Climate Change over the Southwestern U.S. as predicted by Regional Climate Models

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DOE Climate and Earth System Modeling PI Meeting
Washington, D.C.

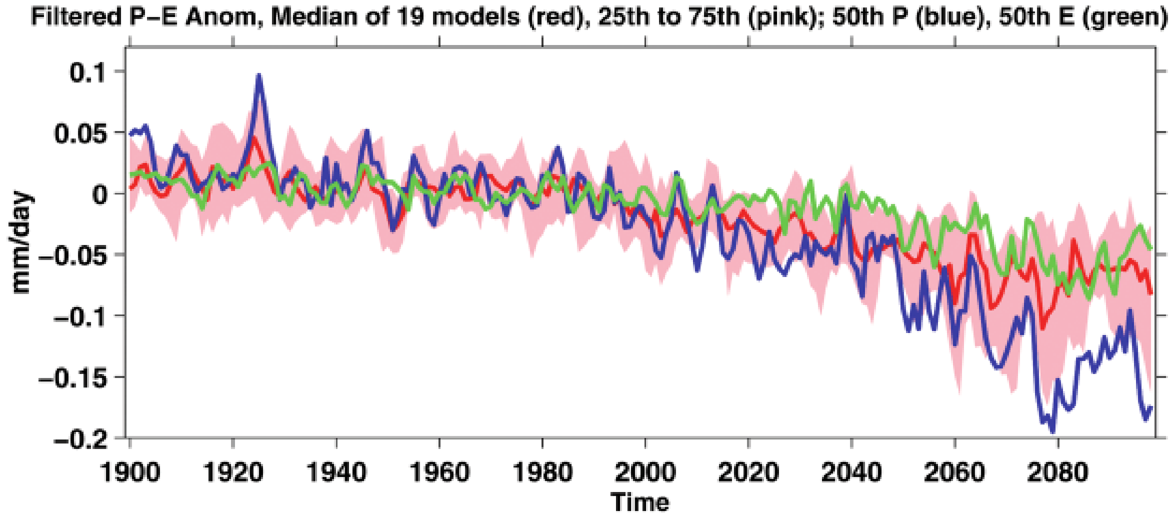
September 19, 2011

GCMs projections

- Global climate models robust predict that Southwestern United States will dry throughout the current century as a consequence of climate change. The drying is manifest as a drop in net precipitation (P-E), with different magnitude.

- Seager et al. (2007) ~permanently drier conditions;
- Milly et al. (2005) ~10-25 percent;
- Christensen and Lettenmaier (2007) ~6 percent.

Projected drying over the Southwestern U.S. (Seager et al., 2007)



- Seager and Vecchi (2010) found that projected P-E changes in GCMs are associated with reduced mean moisture and transient eddy moisture flux convergence.
- How sensitive are these finding to model resolution (GCMs don't capture runoff production at high elevations, which disproportionately affect the water balance of the region

