Do climate change forecasts encourage private adaptation?: Water-saving irrigation investments under uncertainty

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Types of responses to climate change

- Mitigation vs. adaptation

- Mitigation and public adaptation are largely problems of optimal public good provision

- Timing and amount of <u>private</u> adaptation also influences benefit of public good provision

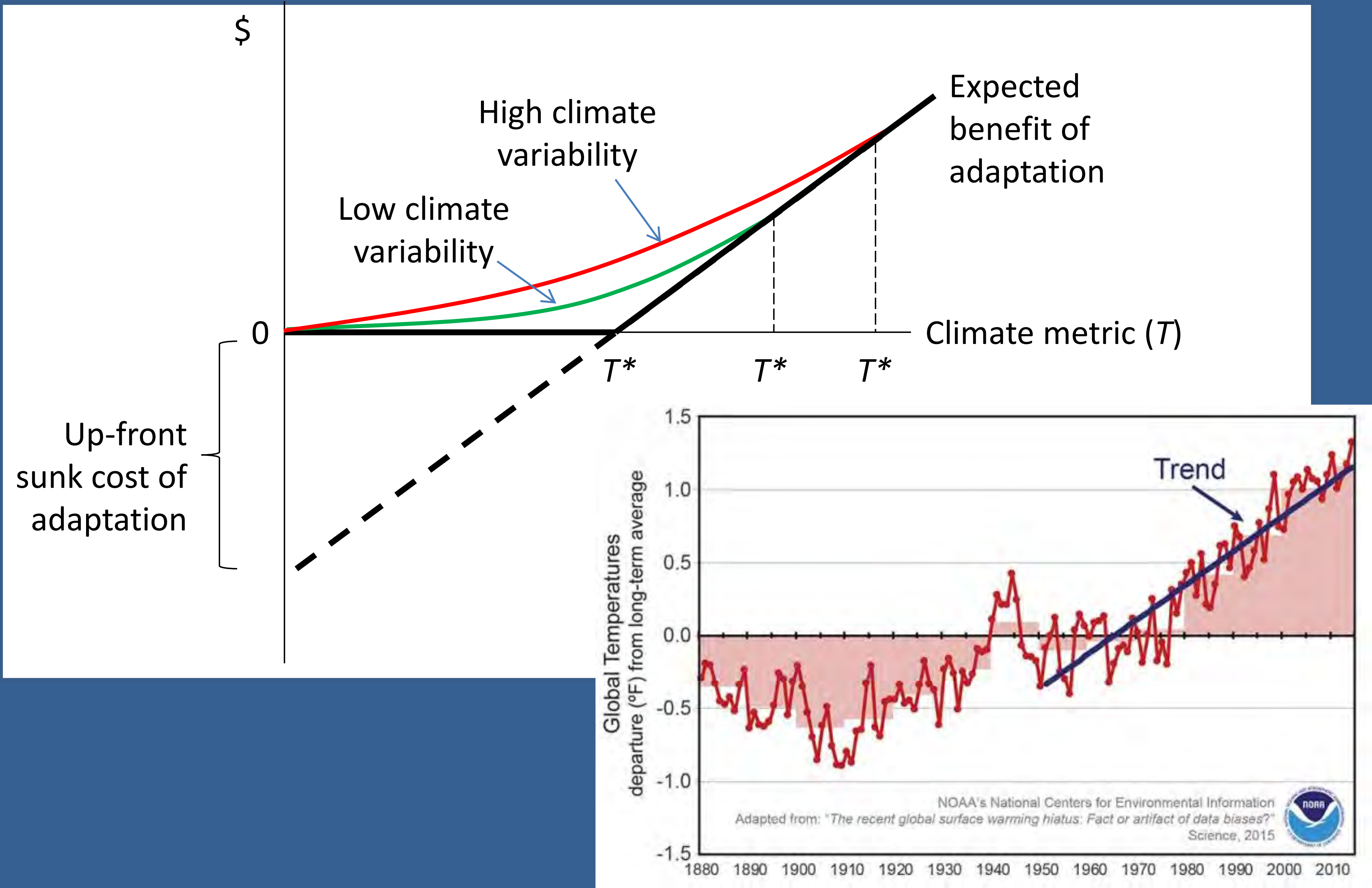
- Private adaptation can be instantaneous changes in behavior (changing cropping patterns) or discrete partially irreversible decisions (selling agricultural land)

