost, sources of funding, and operation and maintenance costs, as well as, the source of the project cost in the table below.

a. Project Costs	**Requested Grant Amount**	**Cost Share: Non-State Fund Source (Local/Federal Funding Match)**	**Cost Share: Other State Fund Source**	**Total Cost**
1. Capital (2013 Dollars)	**2765000**	**$$920,000 OR ☐ DAC**	**0**	**3685000**
2. Annual Operations and Maintenance (O&M)		**$10,000**	**0**	**10000**
b. Can the Project be phased?	**☐ Yes**	**☑ No**		
1. If so provide cost breakdown by phase(s)	**Project Cost**	**O&M Cost**	**Description of Phase**	
Phase 1	**323000**	**0**	**Feasibility Study, Alternative Analysis, Preliminary Design, Cost Estimates**	
Phase 2	**3685000**	**10000**	**CEQA, Permitting, Terminal Tank**	
Phase 3	**4140000**	**50000**	**Well Construction/ Booster Station**	
Phase 4	**18630000**	**50000**	**20" Transmission Main**	
		Source(s)	**Amount**	
c. List secured source(s) of funding for Project cost		**Undetermined**	**$-**No secured funds are presently available	
d. List proposed source(s) of unsecured funding and certainty of the sources for Project cost.		**PCWAPlacer CountyCDPH-SRF**	**$-**Presently Unknown	
e. Explain how operation and maintenance costs will be financed for the 25-year planning period for project implementation (not grant funded).		**O & M will be provided by District when constructed through operating revenues.**		

f. Basis for project cost[1] (e.g. conceptual, planning, bid, etc.)	**Previous study: Alternative Supplemental Water Supply and Enhanced Utilities Feasibility Study 2009 Farr West Engineering.**
g. Has a Cost/Benefit analysis been completed?	☐ **Yes** ☑ **No**
h. Please describe what impact there may be if the project is not funded. (300 words or less)	**The subject of this application is the construction of a terminal tank and the environmental and permitting phase of a larger regional water supply project to import water from the Martis Valley aquifer to the Truckee River, Olympic Valley, and potentially Alpine Springs CWD, and Squaw Valley Mutual Water Company. Should importing water from Martis Valley, a technically feasible project, become the preferred alternative the total cost of the project may be 26 million dollars or more. The District is actively pursuing funding partnerships with other agencies including Placer County Water Agency, Placer County Parks and Recreation (Truckee River Access and Bike Trail Project), Southwest Gas, Suddenlink Cable, Alpine Springs CWD, developers, and other beneficiaries. It is imperative at this stage the District assume a leadership role in establishing the environmental feasibility, obtain permits, and construct the terminal tank. With the Placer County Truckee River Access and Bike Trail project moving forward the opportunity for a joint project is now. If the project is not funded the future redundancy and reliability of the District water source remains uncertain. The eastern subdivisions in Squaw Valley will continue to suffer from pressure fluctuations and water hammer without the terminal tank to balance water demand. The Squaw Valley aquifer may be further depleted by long term impacts of global warming. Regional growth as projected in the Squaw Valley General Plan will not be possible due to lack of water supply resulting in long term economic impact. The opportunity cost of partnering with Placer County and developers who are considering a natural gas pipeline would be lost. Funding for the EIR stage of the project at this time will put the project on track with other stakeholders and pave the way for forming the funding mechanisms for a project of this magnitude.**

1. For the grant application a detailed project cost estimate will need to be provided with the following cost categories; per the IRWM PSP for Round 2, Implementation Grants: Direct Project Administration, Land Purchase/Easement, Planning/Design/Engineering/Environmental Documentation, Construction/Implementation, Environmental Compliance/Mitigation/Enhancement, Construction Administration, Other Costs, and Construction/Implementation Contingency.

VI. Project Status and Schedule -Please provide a status of the project, level of completion as well as a description of the activities planned for each project stage. If unknown enter **TBD**.

Project Stage	Check the Current Project Stage	Completed?	Description of Activities in Each Project Stage	Planned/Actual Start Date (mm/yr)	Planned/Actual Completion Date (mm/yr)
a. Assessment and Evaluation	☑	☐ Yes ☑ No ☐ N/A	Feasibility study completed. Alternative analysis and further evaluation of pipeline alignment is currently funded and progressing	11/1/2013	12/1/2014
b. Final Design	☐	☐ Yes ☑ No ☐ N/A	--	--	--
c. Environmental Documentation (CEQA/NEPA)	☐	☐ Yes ☑ No ☐ N/A	CEQA/ NEPA & project permitting is subject of this application	12/1/2014	12/1/2015
d. Permitting	☐	☐ Yes ☑ No ☐ N/A	CEQA/ NEPA & project permitting is subject of this application	7/1/2014	12/1/2015
e. Construction Contracting	☐	☐ Yes ☑ No ☐ N/A	--	1/1/2016	5/1/2016
f. Construction Implementation	☐	☐ Yes ☑ No ☐ N/A	Construction of Terminal Tank is subject of this application	5/1/2016	11/1/2016

Provide explanation if more than one project stage is checked as current status	The District completed a fatal flaw feasibility study in 2009. Currently funded is a project to select the proffered alternative and alignment, select pumping facilities and terminal tank locations, and preliminary design with engineers estimates; to be

VIII. Project Technical Feasibility

Please provide any related documents (date, title, author, and page numbers) that describe and confirm the technical feasibility of the project.

a. List the adopted planning documents the proposed project is consistent with or supported by (e.g. General Plans, UWMPs, GWMPs, Water Master Plans, Habitat Conservation Plans, TMDLs, Basin Plans, etc.)	Olympic Valley Groundwater Management Plan, May 2007 HydroMetrics LLC, Page 53
b. List technical reports and studies supporting the feasibility of this project	Alternative/Supplemental Water Supply and Enhanced Utilities Feasibility Study. Eco-Logic 2009
c. Concisely describe the scientific basis (e.g. how much research has been conducted) of the proposed project in 300 words or less.	The Squaw Valley Aquifer and future redundant or supplemental water supply has been the source of exhaustive research over the past two decades or more. The following reports and studies are a summary of past efforts: Squaw Valley Public Service District 2002 Capacity & Reliability StudyMarch 2003, ECO:LOGIC Squaw Valley Groundwater Development & Utilization Feasibility Study UpdateAugust 14, 2003, West Yost Associates Squaw Valley 2004 Model Update/Updated Sustainable Yield AnalysisAugust 30, 2004, HydroMetrics Groundwater Management Support Activities Groundwater Characterization ReportMay 12, 2005, West Yost Hydrogeological Information Review and Assessment of ASR PotentialMarch 28, 2005, ASR Systems Olympic Valley Ground Water Management Plan 2007, HydroMetrics Age Dating Squaw Valley WaterNovember 20, 2008, Lawrence Livermore Labs Alternative/Supplemental Water Supply and Enhanced Utilities Feasibility StudySeptember 2009, ECO:LOGIC Olympic Valley Creek Aquifer Study Final Report (Draft)November 2013,

	HydroMetrics Groundwater Resource Evaluation (Martis Valley)November 2000, Nimbus Engineers Independent Appraisal of Martis Valley Groundwater Availability May 2002, Kennedy Jenks Consultants Martis Valley Groundwater Management PlanApril 2013, Balance Hydrologies Martis Valley Surface/ Groundwater Interaction Study2012 Interflow Hydrology The District is currently studying alternatives to importing water from Martis Valley and feasibility of a joint utility corridor to serve residences from Truckee to Alpine Springs; the culmination of years of effort paving the way for the environmental phase of the project.
d. Does the project implement green technology (e.g. alternate forms of energy, recycled materials, LID techniques, etc.)	☑ Yes ☐ No ☐ N/A
1. If so please describe	**The joint utility corridor will bring**
e. If you are an Urban Water Supplier[1]:	
1. Have you completed an Urban Water Management Plan and submitted to DWR?	☐ Yes ☐ No ☑ N/A
2. Are you in compliance with AB1420?	☐ Yes ☐ No ☑ N/A
3. Do you comply with the water meter requirements (CWC §525)	☑ Yes ☐ No ☐ N/A
4. If the answer to any of the questions above is "no", do you intend to comply prior to receiving project funding	☐ Yes ☐ No ☑ N/A Provide Explanation if necessary:District currently serves less than 3,000 customers
f. If you are an Agricultural Water Supplier[2]:	
1. Have you completed and submitted an AWMP (due 12/31/12)?	☐ Yes ☐ No ☑ N/A
2. If not, will you complete and submit an AWMP prior to receiving project funding?	☐ Yes ☐ No ☑ N/A Provide Explanation if necessary:--

g. If the project is related to groundwater:	
1. Has a GWMP been completed and submitted for the subject basin?	☑ Yes ☐ No ☐ N/A
2. If not will a GWMP be completed within 1 year of the grant submittal date?	☐ Yes ☐ No ☑ N/A

1. Urban Water Supplier is defined as a supplier, either publicly or privately owned, providing water for municipal purposes either directly or indirectly to more than 3,000 customers or supplying more than 3,000 acre-feet of water annually.
2. Agricultural Water Supplier is defined as a water supplier, either publicly or privately owned, providing water to 10,000 or more irrigated acres, excluding the acreage that receives recycled water.

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California Water Year 2014 Among Driest Years on Record

Submitted by Pamela Martineau on Tue, 09/30/2014 - 11:27am in Water Supply Challenges All Water Supply Challenges Water News

California's water year 2014 – which ended Sept. 30 – will go down as one of the driest years in the state's recorded history, resulting in a dismally low 5% of water deliveries from the State Water Project and thousands of acres of cropland idled, according to newly released figures from the California Department of Water Resources.

Water year 2014 is ending with less than 60% of average precipitation and is the third consecutive year the state has battled record low precipitation. It is the fourth driest year on record exceeded only by 1977, 1924 and 1931. As a result of the lack of rain, on Sept.1 the state's major reservoirs collectively held only 57% of average storage for the date, or about 36% of capacity, according to DWR figures.

Forecasts are unclear as to whether 2015 will bring more rain. The federally run Central Valley Project has reduced deliveries down to zero for some junior rights holders.

"The immediate certainty is that day-to-day conservation – wise, sparing use of water – is essential as we face the possibility of a fourth dry winter," DWR Director Mark Cowin said in a prepared statement.

Gov. Jerry Brown declared a drought state of emergency in January and called for a 20% reduction in water use. Water agencies up and down the state have responded to the call for conservation, adopting mandatory water restrictions and ramping up their conservation messaging. Many communities have exceeded the 20% reduction in water usage over last year's figures.

Still, some communities are scrambling for drinking water and on September 19, the Governor streamlined the delivery of water to families in need.

Many experts believe the deepening drought has increased the severity of the fire season, with fires spreading more rapidly and farther due to dry conditions.

Officials with DWR note that while cumulative reservoir storage in 1977 – California's driest year on record – was approximately five million acre-feet less than today, the state's population has increased dramatically since that time so the state's water now must serve far more people.

DWR and the Association of California Water Agencies urge all Californians to conserve water by following the advice and tips found at http://SaveOurWater.com.

DWR's California Data Exchange Center websites show current water conditions at the state's largest reservoirs and weather stations.

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TOBY R. AULT

Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York

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Department of Geosciences and Department of Atmospheric Sciences, The University of Arizona, Tucson, Arizona

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ABSTRACT

Projected changes in global rainfall patterns will likely alter water supplies and ecosystems in semiarid regions during the coming century. Instrumental and paleoclimate data indicate that natural hydroclimate fluctuations tend to be more energetic at low (multidecadal to multicentury) than at high (interannual) frequencies. State-of-the-art global climate models do not capture this characteristic of hydroclimate variability, suggesting that the models underestimate the risk of future persistent droughts. Methods are developed here for assessing the risk of such events in the coming century using climate model projections as well as observational (paleoclimate) information. Where instrumental and paleoclimate data are reliable, these methods may provide a more complete view of prolonged drought risk. In the U.S. Southwest, for instance, state-of-the-art climate model projections suggest the risk of a decade-scale megadrought in the coming century is less than 50%; the analysis herein suggests that the risk is at least 80%, and may be higher than 90% in certain areas. The likelihood of longer-lived events (>35 yr) is between 20% and 50%, and the risk of an unprecedented 50-yr megadrought is nonnegligible under the most severe warming scenario (5%–10%). These findings are important to consider as adaptation and mitigation strategies are developed to cope with regional impacts of climate change, where population growth is high and multidecadal megadrought—worse than anything seen during the last 2000 years—would pose unprecedented challenges to water resources in the region.

1. Introduction

Information recorded in paleoclimate archives reveals that the twentieth century does not represent the full range of drought variability experienced in western North America (WNA) during the last millennium (e.g., Woodhouse and Overpeck 1998; Stahle et al. 2007; Cook et al. 2004; Meko et al. 2007). Prolonged droughts comprise a source of climate risk in this region and elsewhere (Woodhouse and Overpeck 1998; Shanahan et al. 2009; Buckley et al. 2010; Haug et al. 2003; deMenocal 2001). Decade-scale droughts like the 1930s Dust Bowl occur, on average, once or twice per century (Woodhouse and Overpeck 1998), and considerably longer periods of aridity (megadroughts) are also apparent in paleoclimate records (Woodhouse and Overpeck 1998). Were such megadroughts to occur today, they would exact regionally unprecedented socioeconomic tolls and

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ecological consequences. For example, during the 1150s, the 25-yr average of reconstructed Colorado River flow dropped to 85% of the twentieth-century mean for 10 consecutive years (Meko et al. 2007). In modern terms, this would be comparable to losing almost the entire allocation for the state of Arizona from the long-term mean for a decade. What is perhaps even more problematic for water resource management is that the 1150s were centered in a 23-yr interval of below-average moisture across WNA, and a similar interval in the twelfth century spanned 22 yr (1276–99; Cook et al. 2007). Older tree-ring records suggest that regional droughts can persist, and have persisted, for longer still (~50 yr; Routson et al. 2011).