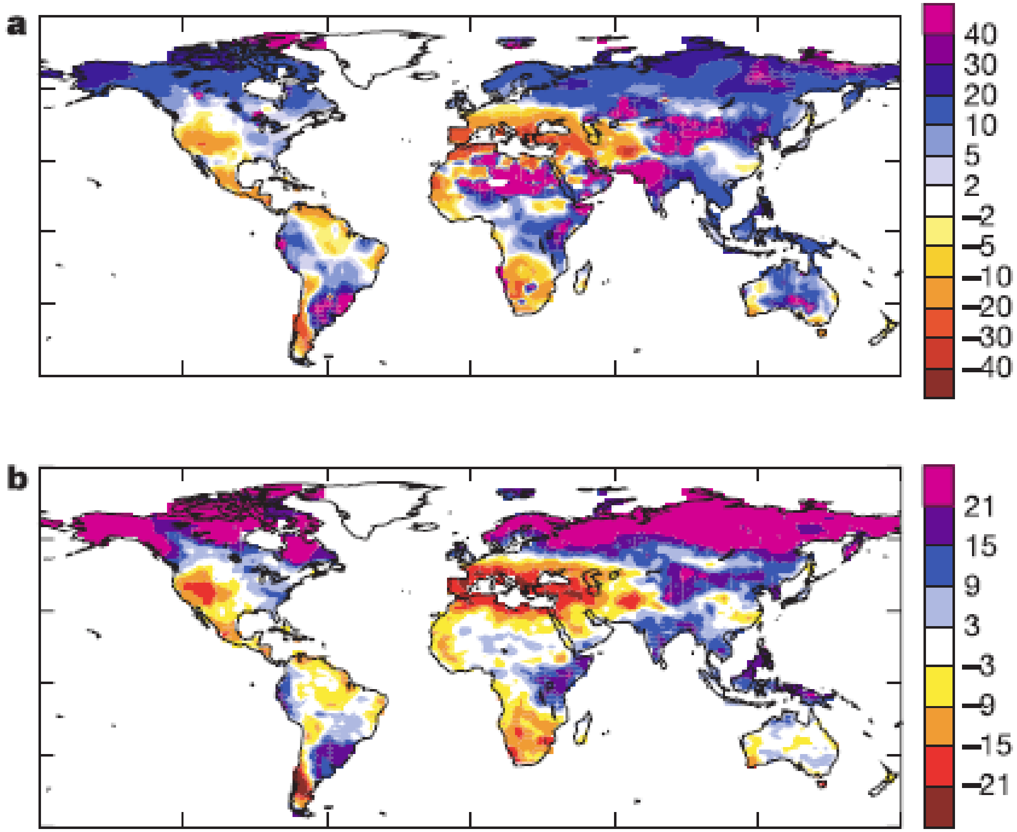


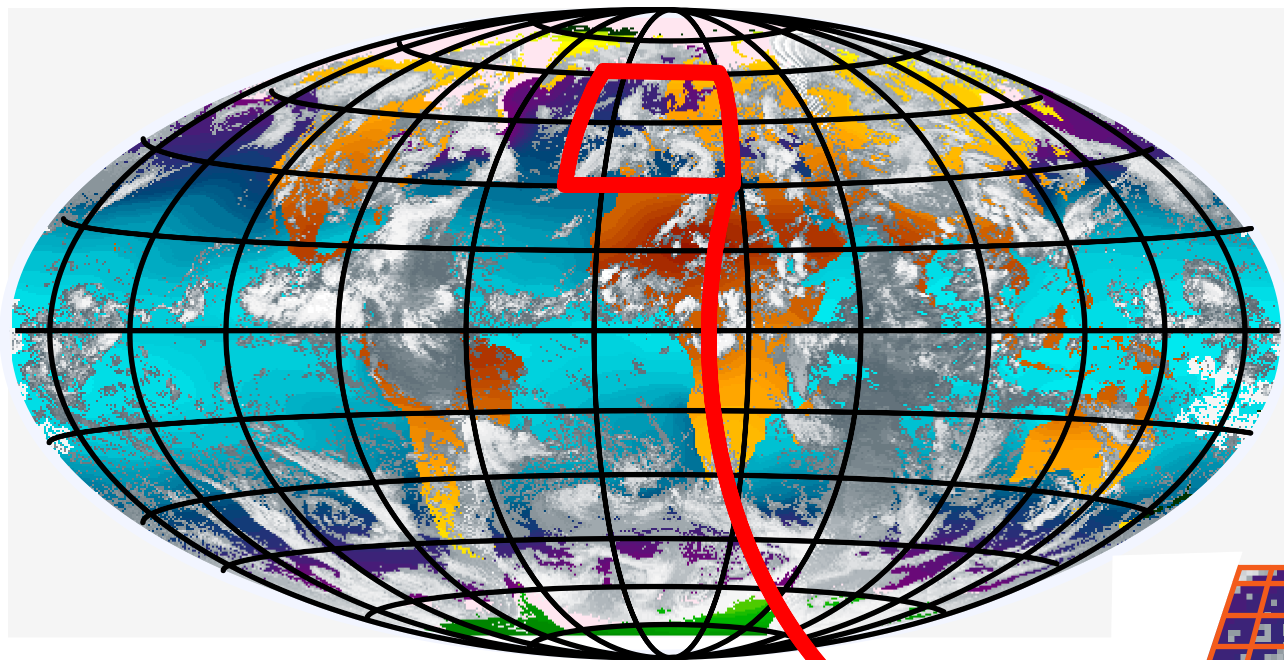
Figure 4 | Relative change in runoff in the twenty-first century.
a, Ensemble (arithmetic) mean of relative change (percentage) in runoff for the period 2041–60, computed as 100 times the difference between 2041–60 runoff in the SRESA1B experiments and 1900–70 runoff in the 20C3M experiments, divided by 1900–70 runoff. **b**, Number of pairs of runs (out of an available total of 24 pairs) showing a positive change minus the number showing a negative change.

- From Milly, Dunne and Vecchia 2005.

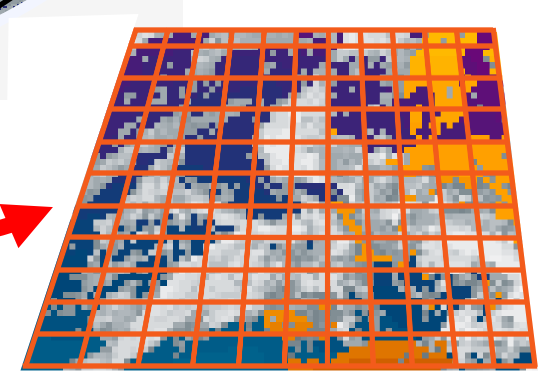
Concerns

- *Will the Colorado River basin, or the U.S. Southwest more generally, transition to a permanent megadrought state over the next century.*