- Climate change trends receive much of the focus but climate variability matters for irreversible (sunk) adaptation decisions

Real options and climate change

- Sunk costs + unpredictable returns → overweight possibility of bad returns
    - Good news for the global environment becomes bad news for mitigation and adaptation investments (Pindyck 2007)
    - Uncertainty (variability) suggests a value to delaying sunk cost investments
- Lots of applications to mitigation (reviewed by Golub et al. 2011) but few applications to adaptation (Fisher and Rubio 1997; Narita and Quaas 2014)
- Main result:
    - Climate variability leads to postponed adaptation and increased damages
    - Perfect foresight predicts too much private adaptation
- Implication: Damages avoided from mitigation and public adaptation may be higher than expected

Adaptation option value



NOAA's National Centers for Environmental Information
Adapted from: "*The recent global surface warming hiatus: Fact or artifact of data biases?*"
Science, 2015

Research Questions

1. How do adaptation decisions based on historic data differ from those based on climate forecasts?

2. Does greater climate variability always lead to delay?

3. Is climate variability more important than other sources of uncertainty?

Water-saving irrigation technologies

- Farm/ranch where irrigation water is the limiting input
- Existing water rights can be supplemented by leasing from spot market
- Upfront investment in more efficient irrigation technology reduces optimal water input (no effect on production level)
- Benefits of investment are uncertain due to year-to-year variations in streamflow and inability to predict water demand
- Option value explains lower than expected uptake of more efficient irrigation technologies (Carey and Zilberman 2002; Anik and Manna 2014)

Irrigated production

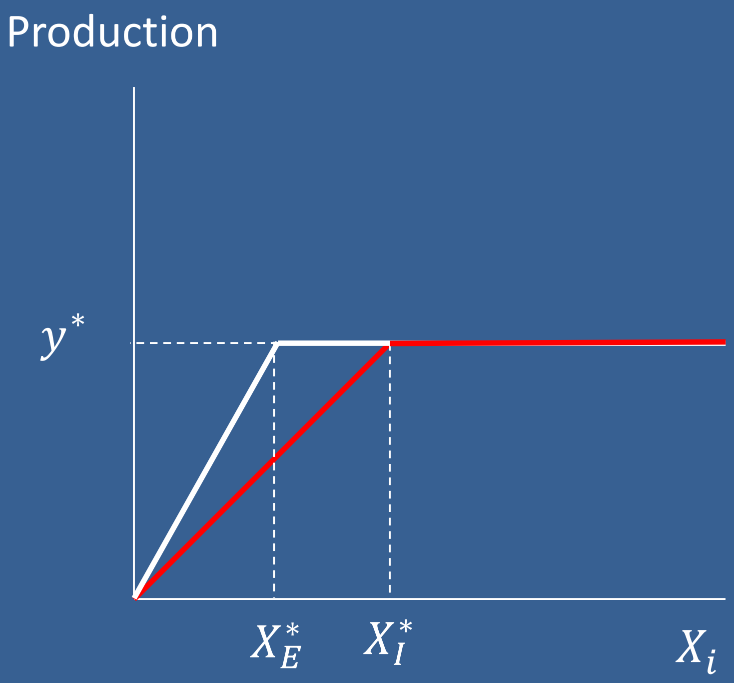
Production represented by Von-Liebig technology

$$y_i = \begin{Bmatrix} \gamma_i B X_i \; when \; X_i < X_i^* \\ y^* \; when \; X_i \geq X_i^* \end{Bmatrix}$$

where X_i^* is the agent's optimal water demand under technology *i* and

$$X_i = \begin{Bmatrix} X_i^* \; if \; A(t) \geq X_i^* \\ X_i < X_i^* \; if \; A(t) < X_i^* \end{Bmatrix}$$

is the amount of water applied production



Available water versus applied water

- Agent receives full water right in wet year and proportion of aggregate water supply in dry year

$$A(t) = \begin{Bmatrix} X_i^* \; if \; W(t) \geq \bar{W} \\ \theta W(t) \; if \; W(t) < \bar{W} \end{Bmatrix}$$

- If $A(t) < X_i^*$, agent leases to supplement his available water for production
- Investment in efficient water technology helps create water surplus by reducing X_i^*