Prolonged droughts have happened during the instrumental era and include the 1930s Dust Bowl (Fye et al. 2003), drought in sub-Saharan Africa (e.g., Charney 1975; Folland et al. 1986), and the recent "Big Dry" in Australia (Leblanc et al. 2012). Since these events occur infrequently, it is difficult to understand their statistics using data from the instrumental era alone. Tree-ring reconstructions partially address this limitation, and in the U.S. Southwest they suggest that events similar to the 1150s Colorado River megadrought would be expected to occur every 400–600 yr (Meko et al. 2012). This view of risk is incomplete, however, because it is specific to the 1150s event and "megadrought risk" could be applied more generally to a wide range of time scales. More critically, the statistics of twenty-first-century climate will be influenced by anthropogenic greenhouse gases (GHG) (Solomon et al. 2007). The risk of future prolonged drought risk will therefore depend on the internal rate at which these events occur as well as any GHG-forced changes in their underlying statistics. In the U.S. Southwest, for instance, precipitation is projected to decrease as a consequence of GHG-forced changes (e.g., Seager et al. 2007; Solomon et al. 2007; Diffenbaugh and Giorgi 2012). Any assessment of future megadrought risk, therefore, should account for both the natural variability inferred from multicentennial paleoclimate records and the changes in rainfall patterns projected to occur in the coming century.

This paper estimates future prolonged drought risk using information from instrumental records, paleoclimate archives, and climate model simulations in simple Monte Carlo realizations of hydroclimate. The motivation for doing so comes from our notion of risk as a fractional quantity referring to the likelihood of prolonged drought occurrence. We rely on global climate model simulations of change during the twenty-first century as estimates of mean conditions in the future, and we use simple statistical models to build up large ensembles for calculating risk. This technique assumes the following:

1) Coupled global climate model simulations of the twenty-first century present a realistic view of the direction, magnitude, and uncertainty in forced precipitation changes, relative to today.
2) Paleoclimate records and observational data can empirically describe the distribution of variance across the frequency spectrum from interannual to multidecadal time scales in regional hydroclimate.
3) Simple models of time series are adequate for simulating the *local* statistical characteristics of hydroclimate across interannual to multidecadal time scales, regardless of whether these characteristics are externally forced or internally generated.

Justifications for statements 1 and 2 are straightforward: state-of-the-art models agree that semiarid subtropical regions throughout the world will tend to dry under climate change (e.g., Diffenbaugh and Giorgi 2012), and paleoclimate records, especially tree rings, are reasonably well validated and widely used to characterize variations of the past for a wide range of water resource management applications (Meko et al. 2012).

Assumption 3 in the list above deserves further elaboration. We begin by noting that in western North America over the last millennium, stochastic variability and autocorrelation alone may account for the magnitude of hydroclimatic variations on time scales from years to decades (Hunt 2011; Ault et al. 2013; Coats et al. 2013b). Second, one can easily imagine a situation where in a single realization of a given model, climatic forcing enhances overall aridity, but megadroughts do not occur because a few intermittent wet years disrupt their duration. Given the statistics of this model, megadroughts might still be likely, but would not be found in this particular realization.

The scenario delineated above is shown schematically in Fig. 1. Here, an idealized time series of some hydrological variable (say $P - E$) has been generated with unit variance and a mean of zero for the first 100 "years" (Fig. 1a). At year 101 the mean is shifted by -0.25σ and an additional 50 years of data are generated while the variance stays the same. Figures 1b and 1c show realizations of 50 yr of data with the same mean and variance as the final 50 yr of the series in Fig. 1a. Although both the time series in Figs. 1b and 1c have the same mean and variance, a prolonged period of time with low values (a "megadrought") is found in the first realization (Fig. 1b), whereas in the second realization (Fig. 1c) it is not.

Implied by Fig. 1 is the possibility that deterministic simulations of climate change using state-of-the-art numerical models may be insufficient for estimating megadrought risk because the ensemble sizes of such

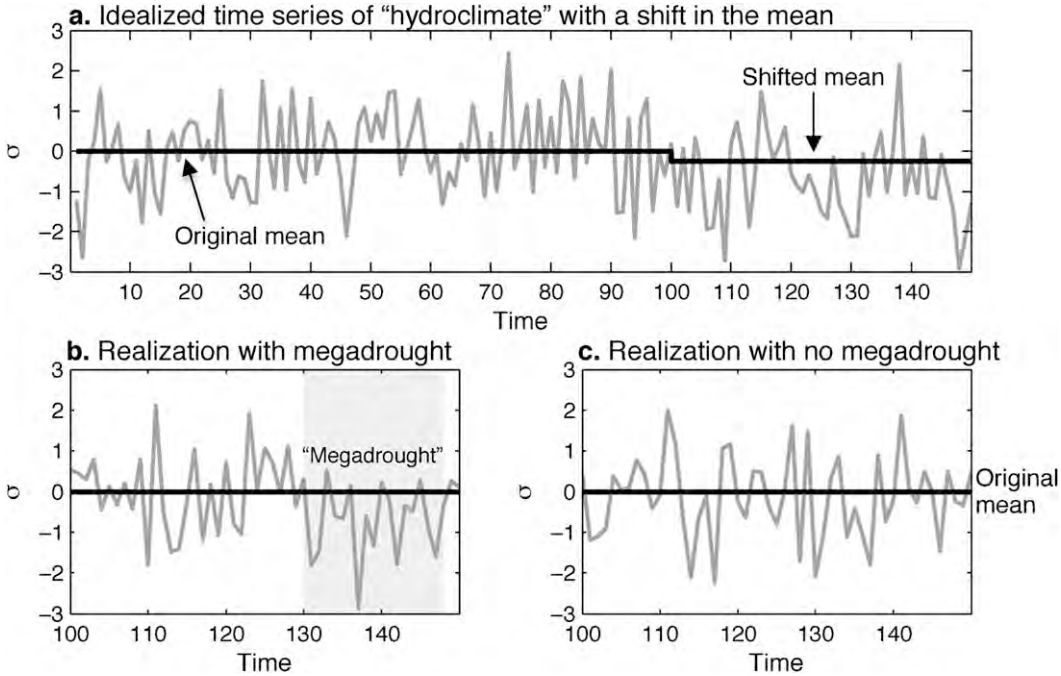

FIG. 1. Schematic illustration of why large ensembles are needed to calculate megadrought risk. (a) The black line shows the original and shifted mean, while (b),(c) the black lines show the original mean for reference. Importantly, the means and variances are the same for the final 50 yr in (a)–(c) but only the realization in (b) experiences a megadrought.

experiments are relatively small (tens of realizations per model at most), and the statistics of infrequent events such as megadroughts might not be robust. Using a multimodel ensemble does not completely guard against this limitation because model simulations disagree on the expression of forced changes in hydroclimate at regional scales (e.g., Diffenbaugh and Giorgi 2012). Instead, we use large ensembles of stochastic variables to emulate the statistics of interannual to decadal variability, and output from global climate models to estimate how precipitation is expected to change this century. The limitations and possible implications of this assumption are discussed in section 4.

2. Data and methods

To establish benchmarks for decadal drought and multidecadal megadrought, we use instrumental precipitation data (Fig. 2; Mitchell and Jones 2005), and several recent reconstructions of hydroclimate including the Palmer drought severity index (PDSI) for the southwestern United States (Cook et al. 2004), Colorado River streamflow reconstructions (Meko et al. 2007), and drought from northern Mexico (Stahle et al. 2011) (Fig. 3). Although the reconstructions are precisely dated, they target different regions and aspects of hydroclimate and hence are not expected to agree with each other through time (and indeed they do not; Fig. 3). In addition to these observational datasets, we use output from 27 coupled general circulation models (GCMs) that are members of the Climate Model Intercomparison Project phase 5 (CMIP5) archive. Models were included if at least one unforced preindustrial control (piControl) and forced ''historical'' (late nineteenth and/or twentieth century) experiment were available, as well as forced climate change simulations for each of the following representative concentration pathways (RCPs; Moss et al. 2010): RCP2.6, RCP4.5, and RCP8.5. For illustrative purposes, the projected changes in mean precipitation are shown for the RCP8.5 scenario in Fig. 4 (cf. Fig. 2 of Diffenbaugh and Giorgi 2012). The number of available runs from each simulation considered here is reported in the legend of the figure. All model and instrumental data were annualized (January–December) prior to analysis, although our results are not sensitive to the months used for annualization.

a. *Standardizing hydroclimate indicators*

Here we develop a systematic approach to normalizing hydroclimate fluctuations so that they retain their essential meaning whether they originate from climate model simulations, observational datasets, or

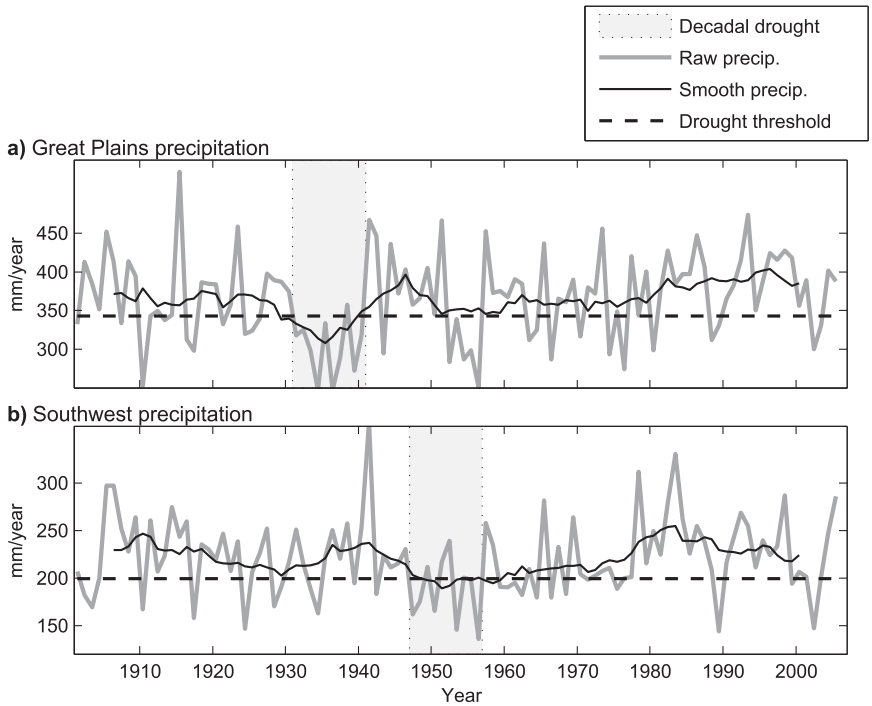

FIG. 2. The 11-yr running means of normalized paleoclimate reconstructions for twentieth-century precipitation data from (a) the U.S. Southwest and (b) the Great Plains. Precipitation data are from the University of East Anglia's Climate Research Unit's time series version 3.1 (TS3.1) dataset (Mitchell and Jones 2005). We identify decadal droughts as -0.5 standard deviations of raw data in the 11-yr mean (vertical gray bars).

paleoclimate reconstructions. We further seek to distinguish between decadal droughts, which have been experienced during the instrumental era (e.g., the 1930s Dust Bowl), and multidecadal megadrought events that are outside the range of variability experienced during the twentieth century. To begin, we consider two of the worst decade-scale droughts during the twentieth century: the 1930s Dust Bowl and the 1950s Southwest drought. Both of these intervals can be identified as -0.5σ departures in the decadal (11-yr) running mean of precipitation (Fig. 2).

Identifying -0.5σ events in the 11-yr means of paleoclimate records requires us to normalize these time series to exhibit unit variance over the twentieth century, so that fluctuations in the past are scaled relative to this baseline period. To that end we represent the entire Colorado streamflow record as normalized departures $[\hat{Z}(t)]$ from the late twentieth-century mean:

$$\hat{Z}(t) = \frac{F(t) - \hat{\mu}}{\hat{\sigma}}, \tag{1}$$

where $F(t)$ is reconstructed flow and $\hat{\mu}$ and $\hat{\sigma}$ are the mean and standard deviation, respectively, of the annual data over the reference period of 1950–2000 CE. The time series of $\hat{Z}(t)$ is a modified z score of $F(t)$, and its values through time are shown in Fig. 3a. Identifying intervals of -0.5σ departures in the running 11-yr mean highlights the 1150s, as well as several other low-flow decades, which occur about once per century (gray vertical bars). Time series from other recent drought studies (Cook et al. 2004; Stahle et al. 2011), normalized in the same way, are also shown in Figs. 3b and 3c. They suggest that the preindustrial rate of comparable decade-long droughts is $\sim$1.5% century^{-1}, which is quite consistent with the literature-based estimate of 1%–2% century^{-1} of Woodhouse and Overpeck (1998).