GCM vs. RCM

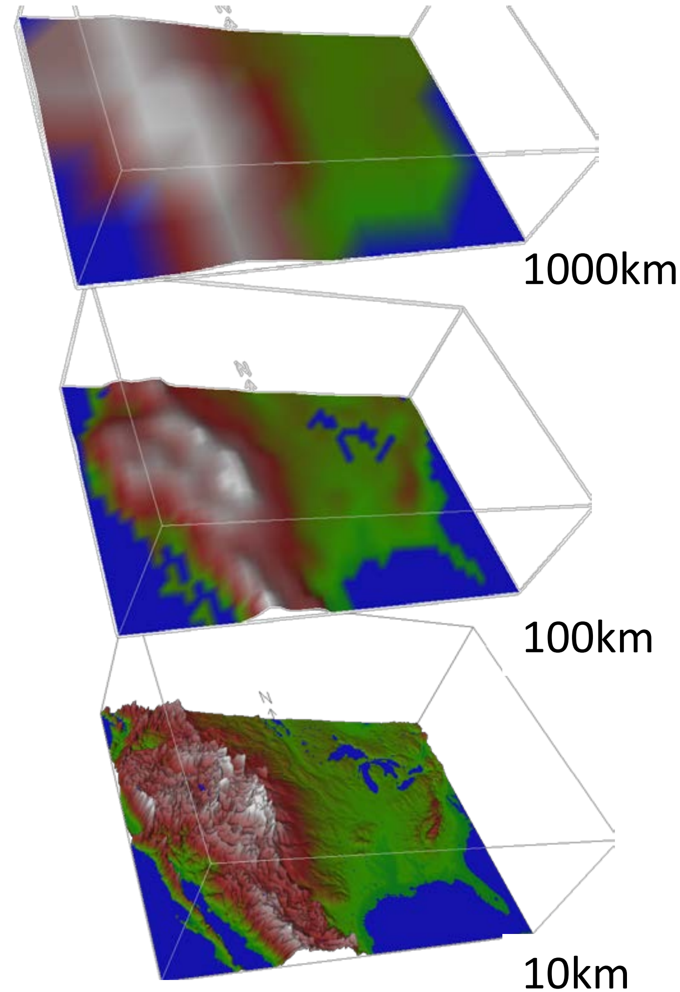


Regional Climate Model **: The RCM is coupled to a global model which regularly provides boundary conditions to the RCM during the integration (e.g., every 6 hours)**



RCM projections

- Previous researches found that better representation of surface forcing allowed the Regional Climate model to produce different climate response from the driving global model (Leung and Ghan 1999; Kim 2001; Kim et al. 2002; Gao et al. 2011).



Colorado River Basin

A large fraction of the annual runoff is generated from a relatively small part of the basin area.

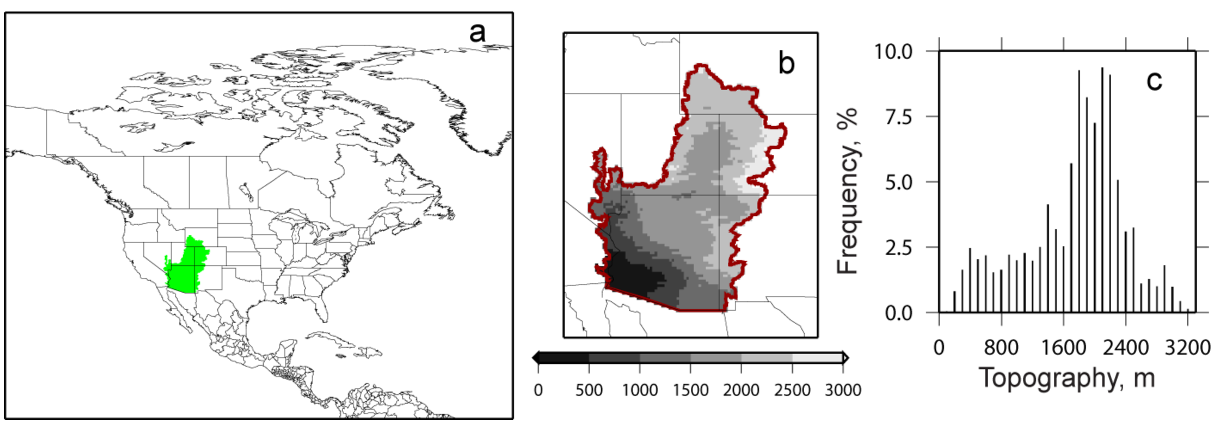


Figure 1 Location (a) and topography distribution (b; unit: m) and histogram of topography (c) for the Colorado River basin.