Optimal water use

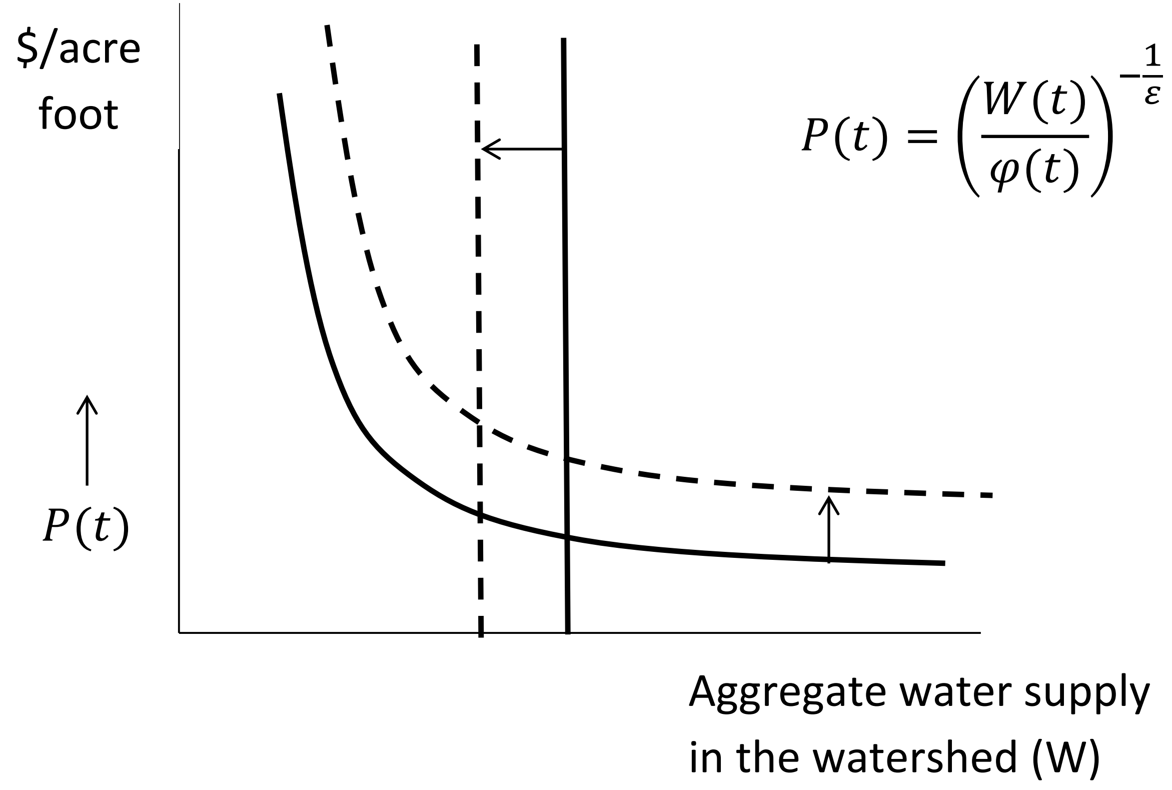
- Applied water chosen to

$$\Pi_i(P, W) = \max_{X_i} P_y \gamma_i B X_i - P(t)\big(X_i - \theta W(t)\big)$$

- When $P(t) \le P_y \gamma_i$ the farmer optimally chooses to apply X_i^*
  - Water conservation lowers cost of production and generates surplus water that can be sold

- When $P(t) > P_y \gamma_i$ the farmer will choose to terminate production and lease all water rights
  - Water conservation has no value

Water price dynamics



$$P(t) = \left(\frac{W(t)}{\varphi(t)}\right)^{-\frac{1}{\varepsilon}}$$

Water price dynamics

- Future water supply and demand are unpredictable

- Two non-stationary random variables modeled as generalized Ito processes

$$dW = \overset{\substack{\text{climate}\\ \text{trend}}}{\alpha(W,t)dt} + \overset{\substack{\text{climate}\\ \text{variability}}}{\sigma(W,t)dz_w}$$

$$d\varphi = \underset{\substack{\text{market}\\ \text{trend}}}{a(\varphi,t)dt} + \underset{\substack{\text{market}\\ \text{variability}}}{b(\varphi,t)dz_\varphi}$$

Adaptation decision

- Based on expectations of future profit, agent can choose to adopt new irrigation technology when the aggregate water supply drops to W^*, which instantly changes production efficiency to $\gamma_E > \gamma_I$

- Adopting the new irrigation technology (adaptation) requires a one-time investment cost K