Our definition of decadal drought captures major intervals of aridity during the twentieth century as well as others during the last millennium (Figs. 3 and 2). We employ a second and more stringent criterion to identify multidecadal megadrought. In this case, -0.5σ departures in the 35-yr mean are identified. Although this definition is somewhat arbitrary, it is useful because the thresholds employed are both longer in time and greater in magnitude than the descriptions of Meko et al. (2007) and Cook et al. (2007) used to characterize the worst droughts of the past millennium in Colorado streamflow and continental-scale hydroclimate, respectively. By setting the criterion for multidecadal megadrought

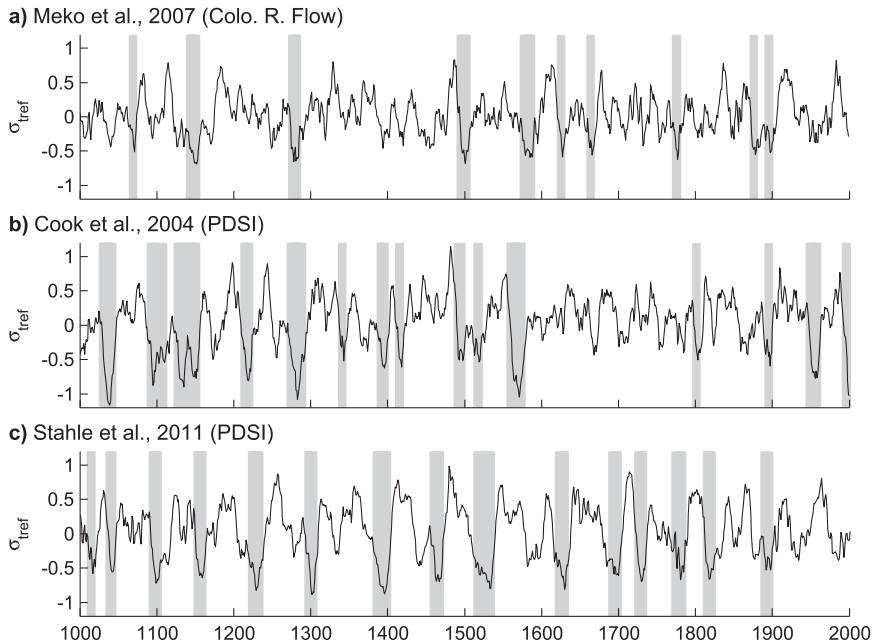

FIG. 3. The 11-yr running means of normalized paleoclimate reconstructions for (a) the Colorado streamflow (Meko et al. 2007), (b) reconstructed PDSI from the southwestern United States (Cook et al. 2004), and (c) reconstructed PDSI from Mexico (Stahle et al. 2011). Vertical gray bars indicate decadal-scale drought (a -0.5σ deviation in the 11-yr mean). All time series are standardized to exhibit one unit of standard deviation and a mean of zero over the 1950–2000 reference period.

beyond anything experienced during the last millennium, we suggest that our results will be insightful for developing adaptation and mitigation strategies for addressing worst-case scenarios. We also note that a 35-yr, -0.5σ event would be on par with the consequential late twentieth-century Sahel drought (e.g., Hoerling et al. 2006). Other similar thresholds (e.g., 25 or 45 yr) would produce qualitatively similar spatial patterns, but the rates of megadrought occurrence and levels of megadrought risk would of course differ from the ones we report here. In particular, for a given magnitude (say -0.5σ) the risk of shorter events would be higher and the risk of longer events would be lower than that for a 35-yr event.

b. *Monte Carlo simulations of drought*

With the definitions of "decadal drought" (an 11-yr, -0.5σ event) and "multidecadal megadrought" (a 35-yr, -0.5σ event) that we have outlined above, we now develop "null" expectations for the rate at which these events would occur from random chance under a stationary climate, but with three different assumptions about the underlying frequency characteristics of hydroclimate variability on interannual to centennial time scales.

We begin by examining the statistics of prolonged drought when interannual hydroclimate fluctuations are simulated as normally distributed white noise with unit variance and standard deviation. An example of one such time series, $X_w(t)$ is shown in Fig. 5. The decadal drought statistics of this type of noise, obtained from 1000 white noise realizations (each of length 100 years), are summarized in Fig. 6. If the distribution of variance across the hydroclimatic continuum were indeed white, then decadal droughts would be expected to occur at a rate of slightly $<1\,(100\,\mathrm{yr})^{-1}$ (Fig. 6a), and the risk of such an event occurring during any given 50-yr period would be around 45% (Fig. 6b). The likelihood of a multidecadal megadrought during any given 50-yr period would be only about 0.45% (Fig. 6b). This preliminary Monte Carlo result establishes a benchmark for the minimum rate at which decadal droughts and megadroughts would occur in a climate with only stochastic interannual variability and no sources of long-term persistence.

Although raw precipitation tends to have a white spectrum on interannual time scales (e.g., Vasseur and Yodzis 2004; Ault and St George 2010), the underlying continuum of hydroclimate may be somewhat "redder" in WNA (Cayan et al. 1998; Ault and St George 2010; Ault et al. 2012, 2013). Moreover, drought indices typically have a source of built-in autocorrelation to accommodate the reality that surface moisture stores

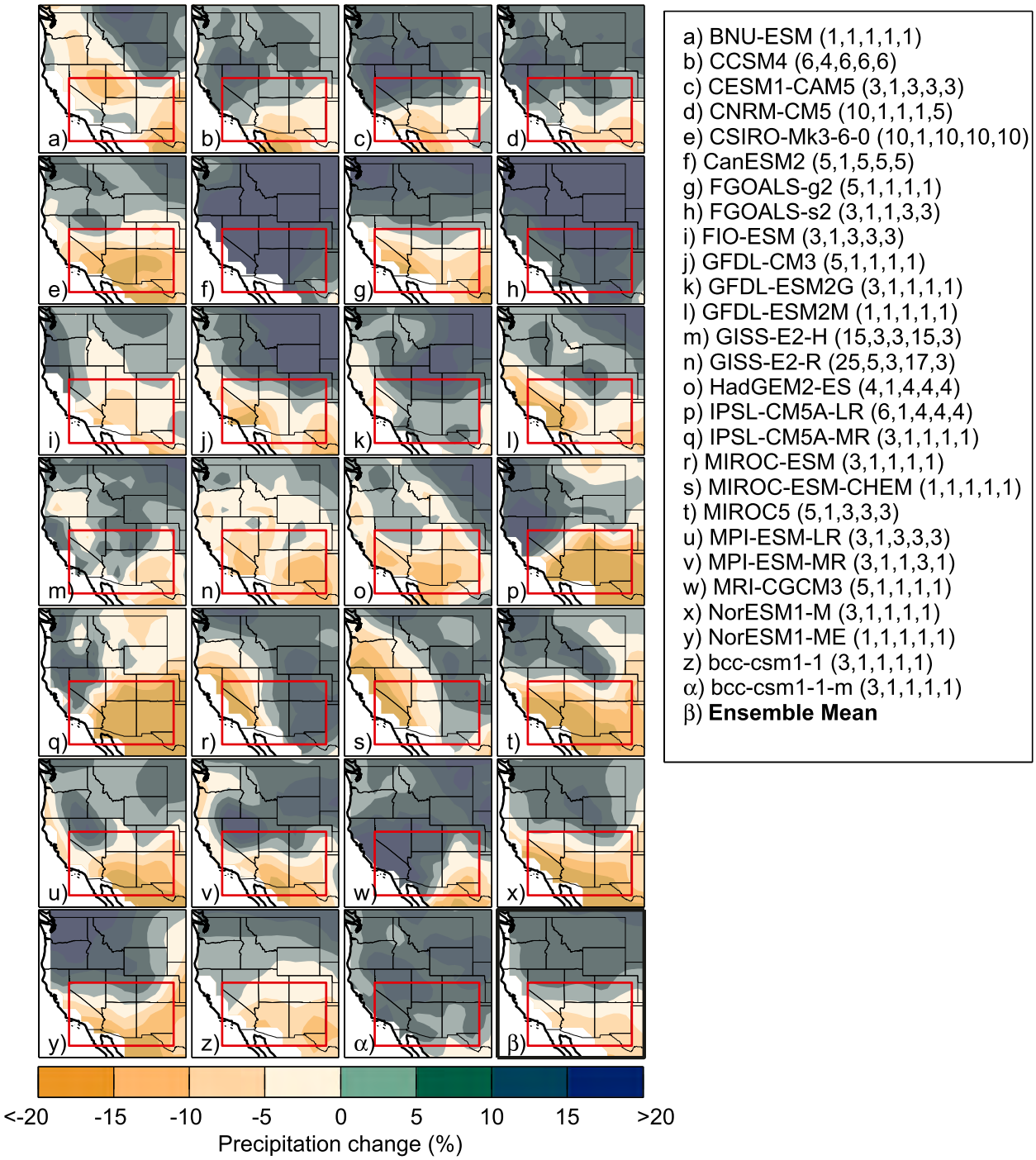

FIG. 4. Map of projected precipitation over the twenty-first-century (2005–2100) change in the RCP8.5 scenario shown as a percentage of twentieth-century precipitation change [as in the global maps of Diffenbaugh and Giorgi (2012)]. For each model, the number of available runs from each experiment is shown in parentheses in the following order: historical, piControl, RCP2.6, RCP4.5, and RCP8.5. The red box shows the greater southwestern United States to emphasize the focus of this study (30°–40°N, 120°–103°W).

depend on their prior states (i.e., they have ''memory''). For example, PDSI models the surface water balance using a simplified approximation of soil moisture, and has a built-in autocorrelation function (e.g., Alley 1984; Wells et al. 2004). Similarly, the standardized precipitation index (SPI) integrates anomalies over a number of predefined lags to measure how aggregated rainfall anomalies deviate from their long-term averages.

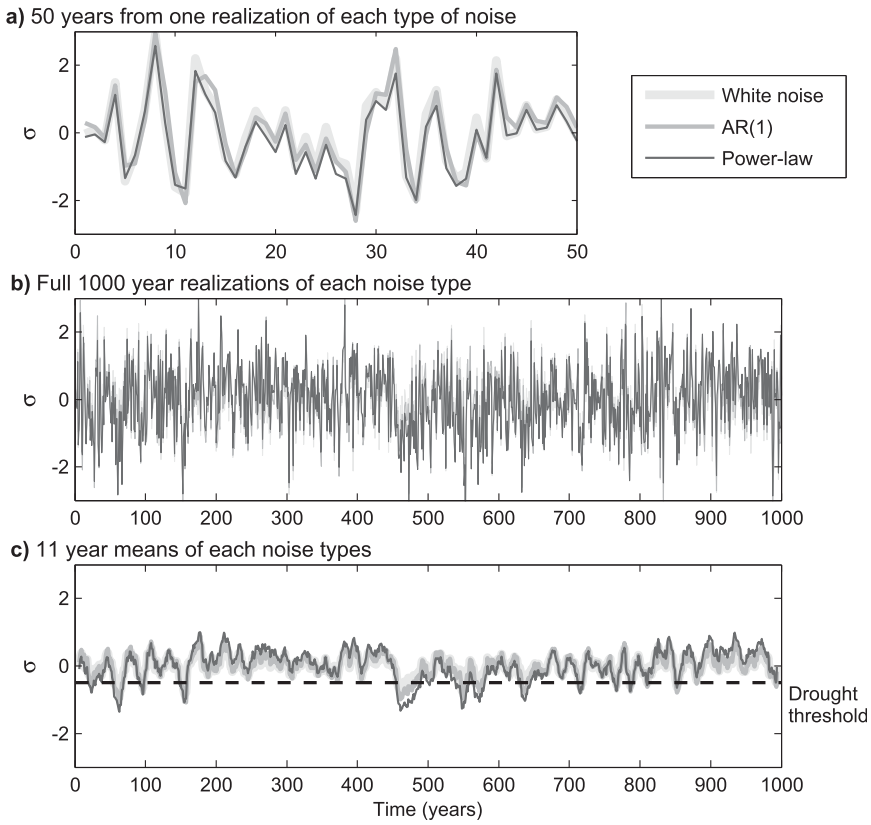

FIG. 5. Examples of Monte Carlo (MC) time series used to simulate decadal drought with three different underlying frequency characteristics [white noise, AR(1), and power law]: (a) 50 yr of a single MC realization of each type of noise, (b) the 1000-yr full realization of each noise type, and (c) the 11-yr running mean of each type of noise, shown with the dashed line denoting a decadal drought (e.g., a -0.5σ in the 11-yr running mean). Importantly, each MC time series has a mean of zero and unit standard deviation, and differ only in the distribution of their variances across the power spectrum. Moreover, the AR(1) and power-law time series are generated by rescaling the white noise data, which is why the different realizations of noise appear so strongly correlated with each other.

In a simplistic sense, year-to-year persistence can be described as a first-order autoregressive [AR(1)] process [$X_{\mathrm{AR}(1)}(t)$]:

$$X_{\mathrm{AR}(1)}(t) = \alpha X_{\mathrm{AR}(1)}(t-1) + X_w(t), \qquad (2)$$

where α is the lag-1 (i.e., 1 yr) autocorrelation coefficient and is derived empirically from data, $X_{\mathrm{AR}(1)}(t)$ is autoregressive red noise, and $X_w(t)$ is the white noise input. In WNA, the value of α is about 0.3 on interannual time scales for the three (tree ring based) paleoclimate reconstructions shown in Fig. 3, as well as for many other hydroclimate indicators (Ault et al. 2013). A single realization of this type of noise (normalized to exhibit unit variance overall) is shown in Fig. 5, and the statistical characteristics of megadroughts in this type of noise are shown in Fig. 6.