Methods and data

- All of the RCM-based analyses reported here used seasonal and annual means derived from 3-hourly NARCCAP output (http://www.earthsystemgrid.org).
- GCMs variables were obtained from WCRP's CMIP3 multi-model dataset (http://www-pcmdi.llnl.gov/ipcc/orientation.php) except HadCM3. HadCM3 was customized for NARCCAP.
- Land surface variables from the 1/8-degree historical North American Land Data Assimilation System (NLDAS) data set (Maurer et al. 2002) were taken as the reference.
- For comparison, both GCM and RCM output were interpolated to 1/8-degree resolution using an inverse distance squared interpolation, and only points within the CRB were compared.

Results: RCM evaluation for historical period

Surface air temperature (T)

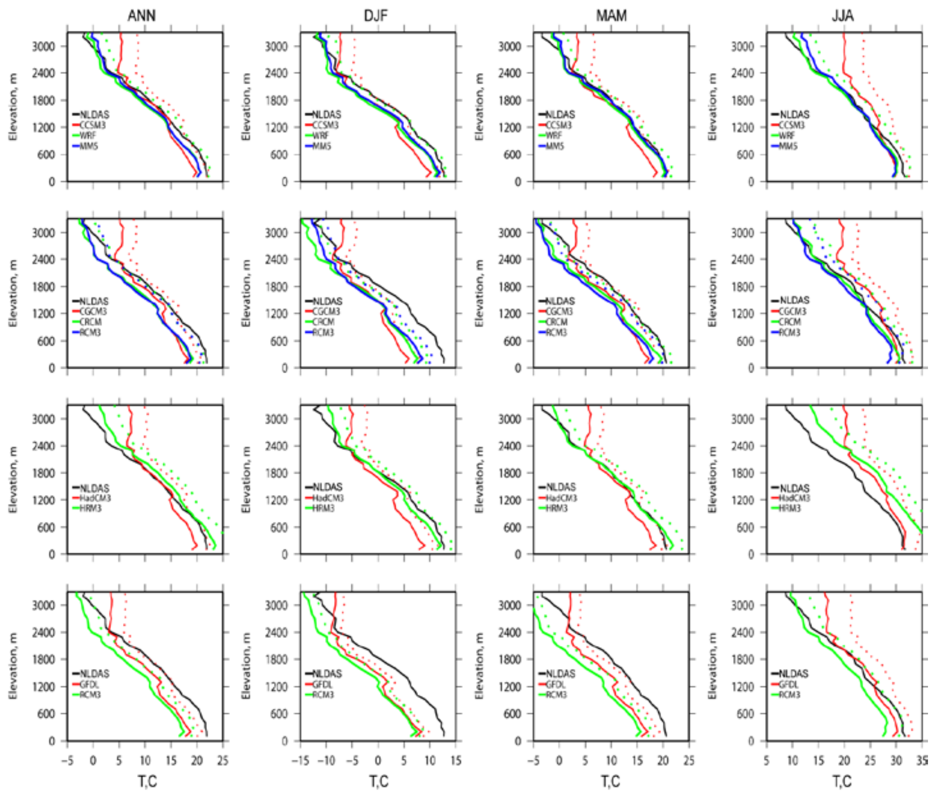


Figure 2 Variations in annual, winter, spring, and summer surface air temperature as elevation from RCMs/GCMs and the host GCMs comparing to the 1/8-degree historical NLDAS data set (OBS) over the CRB (the solid line is the historical period and the dash line is the future period)

- Although the RCMs do not significantly improve the simulation of precipitation, improvements in simulating surface temperature in mountainous regions have important effects on simulating ET, snowpack, and runoff, as indicated by the results. Such improvements seem essential for differentiating the climate change signals between that simulated by regional and global simulations.

Results: Climate Change impact
Runoff (R) at high elevations

Table 2. Annual and seasonal runoff (R) (R change, (2040-2069)-(1970-1999)) for area above 2250 m for RCMs and GCMs (unit:°C)

	ANN		DJF		MAM		JJA		SON	
WRF	-0.03	(-16%)	0	(0%)	-0.11	(-19%)	0	(0%)	0	(0%)
CCSM3	-0.07	(-16%)	0.27	(61%)	-0.56	(-50%)	0.01	(17%)	0	(0%)
CRCM	-0.07	(-16%)	0.06	(200%)	-0.32	(-19%)	-0.03	(-75%)	0	(0%)
CGCM3	-0.04	(-13%)	0.12	(80%)	-0.3	(-27%)	0.01	(100%)	0	(0%)
HRM3	0.05	(5%)	0.15	(88%)	0.2	(7%)	-0.15	(-20%)	0.01	(5%)
HadCM3	0.01	(6%)	0.01	(20%)	0.04	(15%)	-0.02	(-9%)	0	(0%)

- In winter, the RCMs project more runoff increase than the host GCMs.
- In spring, the RCMs project less runoff decrease than the host GCMs.
- Over CRB, annual runoff change for all the RCMs and GCMs is controlled by the change signal in spring . Runoff change in spring comes from changes in snow water equivalent , which is strongly related to temperature change.