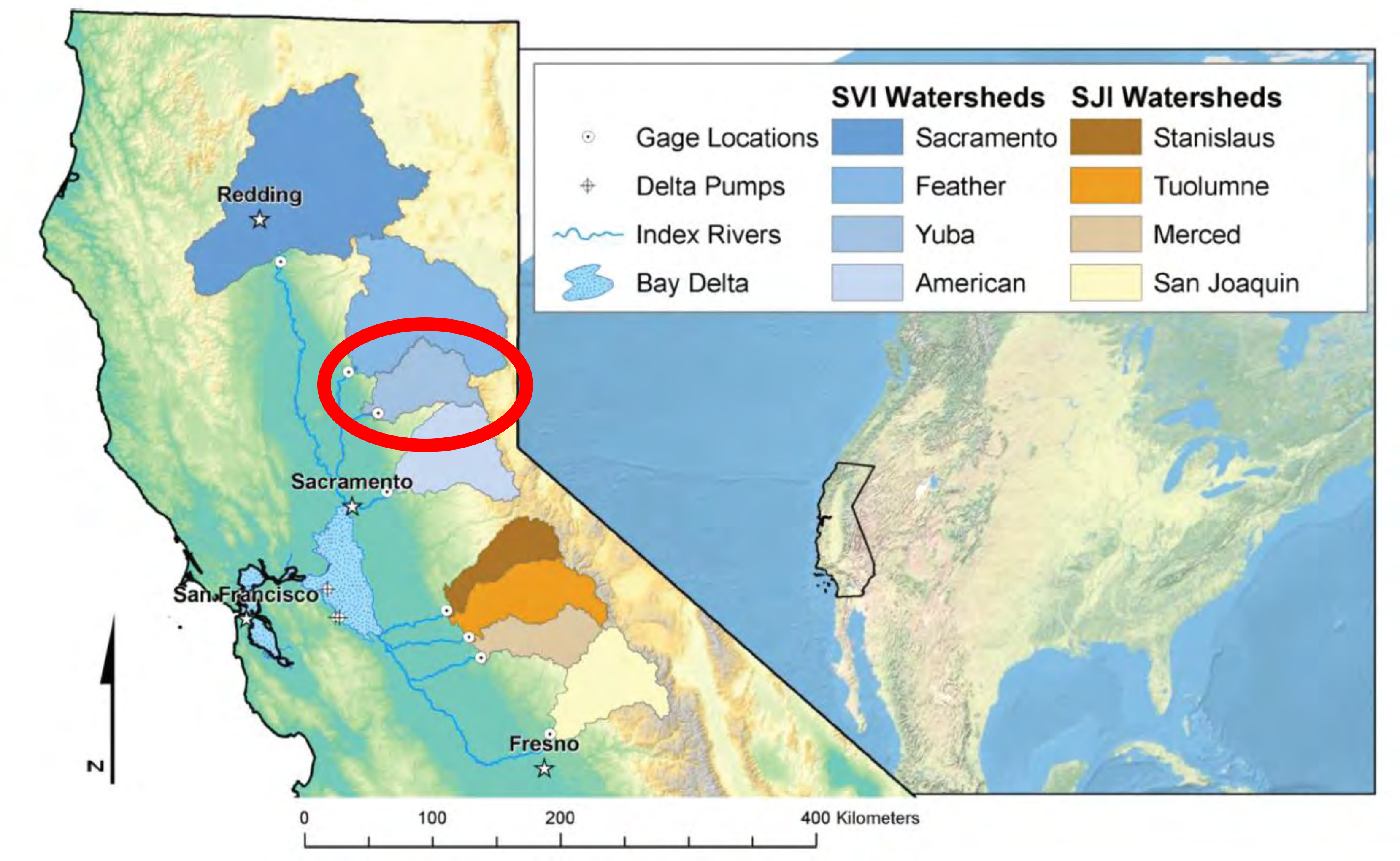
- The optimal adaptation decision $W^*(\varphi)$ satisfies

$$V(W_0, \varphi_0) = \max_{W^*} E_0 \left[\int_0^{t^*} \Pi(W, \varphi) e^{-\rho t}\, dt + \{[V(W, \varphi) - K] e^{-\rho t_E}\} \right]$$