Despite the intuitive and simple representation of hydroclimate as an AR(1) process—moisture deficits tend to persist through time—there is some evidence that such an approximation misses key characteristics of variability on longer time scales (Pelletier and Turcotte 1997; Kantelhardt et al. 2006; Koscielny-Bunde et al. 2006; Ault et al. 2013). As a complementary approach, we also simulate hydroclimate as a process with underlying frequency characteristics that are described by a weak power-law relationship between frequency f and variance $S(f)$, such that $S(f) \propto f^{-\beta}$. Power spectra with higher values of β correspond to time series that exhibit more variance at lower frequencies. To generate time series with this type of frequency behavior, we employ a method similar to the one described by Pelletier and Turcotte (1997) and explained thoroughly in Pelletier (2008). First, we calculate the discrete Fourier transform of

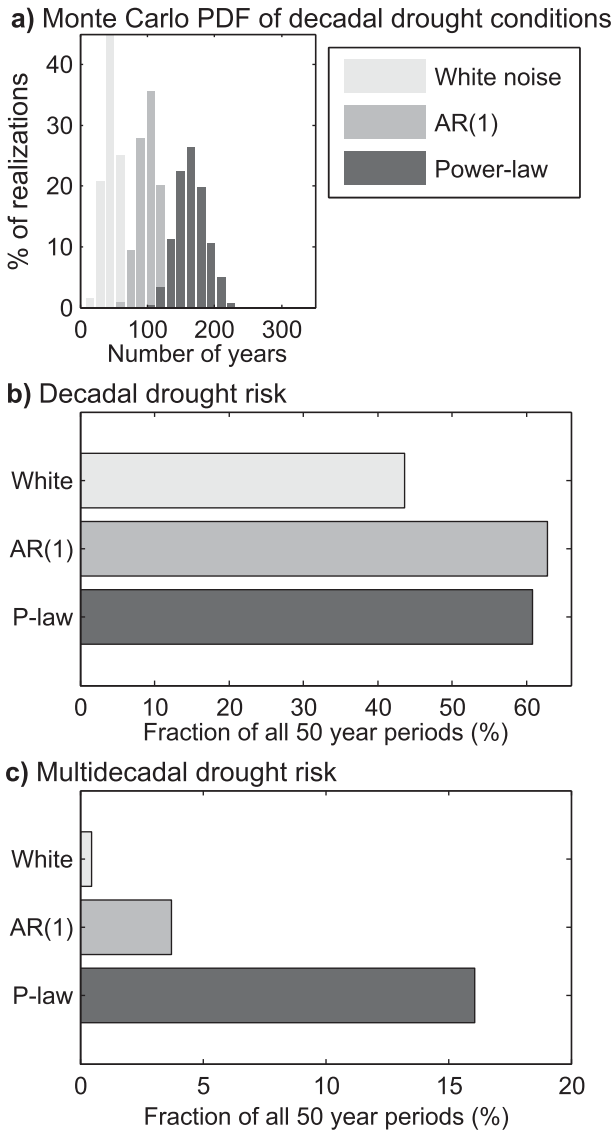

FIG. 6. Statistics summarizing Monte Carlo simulations: (a) distributions of years spent in decadal (≥11 yr) drought conditions for each type of noise (as a percentage of all realizations), (b) risk of *at least* one decadal (≥11 yr) drought during any given 50-yr window in any realizations, and (c) risk of a multidecadal (≥35 yr) drought during any 50-yr window. Risk in (b) and (c) is expressed as a percentage of the total number of simulations.

a white noise time series $X_w(t)$, and filter it to conform to a predefined value of β:

$$\tilde{X}_p(k) = \psi_k \sum_{t=1}^{N} X_w(t) e^{-i2\pi k[(t-1)/N]}, \quad k = 0, \ldots, N-1, \tag{3}$$

where k are the standard Fourier frequencies and N is the length of the time series. The term ψ_k rescales the Fourier coefficients so that they are approximately power-law distributed:

$$\psi_k = \begin{cases} \left(\dfrac{1}{N}\right)^{-\beta/\sqrt{2}} & \text{if} \quad k = 0 \\ \left(\dfrac{k}{N}\right)^{-\beta/\sqrt{2}} & \text{otherwise}. \end{cases} \tag{4}$$

Here the value of β is divided by $\sqrt{2}$ because it is being applied to the raw Fourier coefficients, which have amplitudes proportional to the square root of the power spectrum.

The rescaled Fourier series $\tilde{X}_p(k)$ is then used to generate power-law time series $X_p(t)$ by taking the real part of the inverse Fourier transform of $\tilde{X}_p(k)$:

$$X_p(t) = \mathrm{Re}\left\{\frac{1}{N}\sum_{k=0}^{N-1} \tilde{X}_p(k) e^{-i2\pi k[(t-1)/N]}\right\}, \quad t = 1, \ldots, N. \tag{5}$$

Finally, the mean and variance are restored to the values of the original white noise data (zero and unity, in this case).

We used a value of 0.5 for β to rescale each realization of $X_w(t)$, which was suggested as an appropriate estimate by Ault et al. (2013) from synthesis of tree-ring reconstructions of precipitation, PDSI, and streamflow as well as non-tree-ring estimates of hydroclimate. As a check, we calculated the power laws of the noises after they had been rescaled. We found that the actual values of β varied from one realization to the next, but were generally between 0.4 and 0.6. This range agrees well with instrumental and paleoclimate estimates of this parameter for the region, and is certainly within the observational uncertainty (Ault et al. 2013). Importantly, time series with spectra scaled by power laws of ~0.5 will also appear to exhibit autocorrelation of about 0.3, which in turn implies that the AR(1) and power-law realizations will behave very similarly on short time scales, but not necessarily on longer ones (e.g., Pelletier and Turcotte 1997; Ault et al. 2013). Finally, our use of power-law noises does not make any assumptions about the underlying climate dynamics governing the shape of the power spectrum of hydroclimate: linear and nonlinear processes alike may produce such spectral distributions (Milotti 1995; Penland and Sardeshmukh 2012).

Table 1 highlights a few key features of the two models employed here. In particular, the noise models used to estimate drought risk use parameters that do not vary across space, and all are scaled to the twentieth-century mean and variance. The autocorrelation parameter of 0.3 is a middle-of-the-road value from the time series

TABLE 1. Summary of the two red noise models used here to estimate drought risk in western North America. The key parameters are reported in the second column, and they do not vary spatially. The value of α (0.3) is the approximate autocorrelation of the three time series in Fig. 3, as well as the data analyzed in (Ault et al. 2013, Fig. 2), which supports values between 0.25 and 0.35. The estimate used for β (0.5) is a middle-of-the-road estimate from those reported in (Ault et al. 2013), and also Fig. 7.

Model	Parameters	Estimated from	References
AR(1)	α(0.3)	Streamflow, soil moisture, tree-ring reconstructions	Meko et al. (2007); Cook et al. (2004); Stahle et al. (2011); Ault et al. (2013); this study
Power law	β(0.5)	Long tree-ring chronologies, other hydroclimate proxies	Pelletier and Turcotte (1997); Ault et al. (2013); this study

shown in Fig. 3, and is well within the range of estimates for autocorrelation in the region from other paleoclimate and observational datasets (Ault et al. 2013). The value used for β (0.5) is from the analysis of proxy records in Ault et al. (2013) as well, and is supported by Fig. 7.

Sample time series and statistics of power-law realizations of drought (Figs. 5 and 6, respectively) reveal the importance of low-frequency variability in shaping prolonged drought risk. Over the time scale of 50 years, the white, AR(1), and power-law noises are all remarkably similar to each other [because the initial realization of $X_w(t)$ is rescaled to produce both $X_{\mathrm{AR}(1)}(t)$ and $X_p(t)$]. On the time scale of a millennium (Fig. 5b), the low-frequency differences are more apparent. The running 11-yr mean of each noise type (Fig. 5b) makes the implications for risk clear: the AR(1) and power-law time series spend more time in drought and depict higher levels of risk for megadrought. In Fig. 6a, it is also clear that the fraction of time spent in decadal drought conditions is about 17% for the power-law noise realizations, as opposed to 10% for the AR(1) simulations, and less than 5% for the white noise time series. Although the AR(1) and power-law time series exhibit similar likelihoods that a single decadal drought will occur during any given 50-yr period, the power-law series yields events that persist for longer. Drought risk on longer time scales, however, is clearly far higher for the power-law distributed time series than for the other two, with the risk of a 35-yr (-0.5σ) megadrought being greater than 16% for any given 50-yr segment. We stress that these risks apply to a stationary climate with no local feedbacks or externally forced changes. They are therefore our most conservative baseline estimates of prolonged drought risk during the coming century.

c. *Projected risk of persistent drought in CMIP5 simulations*

Our definition of megadrought is easily extended to climate model data. For instance, projected precipitation at the jth position of each grid of a given model can be transformed as

$$\hat{Z}_j(t) = \frac{P_j(t) - \hat{\mu}_j}{\hat{\sigma}_j}, \tag{6}$$

where $\hat{\mu}_j$ and $\hat{\sigma}_j$ are the late twentieth-century (1950–2000 CE) mean and standard deviation, respectively. The subscript j is used as a spatial index (i.e., a point on a grid).

Certain limitations make estimating megadrought risk in the CMIP5 archive more complicated than simply

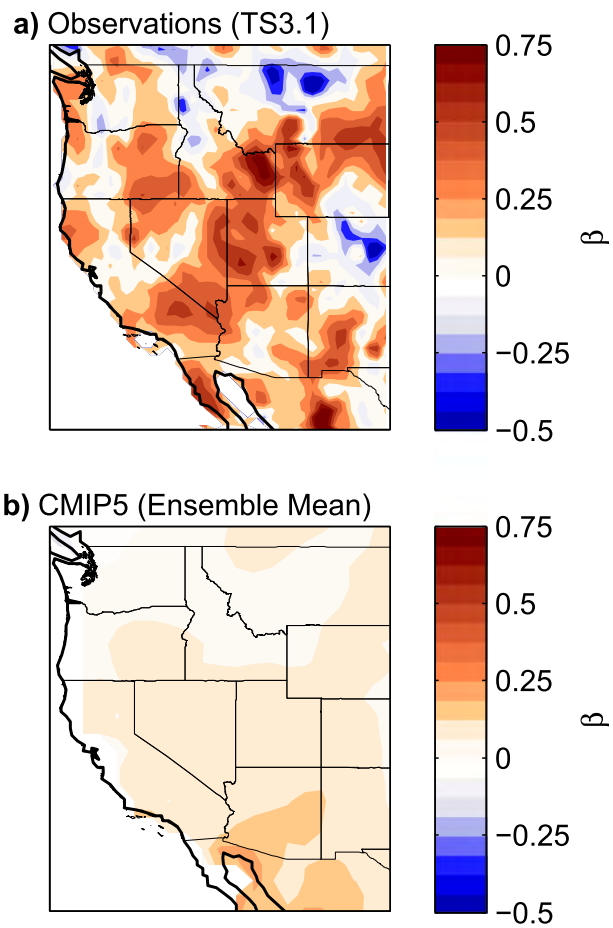

FIG. 7. Power-law estimates (β) from (a) twentieth-century instrumental data and (b) and CMIP5 historical (1850–2005 CE) simulations. Instrumental data originate from the University of East Anglia's TS3.1 data product and, like the CMIP5 records, were annualized prior to calculating β.

calculating how often these events occur in climate projections. First, the number of ensemble members available from each model is small (Fig. 4), and the role for internal variability may be substantial on decadal to multidecadal time scales (Hawkins and Sutton 2009; Deser et al. 2012). This makes it difficult to reliably estimate risks stemming from the combined influences of forced changes and internal variability. Second, the distribution of variance across time scales is different in observational data than in models. In particular, models tend to exhibit power spectra resembling white noise in WNA, even when run for many centuries or forced with the time-evolving boundary conditions of the last millennium (Ault et al. 2012, 2013). To illustrate this point further here, we show power-law estimates from observations and CMIP5 data in Fig. 7. In this case, the power-law coefficients are calculated from each model individually and then averaged together to produce this map. Importantly, the results of individual models appear similar to this ensemble average, supporting recent findings that the continuum of hydroclimate in WNA appears to be considerably redder in observations than in models (Ault et al. 2013, 2012).

We address the aforementioned challenges by developing a Monte Carlo model of hydroclimate variability to emulate the statistics of both natural variability and climate change in WNA. This approach enables us to evaluate projected risk of prolonged drought in the twenty-first century for a given climate change scenario. We use the underlying frequency characteristics of observational data (including paleodata), as well as projected changes in precipitation simulated by models archived as part of CMIP5. The Monte Carlo model is described by

$$\hat{Z}_{ij}(t) = X_w(t)\left(\frac{\hat{\varrho}_{ij}}{\hat{\sigma}_{ij}}\right) + \xi(\Delta\hat{\mu}_{ij}, \sigma^2_{\mu_{ij}}), \qquad (7)$$

where $\hat{Z}_{ij}(t)$ is normalized precipitation of the ith model at the jth point on a grid, and $X_w(t)$ is a normally distributed time series of white noise with unit variance. The quantity $\hat{\varrho}_{ij}/\hat{\sigma}_{ij}$ scales the white noise by normalizing the twenty-first-century standard deviations ($\hat{\varrho}_{ij}$) from a given model grid point by the corresponding twentieth-century reference standard deviation ($\hat{\sigma}_{ij}$). Twentieth- to twenty-first-century differences in mean precipitation at each point in each model are represented by the random, normally distributed variable ξ_{ij}, with expected mean of $\Delta\hat{\mu}_{ij}$ (the change in precipitation) and variance ($\sigma^2_{\mu_{ij}}$), estimated from ensembles of runs when possible, and otherwise set to zero. Finally, to generate Monte Carlo twenty-first-century realizations of hydroclimate with AR(1) and power-law distributions in frequency space, we rescale $\hat{Z}_{ij}(t)$ following the same methods described above.