Terrestrial and Atmospheric Water Balance

Atmospheric moisture convergence has been shown to be a good approximation of P-E (Serreze et al. 2005, 2006). The basic equation in an isobaric coordinate system is written as:

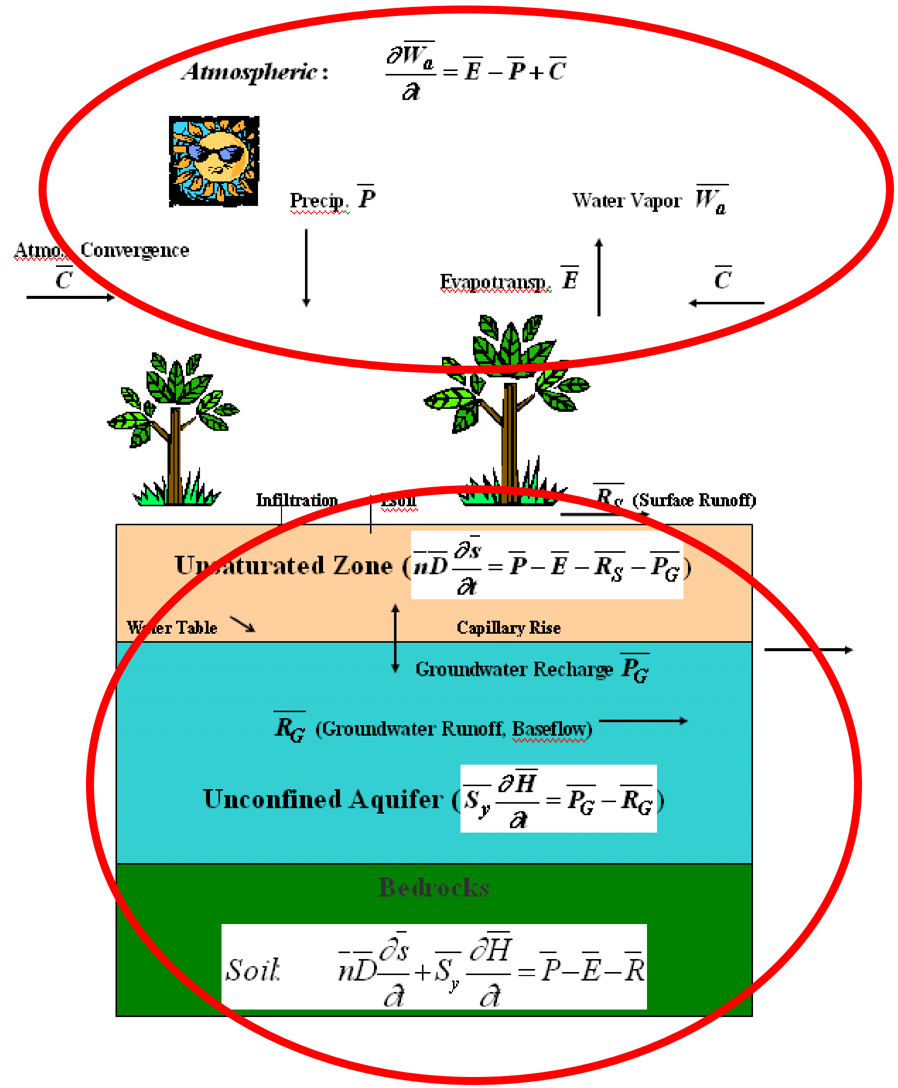
$$\rho_w g(P-E) = -\frac{\partial W}{\partial t} - \nabla \bullet F \ (1)$$

$$W = \int_{P_0}^{P_s} q\,dp$$

$$F = \int_{P_0}^{P_s} \vec{V} q\,dp$$

When time average is taken, the *F* can be divided into the mean and transient components. And moisture flux transportation can be divided into two components:

$$\rho_w g(P-E) = -\int_{p_0}^{p_s} \nabla \cdot (\overline{\vec{V}} \cdot \overline{q})dp - \int_{p_0}^{p_s} \nabla \cdot (\overline{\vec{V}' q'})dp(2)$$



*hydro.iis.u-tokyo.ac.jp/~patyeh/Lecture2_2010.**ppt***

Methods

- Computation of vertically integrated MFC is one of the most delicate aspects of the estimation of atmospheric moisture budgets.
- Although we were cautious in our approach to post-processing, the MFC calculations nonetheless still yielded non-negligible residuals (i.e., imbalance between MFC and P-E).
- Although biases exist in our MFC estimation, we find that the MFC changes are mostly not correlated with or unaffected by the residuals. So, in spite of the residual between MFC and P-E, the MFC could still be used to estimate water cycle changes over land.