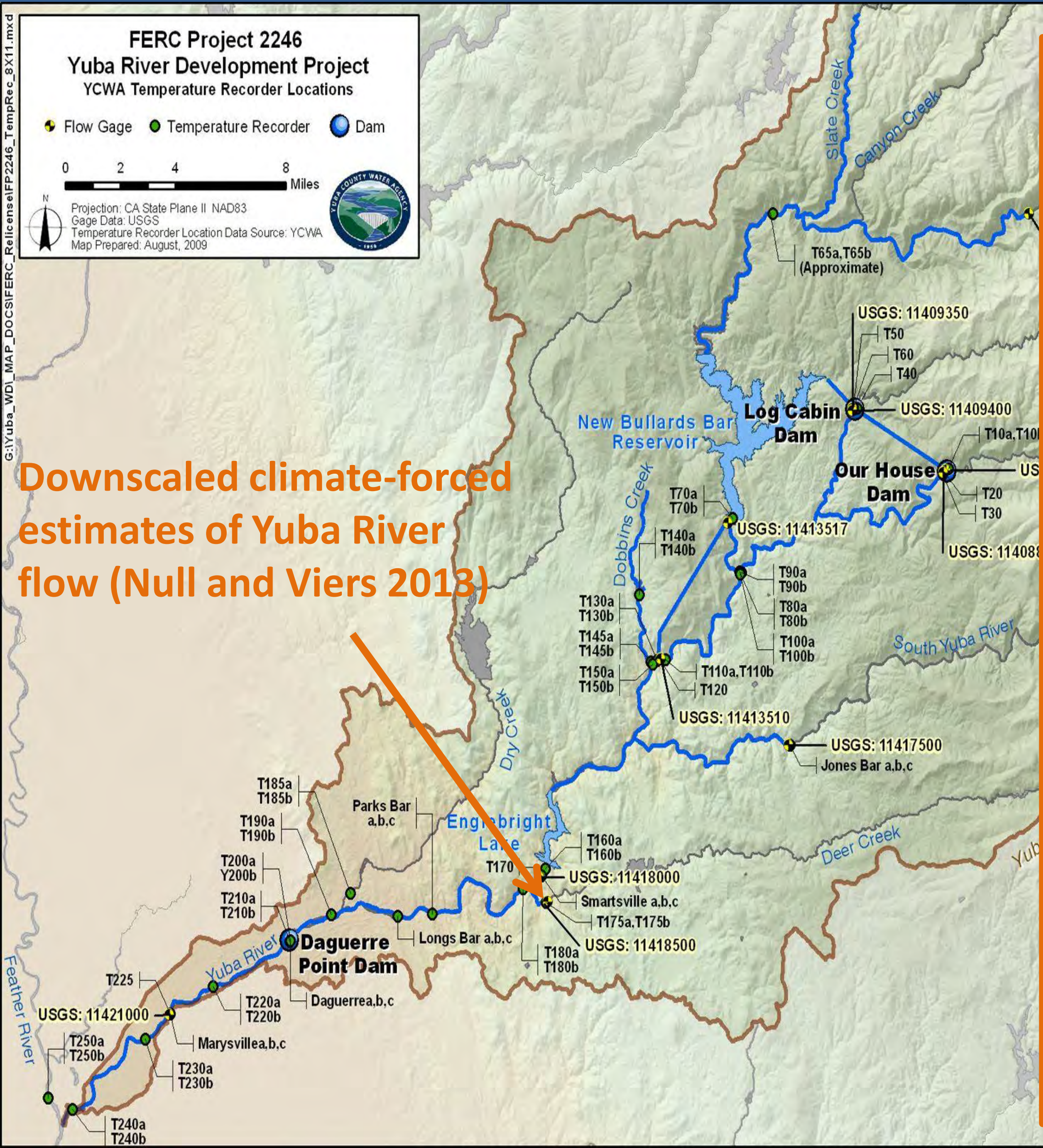
subject to $dW, d\varphi, W(0) = W_0, \varphi(0) = \varphi_0$.