We estimate decadal drought and multidecadal megadrought risk in three climate change scenarios (RCP2.6, RCP4.5, and RCP8.5) for each of the 27 CMIP5 models considered here by generating 1000 stochastic (white noise) realizations, each 1000 years long, of WNA hydroclimate using Eq. (7), as well as the AR(1) and power-law rescaling procedures. In each model, and for each RCP, estimates of $\hat{\sigma}$ are made using the 1950–2000 portion of the model's historical simulation, and $\hat{\varrho}$ is estimated over the 50-yr interval spanning 2050–2100. Likewise, $\Delta\hat{\mu}$ and σ^2_{μ}, are estimated from the differences between historical (1950–2000) and late twenty-first-century (2050–2100) precipitation means. We then identify the percentage of all 1000 realizations that experience decadal drought or multidecadal megadrought conditions in each RCP, model, and type of noise.

3. Results

In the CMIP5 control runs, rates of decadal drought occurrence (the average number of events per century) are spatially uniform and close to one (Fig. 8a). Similarly, white noise realizations also tend to produce about one event per century. Under climate change, rates of decadal drought occurrence show more regional diversity than in the controls (Figs. 8b–d). In the northern part of WNA, rates are close to zero, whereas throughout much of the U.S. Southwest they are between 1.5 and 1.75. Multidecadal megadrought rates are close to zero in the control runs of the CMIP5 archive (Fig. 8e). Under climate change, these rates are closer to 0.5 (or 1 event per 200 yr), but they are still quite rare (Figs. 8f–h).

The risk of a single decade-long drought over any given 50-yr period in the control runs is about 50% (Fig. 9a), which is intuitive because the corresponding rate is about one per century. Decadal drought risk in the climate change scenarios, estimated over the period 2050–2100, depicts a decrease in the northern regions, and an increase to between 60% and 80% (Figs. 9b–d) in the U.S. Southwest. Moreover, risk increases in the U.S. Southwest with the intensity of the warming; the highest levels are found under the RCP8.5 scenario.

In the unforced control runs, the risk of a multidecadal megadrought is less than 1% throughout the region (Fig. 9e). Under climate change, however, risks in the U.S. Southwest increase to 10%–20% in RCP2.6 (Fig. 9f), 20%–40% in RCP4.5 (Fig. 9g), and 30%–50% in RCP8.5 (Fig. 9h).

A qualitatively similar picture of risk to that in Fig. 9 is seen in Figs. 10 and 11, which summarize our Monte

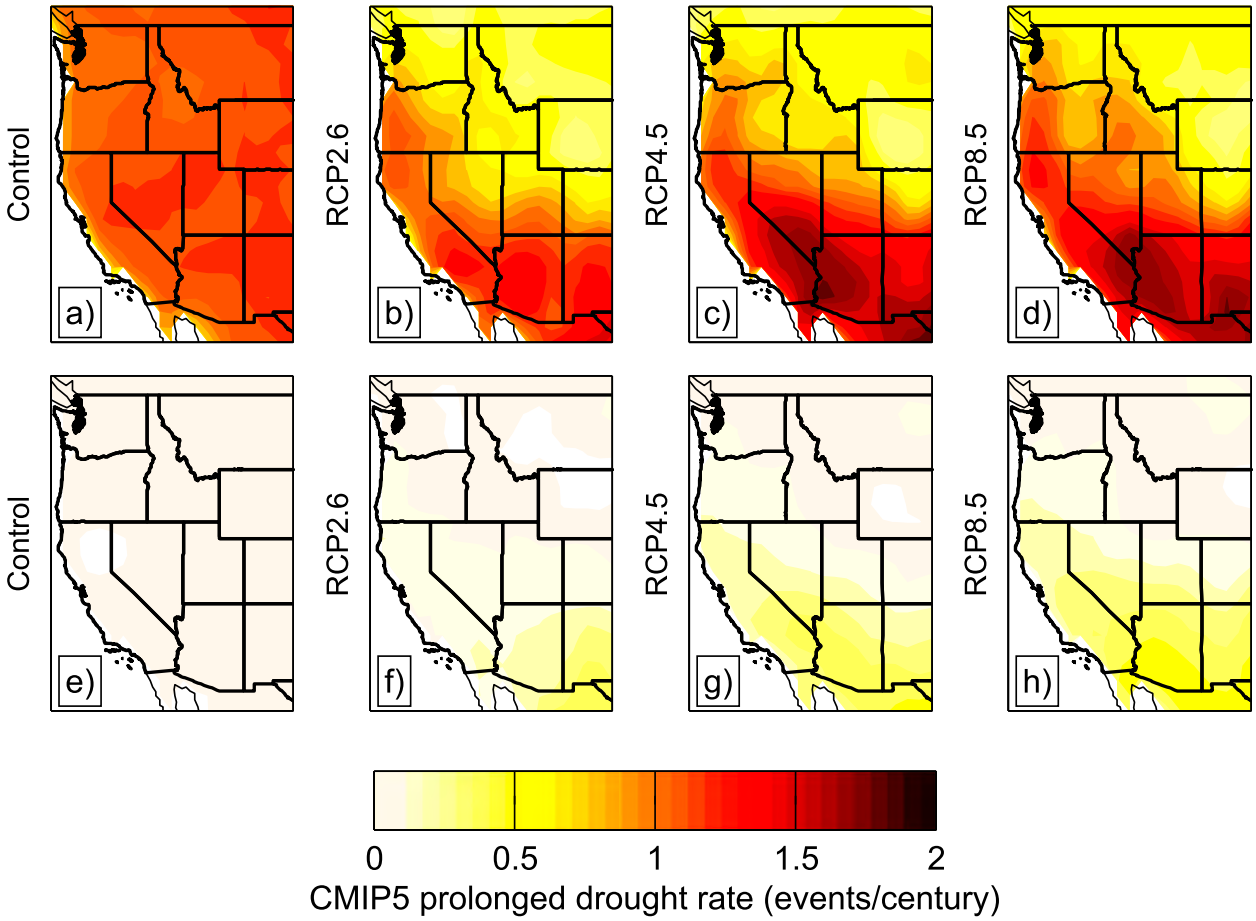

FIG. 8. Estimated rate of prolonged drought occurrence in (a),(e) control and (b)–(d),(f)–(h) forced CMIP5 simulations. The rate is calculated as the number of events per century averaged across all models, and across all centuries in the control cases in (a) and (e). (top) Indicates the rate of decadal (≥11 yr) drought, and (bottom) the rate of multidecadal (≥35 yr) megadrought occurrence. Forcing scenarios are indicated to the left of each map.

Carlo experiments using Eq. (7) to generate stochastic hydroclimate realizations, and the procedures described in section 2b to rescale them to exhibit AR(1) and power-law frequency distributions. In the U.S. Southwest, for example, risk of droughts at both decadal and multidecadal time scales increases with the intensity of the greenhouse gas forcing (columns) and type of noise (rows). Uncertainty in our risk estimates is depicted by the standard deviations of the individual model estimates of risk in Fig. 12. Results for the multidecadal megadrought risk standard deviations are shown in Fig. 13.

Thus far, we have only considered the risk of a prolonged period of aridity using two somewhat narrow definitions of decadal drought and megadrought. To develop a more complete representation of drought risk across a wide range of time scales and magnitudes, we examine the two-dimensional probability density function of drought risk using the same time scale-independent definition employed by Ault et al. (2013). Specifically, a drought is defined as a period of time during which 3/5 of the antecedent years are below a particular threshold. These thresholds are the values of the x axes on the individual panels of Fig. 14, and the time scales are shown on the y axes of that figure. As in the earlier figures, risk is estimated from all Monte Carlo simulations of each model for each RCP, then averaged across the individual CMIP5 members to produce the "magnitude versus duration" diagrams in Fig. 14.

The results in Fig. 14 show that risk increases with GHG forcing intensity across all time scales in the raw CMIP5 archive (Figs. 14a–c), as well as for each type of noise. It also illustrates that the AR(1) and power-law distributions depict higher levels of risk on decadal and longer time scales than the white noise and CMIP5 ensembles. To emphasize this point further, we show the differences in drought risk across time scales between each type of noise and the raw CMIP5 estimates in Fig. 15. From this figure, it is clear that the low-probability (but

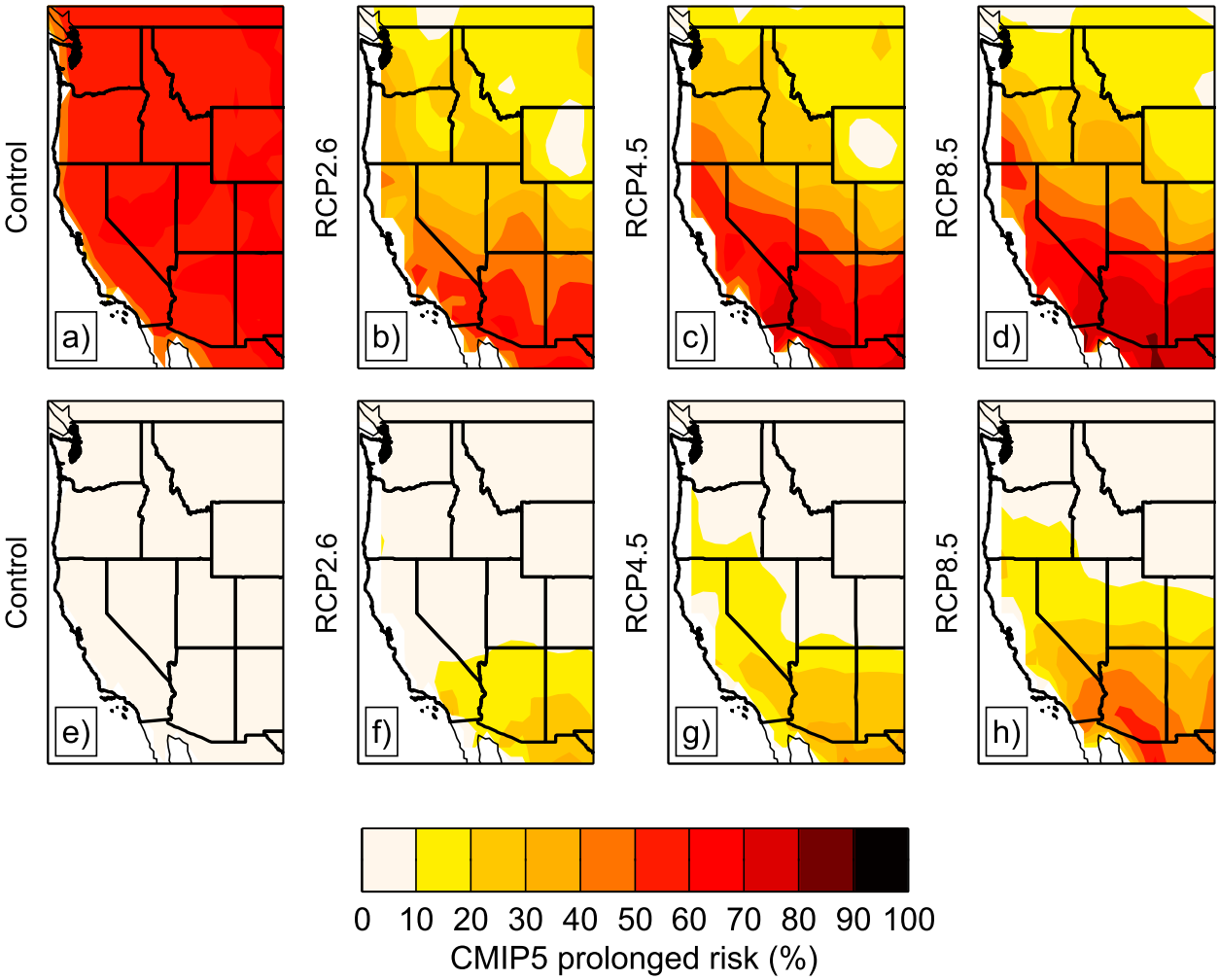

FIG. 9. Estimated risk of at least one prolonged drought in (a),(e) control and (b)–(d),(f)–(h) simulations. (top) Indicates the risk of decadal (>11 yr) drought, and (bottom) indicates the risk of multidecadal (>35 yr) megadrought. The risk is calculated as the percent of the total number of models (27) that simulate decadal or multidecadal megadrought. Forcing scenarios are indicated to the left of each map.

presumably consequential) "tails" of the distributions are far more likely in the AR(1) and power-law noises than in the raw CMIP5 archive. For instance, under the RCP8.5 scenario, the risk of a 0.5σ event on 40-yr time scales is below 5% as estimated from CMIP5 runs (Fig. 14c), but closer to 10% in the power-law noise realizations (Fig. 14i).

We extend our analysis of megadrought risk in the western United States to the rest of the world by examining raw CMIP5 estimates of decadal drought and multidecadal megadrought from the three RCP scenarios (Fig. 16). Risks throughout the subtropics appear as high as or higher than our estimates for the U.S. Southwest (e.g., in the Mediterranean region, western and southern Africa, Australia, and much of South America). We do not attempt to develop regionally appropriate stochastic realizations of precipitation at this time, although such an endeavor could be straightforward in areas where instrumental and paleoclimate data are adequate to characterize the underlying continuum of hydroclimate. In areas where low-frequency variability in precipitation is substantial and not well simulated by climate models (e.g., West Africa; Ault et al. 2012), the results shown here likely underestimate future risk of persistent drought.