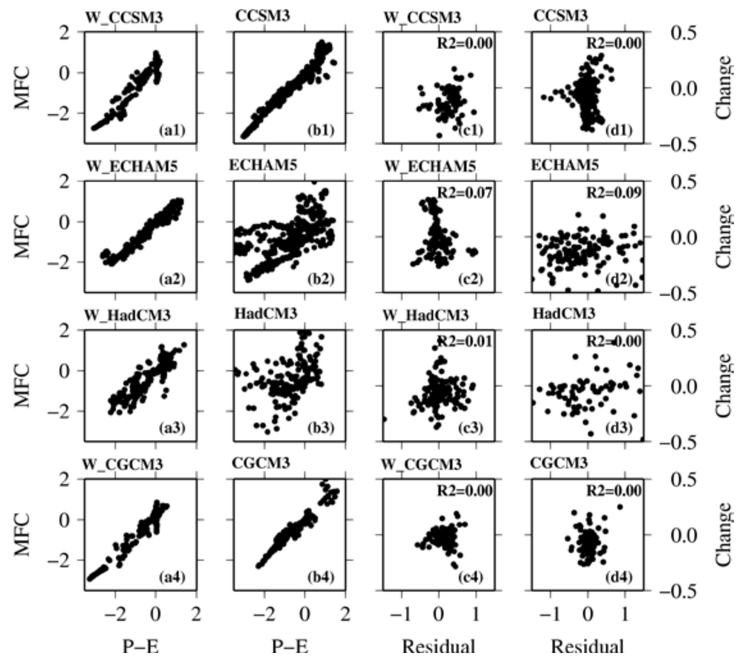


Fig. 5: Comparison of MFC and P-E and residuals for RCMs and host GCMs. Panels a and b: Scatterplots of the meridional mean MFC and P-E for GCMs and RCMs for the latitude band 25°N-40°N; Panels c and d: scatterplots of the meridional mean of MFC changes and MFC biases for GCMs and RCMs for the latitude band 25°N-40°N.

RCMs Datasets

- We used four sets of RCM simulations performed using the Weather Research & Forecasting (WRF) model. We analyzed two common time slices of 30 years (1970-1999 and 2040-2069) simulated by each of the four WRF runs (although the W_ECHAM5 and W_HadCM3 simulations are longer, we used only the periods that were common to all of the model runs).

Table 1 Summary of four RCM simulations.

RCM run designation	SRES emissions scenario	GCM ensemble numbers*	RCM resolution	RCM Domain†	Vertical levels	Multiple nesting	nudging
W_CCSM3	A2	run5/run5	50km	197.4°-328.6°E 17.6°-71.5°N	34	no	no
W_CGCM3	A2	run4/run4	50km	197.4°-328.6°E 17.6°-71.5°N	34	no	no
W_ECHAM5	A1B	run1/run2	36km	210.5°-310.2°E 15.7°-59.8°E	31	yes	no
W_HadCM3	A2	customized	35km	224.1°-300.9°E 11.8°-52.1°E	27	no	Spectral nudging

*GCM ensemble numbers are labeled as ensemble number for the historical period (1970-1999) / ensemble number for the future period (2040-2069).

†The longitude and latitude here refer to the minimum and maximum value of the domain coverage since WRF uses Lambert Conformal projection.

Surface air temperature and SWE change

- changes in surface air temperature indicate that the SW is less susceptible to a warming climate in the RCMs than in the host GCMs(right).
- SWE reductions in the GCMs are much larger than in the RCMs, except ECHAM5 (left) due, in part to the inadequate representation of the altitudinal variation of snowfall in the GCMs when compared to RCMs.

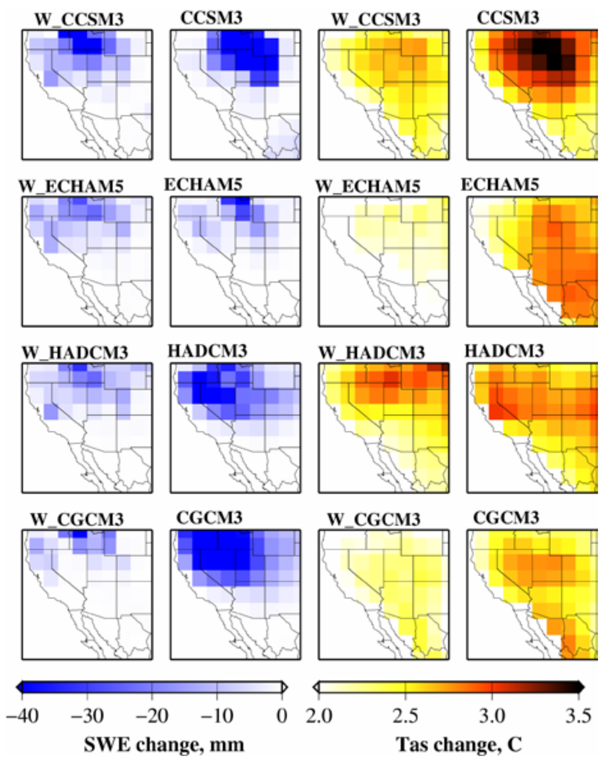


Fig. 1 Distribution of the average (over years) of each year's maximum snow water equivalent (SWE, units: mm) and mean annual surface air temperature (T, units: °C) change from four WRF simulations and their forcing GCMs for the future period (2040-2069) compared to the historical period 1970-1999 over the SW (125°W to 95°W and 25°N to 40°N, land areas only**).**

P-E changes

- Projected changes in P-E from the RCMs indicate that the SW is less susceptible to a warming climate than is indicated from GCM output.