We stress that our results have only used precipitation, yet temperature may play a substantial role in driving or exacerbating drought. Also, we used the low end of β estimates from Ault et al. (2013) to generate the power-law noises, but higher values might be realistic on long time scales, according to the preponderance of paleoclimate evidence considered in that study, and would raise the levels of risk. Hence, to the extent that the global climate models simulate future change realistically and

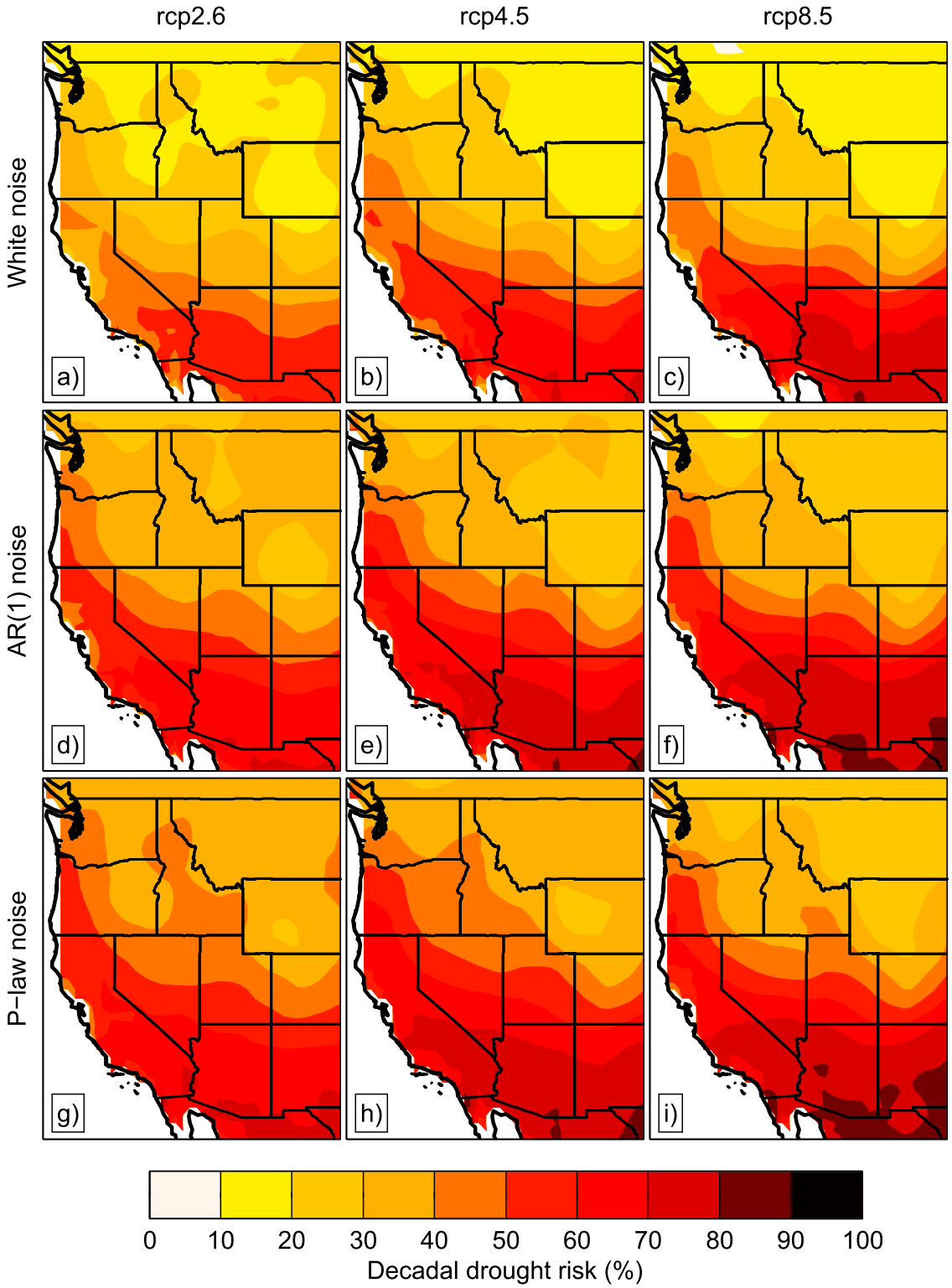

FIG. 10. Decadal (>11 yr) drought risk estimates obtained from Monte Carlo simulations of projected precipitation changes across all models in three different climate change scenarios (columns) and for three different types of noises (rows). These maps express the average risk estimates obtained from Monte Carlo simulations of precipitation in each model under three climate change scenarios. For each of the 27 individual CMIP5 models, risk is calculated as the percentage of the total number of Monte Carlo simulations (1000) that show a decadal drought. Here, those estimates of risk are averaged across the multimodel archive.

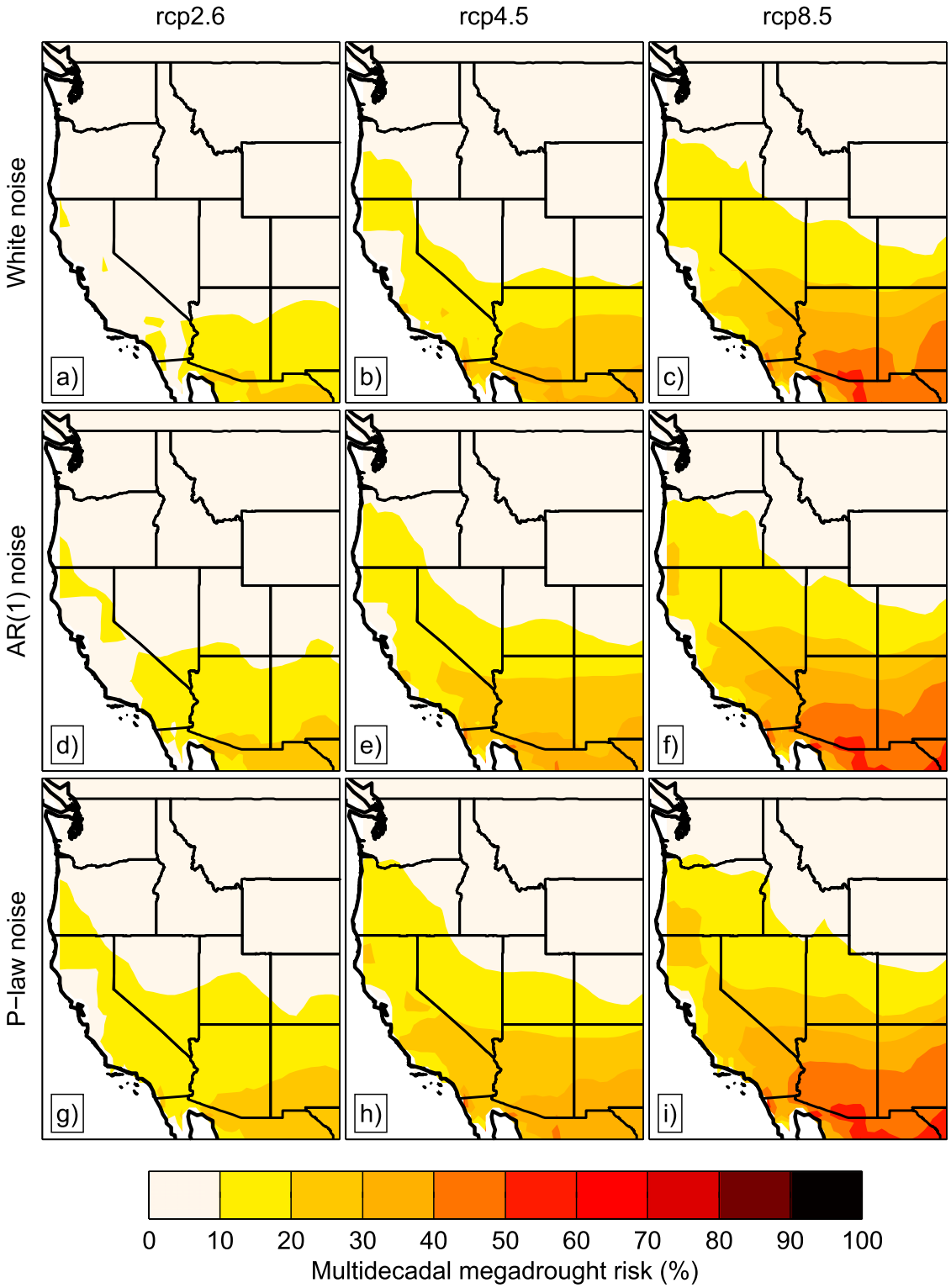

FIG. 11. Multidecadal (>35 yr) megadrought risk estimates obtained from Monte Carlo simulations of projected precipitation changes across all 27 CMIP5 models in three different climate change scenarios (columns) and for three different types of noises (rows). These maps express the average risk estimates obtained from Monte Carlo simulations of precipitation in each model under three climate change scenarios. For each of the 27 individual CMIP5 models, risk is calculated as the percentage of the total number of Monte Carlo simulations (1000) that show a multidecadal megadrought. Here, those estimates of risk are averaged across the multimodel archive.

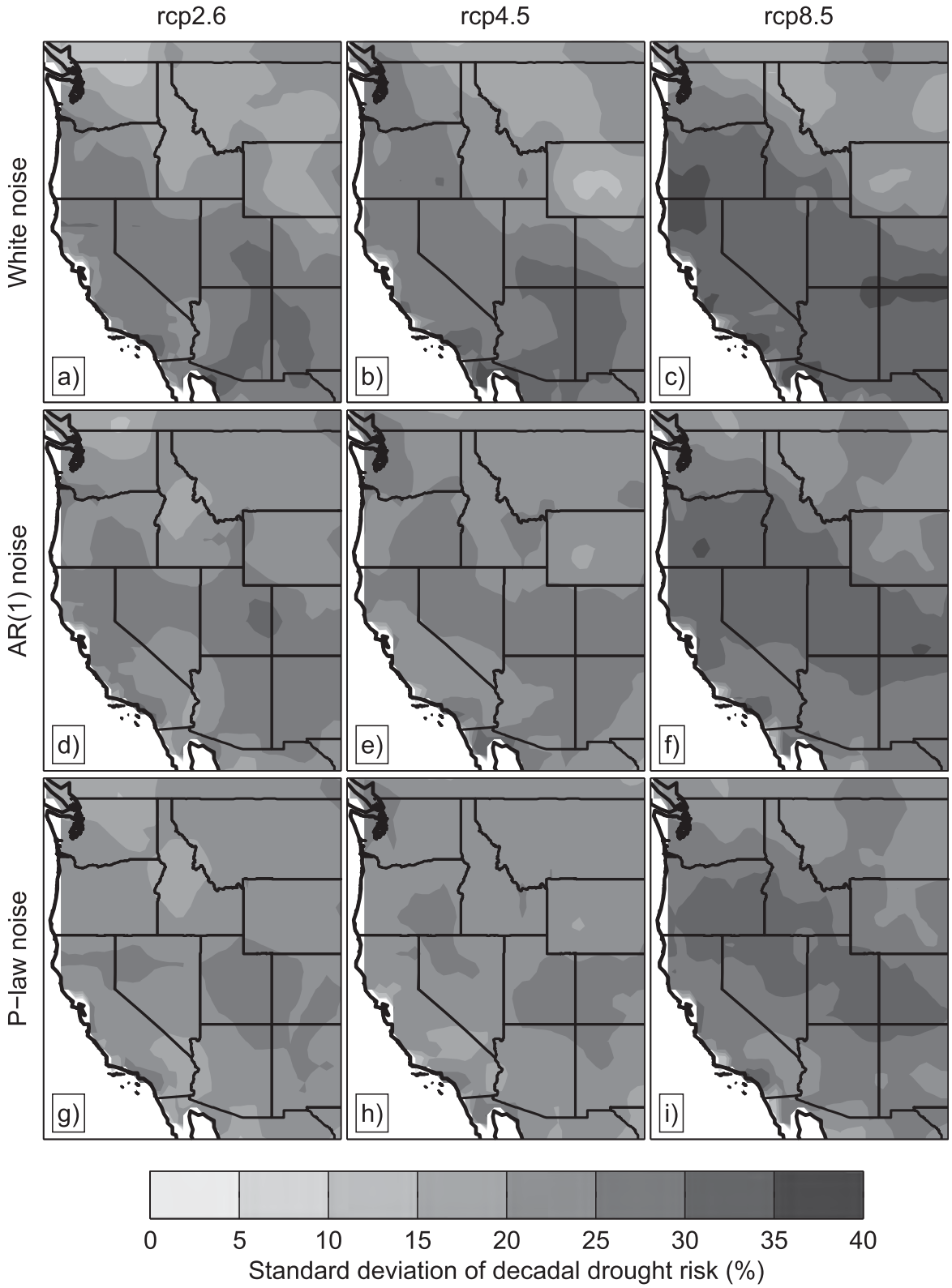

FIG. 12. Standard deviations of decadal (>11 yr) drought risk estimates in Fig. 10. Standard deviations are calculated from the individual risk estimates of each model at each point for three different climate change scenarios (columns) and for three different types of noises (rows). These maps express the spatial variability of uncertainty in the risk estimates of Fig. 10.

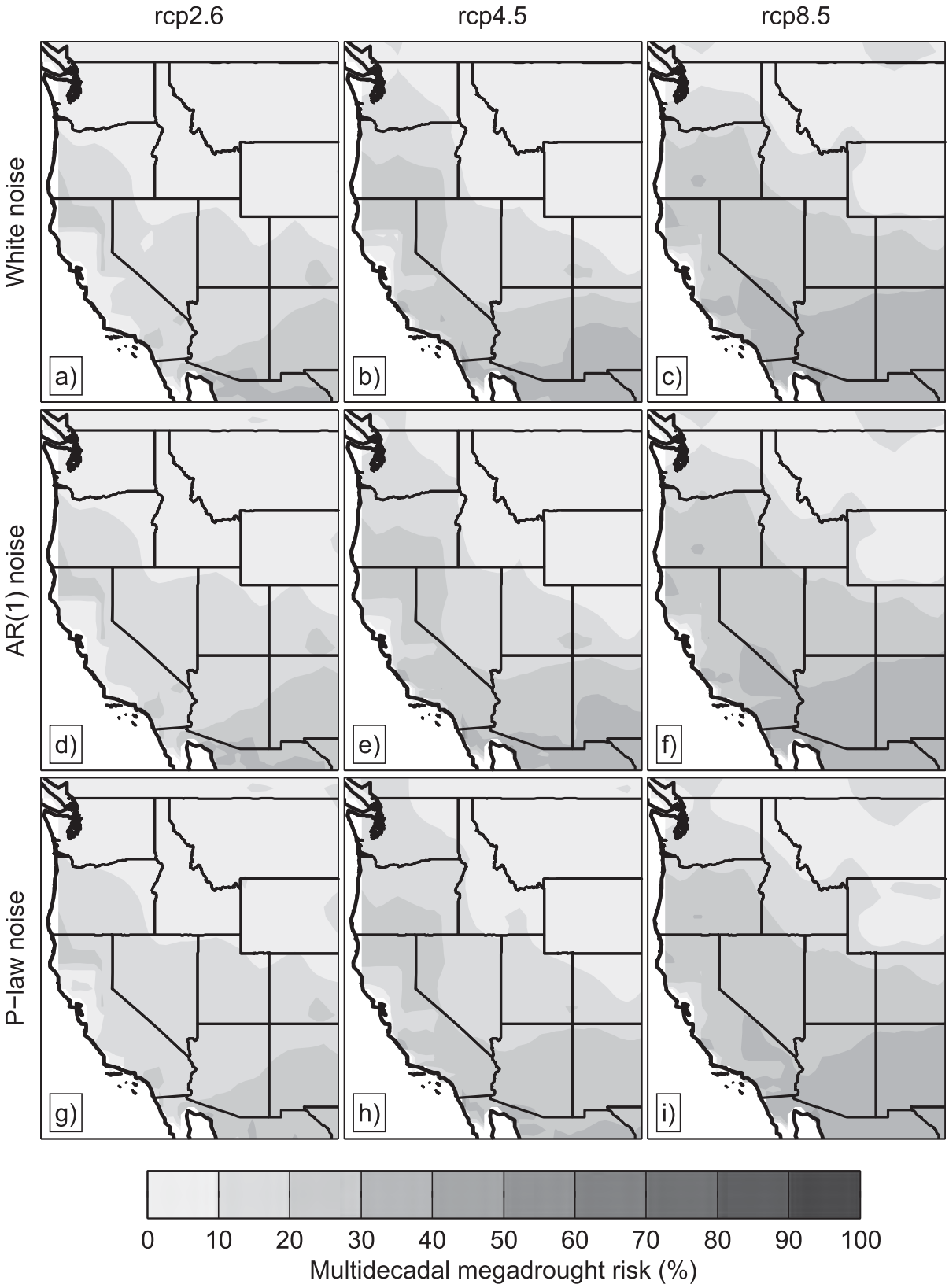

FIG. 13. Standard deviations of drought risk estimates as in Fig. 12, but for multidecadal (>35 yr) megadrought risk.

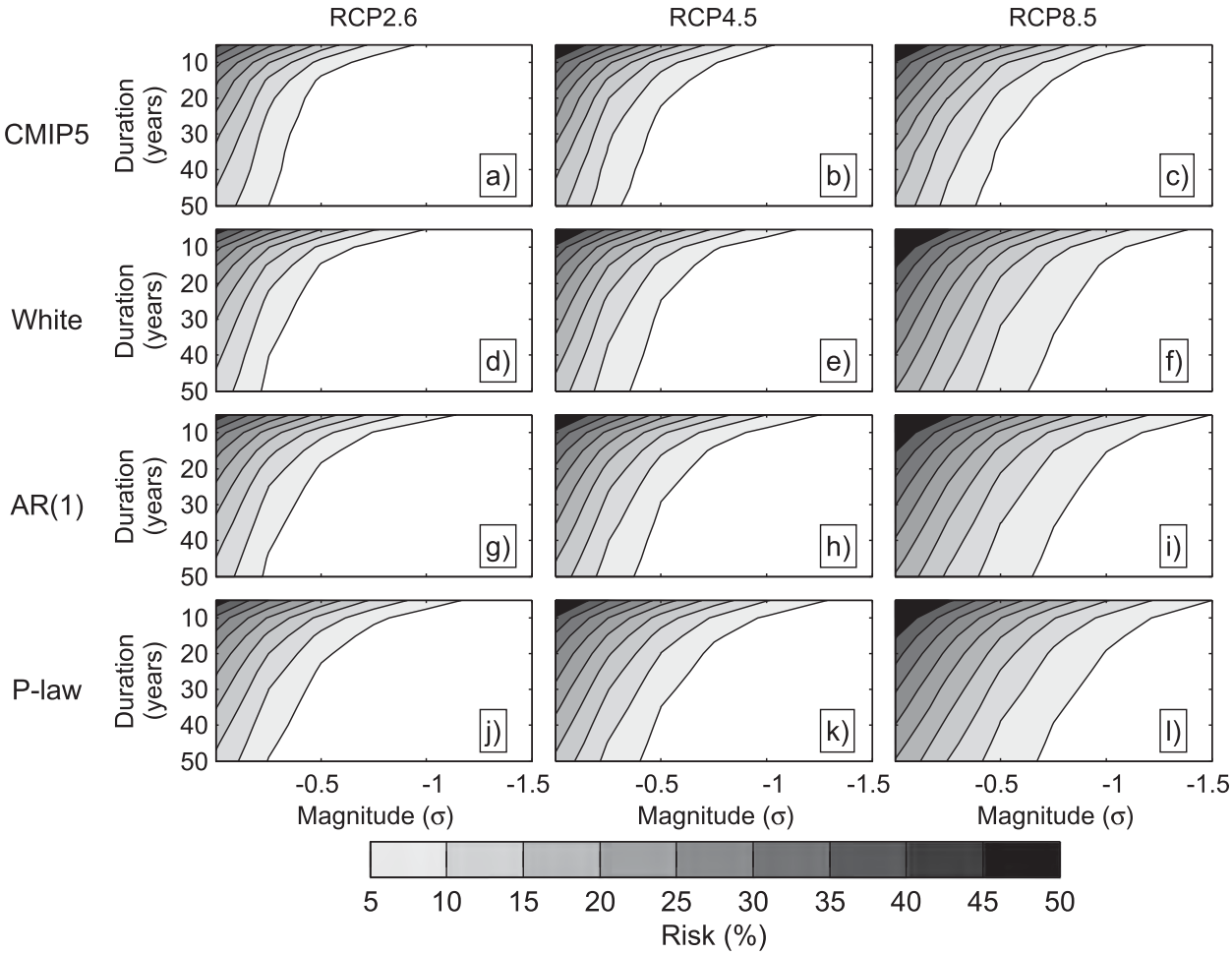

FIG. 14. Drought magnitude vs duration for realizations of southwestern U.S. precipitation time series in each climate change scenario, obtained from the following sources: (a)–(c) raw CMIP5 projections, (d)–(f) white noise, (g)–(i) AR(1) realizations, and (j)–(l) power-law realizations.

our simple Monte Carlo models are adequate, the view of risk presented here is quite conservative.

4. Discussion and conclusions

In the current generation of global climate models, the risk of a decade-scale drought occurring this century is at least 50% for most of the greater southwestern United States and may indeed be closer to 80% (Figs. 9 and 10). The probability of multidecadal megadrought is also high: the likelihood of a 35-yr event is between 10% and 50% depending on how much climate change is realized during the coming century. The probability of even longer events (>50-yr, or "permanent," megadrought) is nonnegligible (5%–10%) for the most intense warming scenario (Fig. 14). Risk levels correspond to the intensity of forcing and the underlying distribution of hydroclimatic variance across the frequency continuum. The RCP8.5 scenario, for instance, depicts the highest levels of risk regardless of the underlying noise type. Likewise, the power-law noises produce higher megadrought likelihoods for each RCP than the other noises.

An obvious limitation of our work is that it is "blind" to certain aspects of dynamically driven changes in prolonged drought risk. For instance, changes in the magnitude, frequency, or teleconnection patterns of El Niño and La Niña (e.g., Coats et al. 2013a) may alter the statistics of interannual variability in ways that are not captured by our simple models. Further, megadrought statistics over the last millennium may be forcing dependent, as suggested by Cook et al. (2004), for instance, which shows that megadroughts were more common during the medieval climate era of 850–1200 CE. Another very serious limitation is imposed by the reliability of the models themselves to make realistic predictions of changes in climatological precipitation for the end of the twenty-first century.

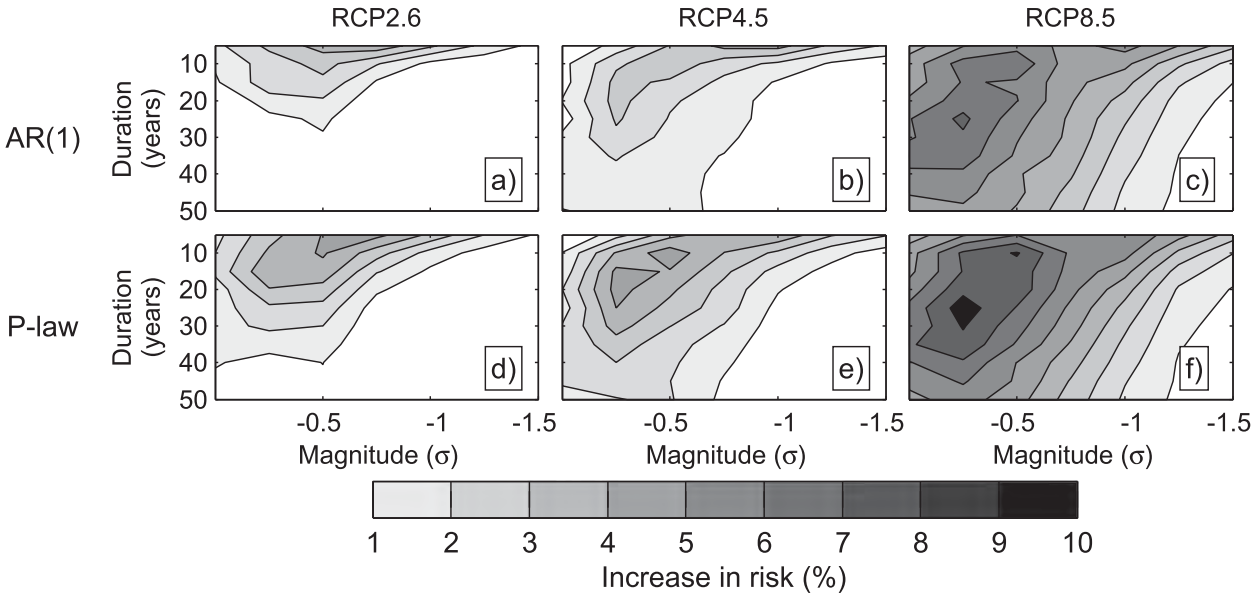

FIG. 15. Differences in duration vs magnitude risk estimates between raw CMIP5 and the two types of noises with low-frequency variability. These results are for the southwestern U.S. region, and they illustrate the difference in drought risk at a given magnitude and duration if low-frequency noise is prominent. Under the strongest forcing, the low-frequency noise models increase the risk of a multidecadal megadrought by about 8%–10%.

The projected increases in risk for the U.S. Southwest reflect forced changes in the global hydrological cycle (e.g., Held and Soden 2006; Solomon et al. 2007; Vecchi and Soden 2007; Seager et al. 2010). As such, the global picture of persistent drought risk in the CMIP5 archive (Fig. 16) bears a striking resemblance to the projected decreases in precipitation throughout many semiarid regions of the world (Diffenbaugh and Giorgi 2012; Knutti and Sedlacek 2013). It follows that prolonged drought risk is a function not only of forced changes in the global hydrological cycle and the severity of future warming, but also of the accuracy with which GCMs project large-scale changes in hydroclimate (e.g., Held and Soden 2006; Seager et al. 2007; Vecchi and Soden 2007; Seager et al. 2010). Moreover, we have based our analysis on precipitation projections, yet this variable has been notoriously challenging for GCMs to simulate accurately and large biases may remain in some models (e.g., Knutti and Sedlacek 2013; Jiang et al. 2012). Our estimates of risk are consequently only as accurate as climate model projections of changes in precipitation. An alternative approach, employed for instance by Seager et al. (2007, 2010), examines the role of large-scale dynamic and thermodynamic controls on precipitation minus evapotranspiration ($P - E$). Such studies have found that drought conditions like the Dust Bowl will become normal in the Southwest and in other subtropical dry zones. If such transitions are indeed "imminent," as stated in those studies, then the risk of decadal drought is 100%, and the risk of longer-lived events is probably also extremely high. By orienting our analysis around precipitation, the risks of prolonged drought we show here are in fact the lowest levels consistent with model simulations of future climates.

From Fig. 16 it is also clear that several other areas may be facing similar (or worse) levels of prolonged risk in the coming century. Synthesis of paleoclimatic, instrumental, and model data for these regions may lead to improvements in projecting risks in these areas and preparing appropriate adaptation and mitigation strategies. For example, high-resolution tree-ring and cave records are available from Southeast Asia (e.g., Cook et al. 2010a; Buckley et al. 2010; Sinha et al. 2007, 2011; Zhang et al. 2008) and could be used in conducting such an analysis for that region.