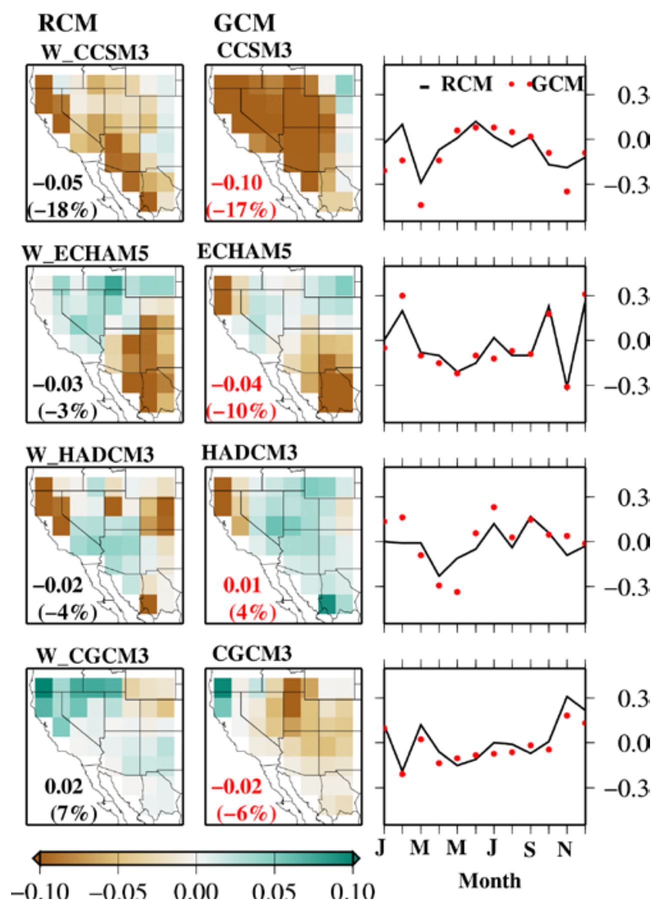


Fig. 2 Distribution of annual P-E change (units: mm d-1) from four WRF simulations and their forcing GCMs (left panels) for the future period (2040-2069) compared to the historical period 1970-1999 over the southwestern United States (125°W to 95°W and 25°N to 40°N, land areas only). Right panels show domain-averaged monthly distributions of RCMs and GCMs changes. Numbers at the left-bottom corner of each left panel are the domain average of annual P-E change. Digits on the left-bottom corner are the domain average annual P-E changes for RCMs and GCMs (units: mm d-1 (%)).

Causes of winter P-E changes

- Although there are slight differences between RCMs and GCMs in terms of mean MFC change, it is clear that all RCMs and GCMs projected decreases in the mean MFC.
- W_CCSM3, W_ECHAM5 and W_CGCM3 predict larger intensification in transient moisture flux convergence than do their host GCMs. W_HadCM3, on the other hand, predicts less intensification compared to its host GCMs.