Despite the simplicity of our Monte Carlo model of hydroclimate in WNA, our results illustrate a crucial point for water resource managers in the region: CMIP5 models alone underestimate megadrought risk. This argument was implied in several recent studies (Cook et al. 2010b; Ault et al. 2012, 2013), but its details and implications are laid out more explicitly here (Fig. 15 specifically). Future work could refine estimates of future risks by adding additional layers of complexity to the framework we have outlined. For example, we have only used annual precipitation, which we found to be approximately normally distributed in most of WNA in most models. A more sophisticated approach could simulate the joint PDF of

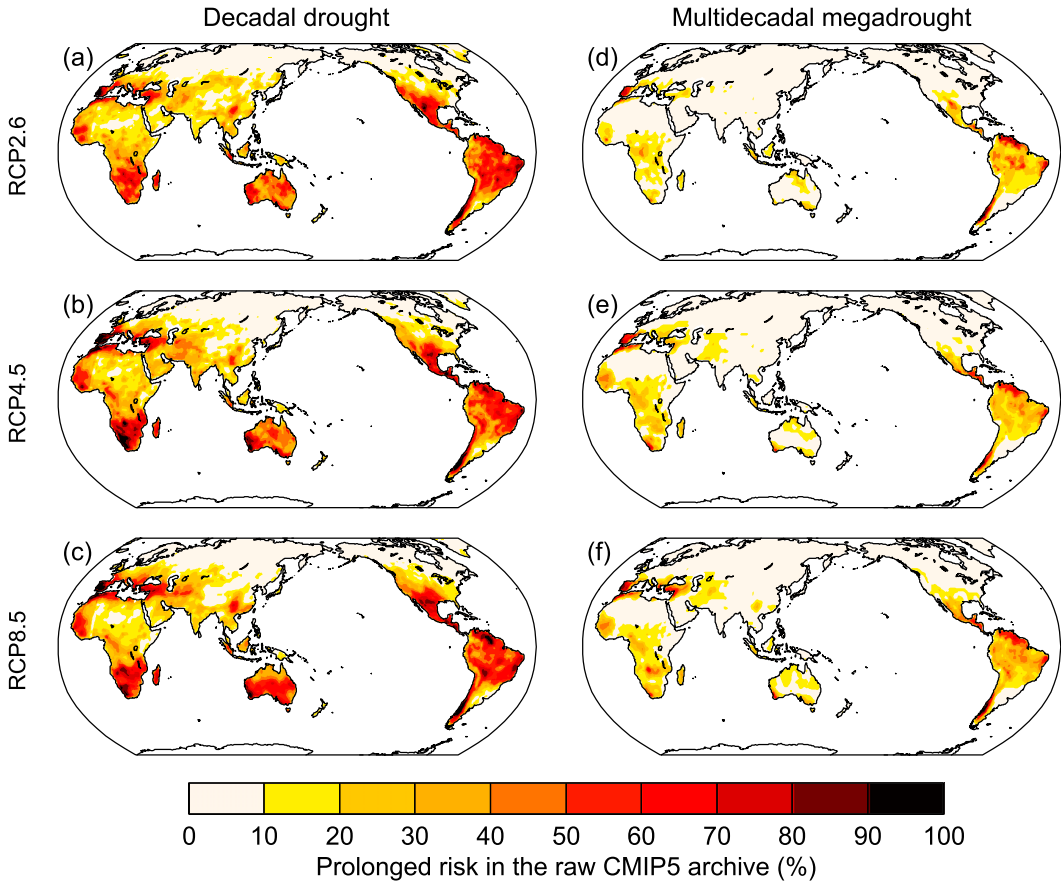

FIG. 16. Global estimates of (left) decadal and (right) multidecadal megadrought in the raw CMIP5 archive. As in Fig. 9, risk is calculated as the percent of the total number of models (27) that simulate a decadal or multidecadal megadrought. Forcing scenarios are indicated to the left of each map.

temperature and precipitation at monthly resolution, and use a more fine-tuned type of distribution and various drought indices to do so. Moreover, our noise simulations are one-dimensional in the sense that we did not build spatial autocorrelation into the noises. Developing and applying a model with realistic spatial covariance structures could help in addressing risks associated with persistent drought across large geographic scales. Likewise, it is possible that improvements in climate models, along with increasing computer power to run larger and larger ensembles, will allow for dynamically constrained assessments of megadrought risk using future generations of fully coupled climate models. In the meantime, our results provide quantitative benchmarks for water management and climate modeling communities.

5. Implications

Droughts in the past have had particularly notable human and financial costs. In the United States alone, for instance, the Federal Crop Insurance Corporation spent an average of $1.7 billion annually to compensate losses from 1980 to 2005, and this number has been increasing (Stephenson 2007). In the future, such losses might be curtailed if the full range of natural and forced hydroclimatic variability can be included in megadrought risk mitigation strategies. Here, we have described a method for combining insights from observational data and projections from climate models to estimate the risk of persistent intervals of aridity in the coming century in the U.S. Southwest. In this region where high-quality proxy records of hydroclimate have been used to constrain the underlying features of hydroclimate on decadal and longer time scales, the risk of decadal drought is at least 70% and may be higher than 90%. The risk of a multidecadal megadrought may be as high as 20%–50%, and the likelihood of an unprecedented 50-yr drought is nonnegligible (5%–10%). A number of other regions face similarly high levels of risk including southern Africa, Australia, and the Amazon basin. Moreover, future drought severity will be exacerbated by increases in temperature, implying that

our results should be viewed as conservative provided that the models depict accurate forced trends in regional hydroclimate. These findings emphasize the need to develop drought mitigation strategies that can cope with decadal and multidecadal droughts in changing climates with substantial sources of low-frequency variability.

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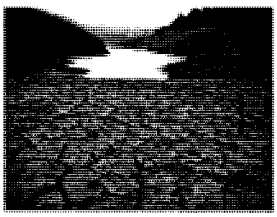
California's 100-year drought

MEGADROUGHTS A THREAT TO CIVILIZATION

Megadroughts are extreme dry spells that can last for a decade or longer. They have parched the West, including present-day California, long before Europeans settled the region in the 1800s.

Lamont Doherty Earth Observatory of Columbia University; U.S. Drought Monitor; Cornell University
Doyle Rice, Frank Pompa and Julie Snider, USA TODAY

Doyle Rice, USA TODAY *9:23 a.m. EDT September 3, 2014*



(Photo: Justin Sullivan, Getty Images)

California is in the third year of one of the state's worst droughts in the past century, one that's led to fierce wildfires, water shortages and restrictions, and potentially staggering agricultural losses.

The dryness in California is only part of a longer-term, 15-year drought across most of the Western USA, one that bioclimatologist Park Williams said is notable because "more area in the West has persistently been in drought during the past 15 years than in any other 15-year period since the 1150s and 1160s" — that's more than 850 years ago.

"When considering the West as a whole, we are currently in the midst of a historically relevant megadrought," said Williams, a professor at the Lamont-Doherty Earth Observatory of Columbia University in New York.

Megadroughts are what Cornell University scientist Toby Ault calls the "great white sharks of climate: powerful, dangerous and hard to detect before it's too late. They have happened in the past, and they are still out there, lurking in what is possible for the future, even without climate change." Ault goes so far as to call megadroughts "a threat to civilization."

WHAT IS A MEGADROUGHT?

Megadroughts are defined more by their duration than their severity. They are extreme dry spells that can last for a decade or longer, according to research meteorologist Martin Hoerling of the National Oceanic and Atmospheric Administration.

Megadroughts have parched the West, including present-day California, long before Europeans settled the region in the 1800s.

Most of the USA's droughts of the past century, even the infamous 1930s Dust Bowl that forced migrations of Oklahomans and others from the Plains, "were exceeded in severity and duration multiple times by droughts during the preceding 2,000 years," the National Climate Assessment reported this year.

The difference now, of course, is the Western USA is home to more than 70 million people who weren't here for previous megadroughts. The implications are far more daunting.

Overall, "the nature of the beast is that drought is cyclical, and these long periods of drought have been commonplace in the past," according to Mark Svoboda, a climatologist at the National Drought Mitigation Center in Lincoln, Neb. "We are simply much more vulnerable today than at any time in the past. People can't just pick up and leave to the degree they did in the past."

Ault agrees that this long-term Western dry spell could be classified as a megadrought. "But this is not as bad as it could get," he warned.

How do scientists know how wet or dry it was centuries ago? Though no weather records exist before the late 1800s, scientists can examine paleoclimatic "proxy data," such as tree rings and lake sediment, to find out how much — or little — rain fell hundreds or even thousands of years ago.

At the most simplistic level, tree rings are wider during wet years and narrower during dry years.

"Prolonged droughts — some of which lasted more than a century — brought thriving civilizations, such as the ancestral Pueblo (Native Americans) of the Four Corners region, to starvation, migration and finally collapse, " Lynn Ingram, a geologist at the University of California-Berkeley, wrote in her recent book *The West Without Water*.

Ault says decade-long droughts happen once or twice a century in the Western USA, but much worse droughts, ones that last for multiple decades, occur once or twice per millennium.

Has California reached megadrought status? Not yet: "This one wouldn't stand out as a megadrought," Hoerling said. Even so, "this is the state's worst consecutive three years for precipitation in 119 years of records," he said.

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Because of the dryness, Calif. Gov. Jerry Brown declared a statewide drought emergency this year [illegible] d to drop, and as of late August, they were down to about 59% of the historical average.

Regulations restricting outdoor water use were put in place in late July for the entire state. People aren't allowed to hose down driveways and sidewalks, nor are they allowed to water lawns and landscapes (if there is excess runoff). There are reports of wells running dry in central California.

About 1,000 more wildfires than usual have charred the state, including some unusual ones in the spring.

The drought is likely to inflict $2.2 billion in losses on the agricultural industry, according to a July study from the University of California-Davis.

HOW BAD CAN IT GET IN CALIFORNIA?

"If California suffered something like a multi-decade drought," University of Arizona climate scientist Gregg Garfin said, "the best-case scenario would be some combination of conservation, technological improvements (such as desalinization plants), multi-state cooperation on the drought, economic-based water transfers from agriculture to urban areas and other things like that to get humans through the drought.

"But there would be consequences for ecosystems and agriculture," he said.

"In the worst-case scenario, there might be out-migration and/or ghost towns," Garfin said. As a way to avoid this, "we could simply suck down more and more groundwater, which would have its own set of ramifications for local aquifers and the environment."

Even in the worst case of severe multi-decade drought, "it is hard for me to imagine people and businesses being banned from moving into urban areas of California," he said.

"We have much better resilience now than in the 'ghost town days,' with the ability to drill deeper, along with various ways of importing water and trading for water," Garfin said. "A more subtle way of restricting people (not banning them) is what Santa Fe has done — where new housing developments must either come with their own new source of water, or they must offset the water through conservation."

Overall, if the drought worsened, "we'd have to learn how to use water more efficiently," Ault said. "This is a glimpse of the future."

ROLE OF CLIMATE CHANGE

What role does climate change play in this drought or in future droughts?

Scientists such as Hoerling and Ault say they don't have the tools to tease out how much of this specific drought might be attributed to climate change.

"As of now, probably very little of the California drought can be attributed to climate change with any certainty," said tree-ring scientist Edward Cook of Lamont-Doherty.

Overall, past droughts have probably been due to subtle changes in water temperatures in the tropical Pacific Ocean. Cooler water temperatures — known as La Niñas — tend to produce drier conditions in the West.

Droughts in North America's "Medieval Warm Period" (roughly 950-1250) were associated with high temperatures in the Southwest and were probably caused by persistently cool La Niña-like conditions in the tropical Pacific Ocean. Since 2000, the dominant climate pattern has been La Niña.

Hoerling noted that some computer models from the Intergovernmental Panel on Climate Change, a United Nations science panel, show that California could actually see more, not less, winter rain and snow because of climate change.

However, overall rising temperatures would tend to favor more droughts, University of Arizona scientist Jonathan Overpeck said.

"It's been anomalously hot recently, which was not likely to have occurred without global warming," Overpeck said. "The odds are only going up that we could have a megadrought as the Earth warms."

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Trends toward warmer temperatures could lead to a long-term dry spell in the region, according to a 2004 study led by Cook in the journal *Science*.

What's troubling is that the 20th century — during which time California's population increased from about 1.5 million to almost 40 million — may well have been an outlier, an unusually wet century: "Overall, the 20th century experienced less drought than most of the preceding four to 20 centuries," the *Science* study said.

Ault continues to investigate the relationship between climate change and megadroughts and the likelihood that an even more severe megadrought might hit in the next hundred years in the Southwest — one that's worse than any other drought in the past 1,000 years.

Specifically because of global warming, Ault says, the chances of the Southwestern USA experiencing a decade-long drought is at least 50% (but may be closer to 80%-90%), and the chances of a three-decade-long megadrought range from 20% to 50% over the next century. Ault is writing a study about this that will be published in a forthcoming issue of the American Meteorological Society's *Journal of Climate*.

"For the Southwestern U.S., I'm not optimistic about avoiding real megadroughts," Ault said. "As we add greenhouse gases into the atmosphere — and we haven't put the brakes on stopping this — we are weighting the dice for megadrought conditions.

"The risks would be lower if we didn't warm the planet as much as is expected to occur, but they aren't zero, because we know these things happen naturally," he said.

This is serious stuff: "Megadroughts are a threat to civilization," Ault said at an American Geophysical Union conference this year. "They could possibly be even worse than anything experienced by any humans who have lived in that part of the world for the last few thousand years."

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