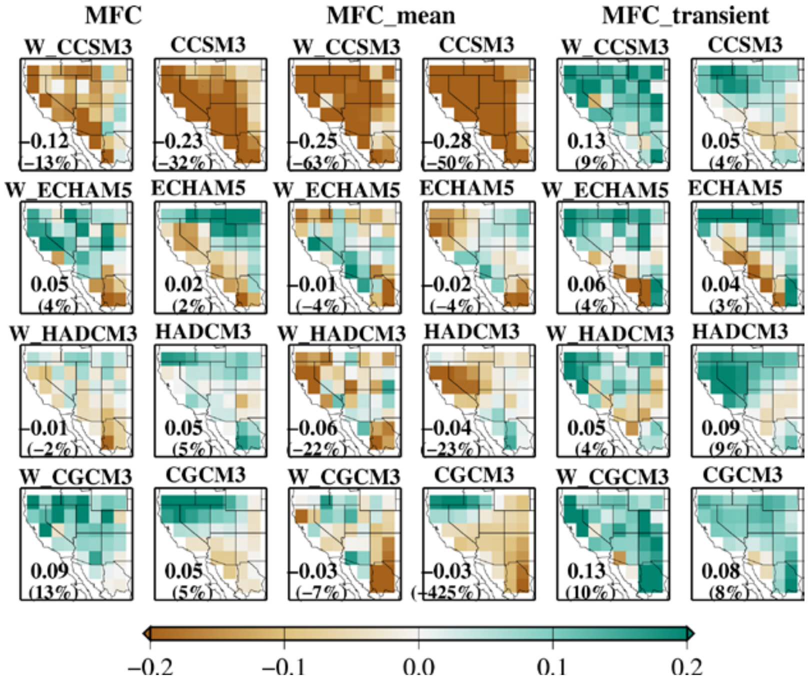


Fig. 3 Distribution of the vertical-integrated moisture flux convergence change (MFC); the mean moisture flux convergence change (MFC_mean) and the transient eddy moisture flux convergence change (MFC_transient) in winter from four WRF simulations and their forcing GCMs for 2040-2069 as compared to 1970-1999 over the SW (125°W to 95°W and 25°N to 40°N, land areas only). Digits on the left-bottom corner are the domain average winter changes for annual with RCMs changes in black and GCMs in red (units: mm d-1 (%)).

Interpretation of causes of winter P-E changes

- The difference between the GCM and RCM transient eddy MFC is related to underestimation by the GCMs of blocking of the westerly transient flow that encounters the north-south oriented mountain ranges, which are too smooth in the GCMs.
- Fig. 4e shows that similar differences (i.e., enhanced moisture convergence upwind and reduced moisture convergence downwind) exist in the westerly moisture flux flow in the North American Regional Reanalysis (NARR) with 32-km resolution relative to the National Centers for Environmental Prediction/Department of Energy reanalysis (NCEP/DOE) with 2.5-degrees resolution.

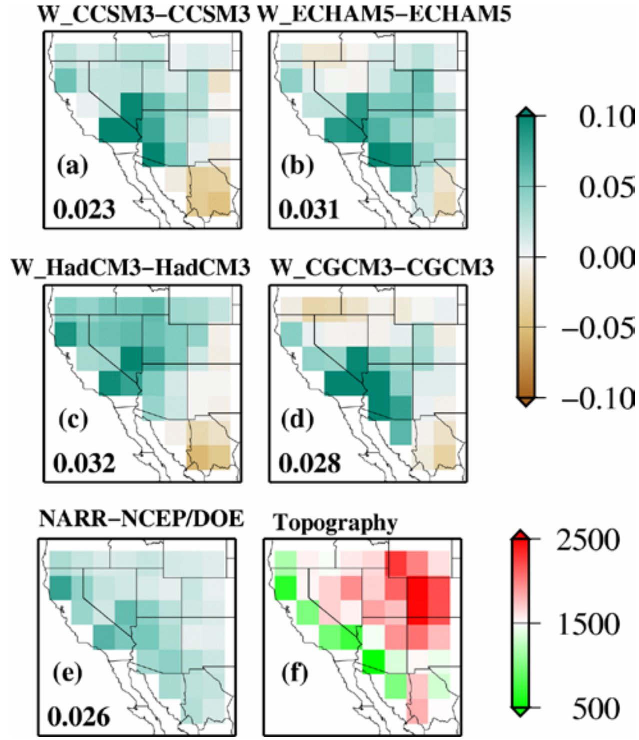


Fig. 4 (a-e): Distribution of the westerly transient moisture flux fraction (transient moisture flux / (mean + transient moisture fluxes)) differences in winter between high resolution simulations (W_CCSM3, W_ECHAM5, W_HadCM3, W_CGCM3 and NARR) and coarse resolution simulations (CCSM3, ECHAM5, HadCM3, CGCM3 and NCEP/DOE) and (f) topography (units: m) over the SW. Blue indicates more transient moisture fluxes in the RCM output compared to GCM output.

Conclusions (1)

- Although the RCMs do not significantly improve the simulation of precipitation, improvements in simulating surface temperature in mountainous regions have important effects on simulating ET, snowpack, and runoff, as indicated by the results. Such improvements seem essential for differentiating the climate change signals between that simulated by regional and global simulations.

- Results for all GCMs and RCMs suggest T increases, SWE decreases, and P-E decreases in the mid 21st century relative to the late 20th century. However, the magnitudes of change in all three variables are generally less in the RCMs as compared to their companion GCM simulations, indicating that **the SW may be less susceptible to a warming climate than has previously been inferred from GCM simulations**.

Conclusions (2)

- The transient eddy flow convergence keeps the climatology of net precipitation positive over the SW. The mean moisture flux divergence intensifies from the late 20th century to the mid 21st century in both RCM and GCM results. However, while the GCMs project reductions or slight increases in the transient flux convergence, the RCMs project larger increases that counter the drying caused by the enhanced mean moisture flux divergence. This leads to reduced susceptibility to hydrological change as compared with predictions by GCMs.

- The larger increase in transient moisture flux convergence in the RCMs as compared to GCMs is related to the GCMs underestimating the blocking of the westerly flow that encounters the north-south oriented mountain ranges because of their smooth topography.