- If $W > W^*$ (or water price is below P^*) delay adaptation
- If $W \leq W^*$ (or water price is above P^*) adapt immediately

Adaptation in the Yuba River watershed



Climate change and variability in the Yuba



Downscaled climate-forced estimates of Yuba River flow (Null and Viers 2013)

Two time scales: historic (1950-2000) and “short-term” forecasts (2001-2050)

4 climate models: CCSM4.1, CNRM-CM5.1, MIROC5.1, MIROC-ESM

2 emission scenarios:
Moderate: maximum CO2 emissions of 450 ppm, global population that peaks mid-century, and introduction of resource-efficient technology
Severe: maximum CO2 emissions of 850 ppm, continuously increasing global population, and slow economic growth

Climate change and variability in the Yuba

Tests indicate all time series are trend stationary (at odds with literature) → river flow stochastically reverts to an affine trend $\overline{W} - \mu t$

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$$d(W - \mu t) = \alpha(\overline{W} + \mu t - W)dt + \sigma dz$$

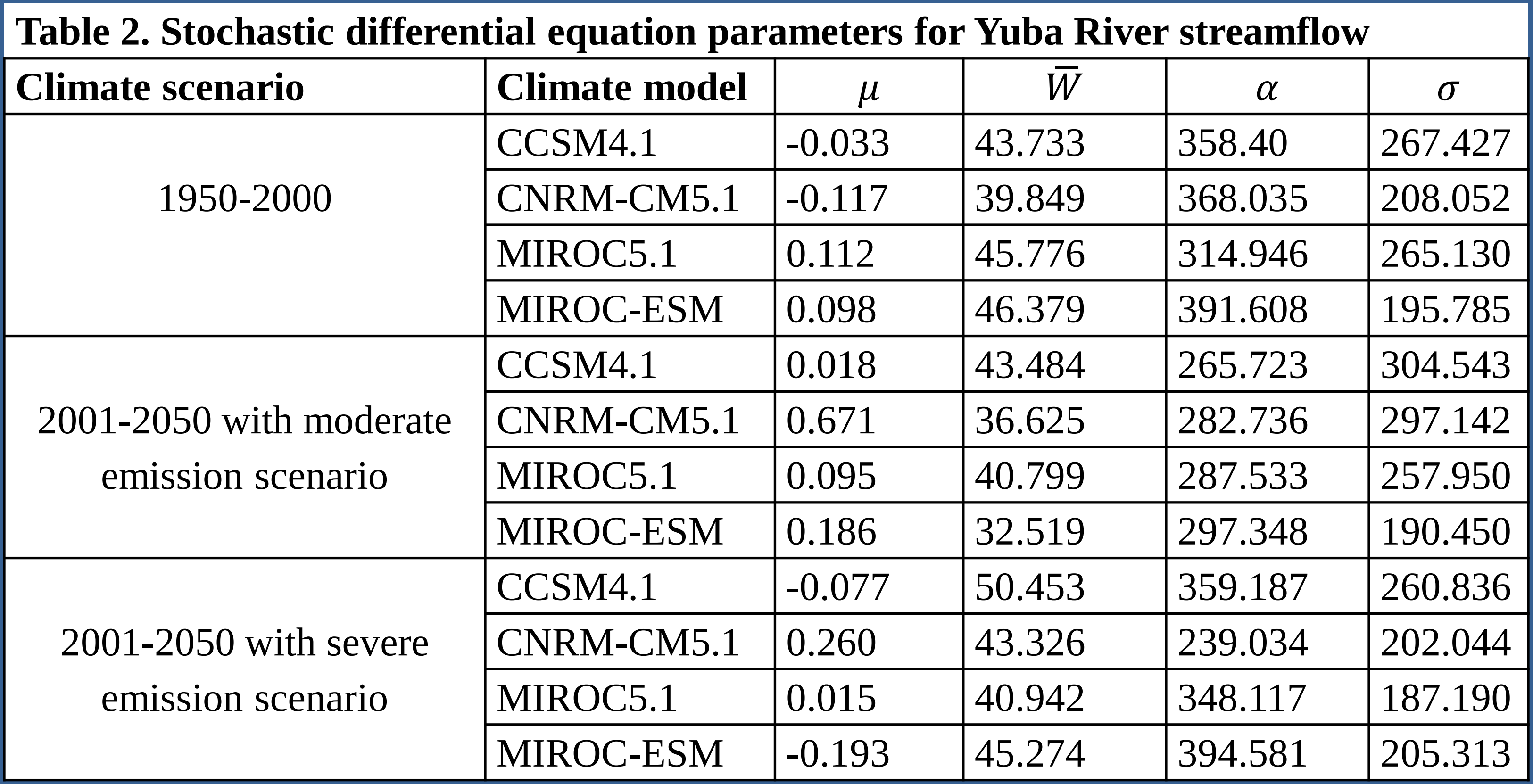
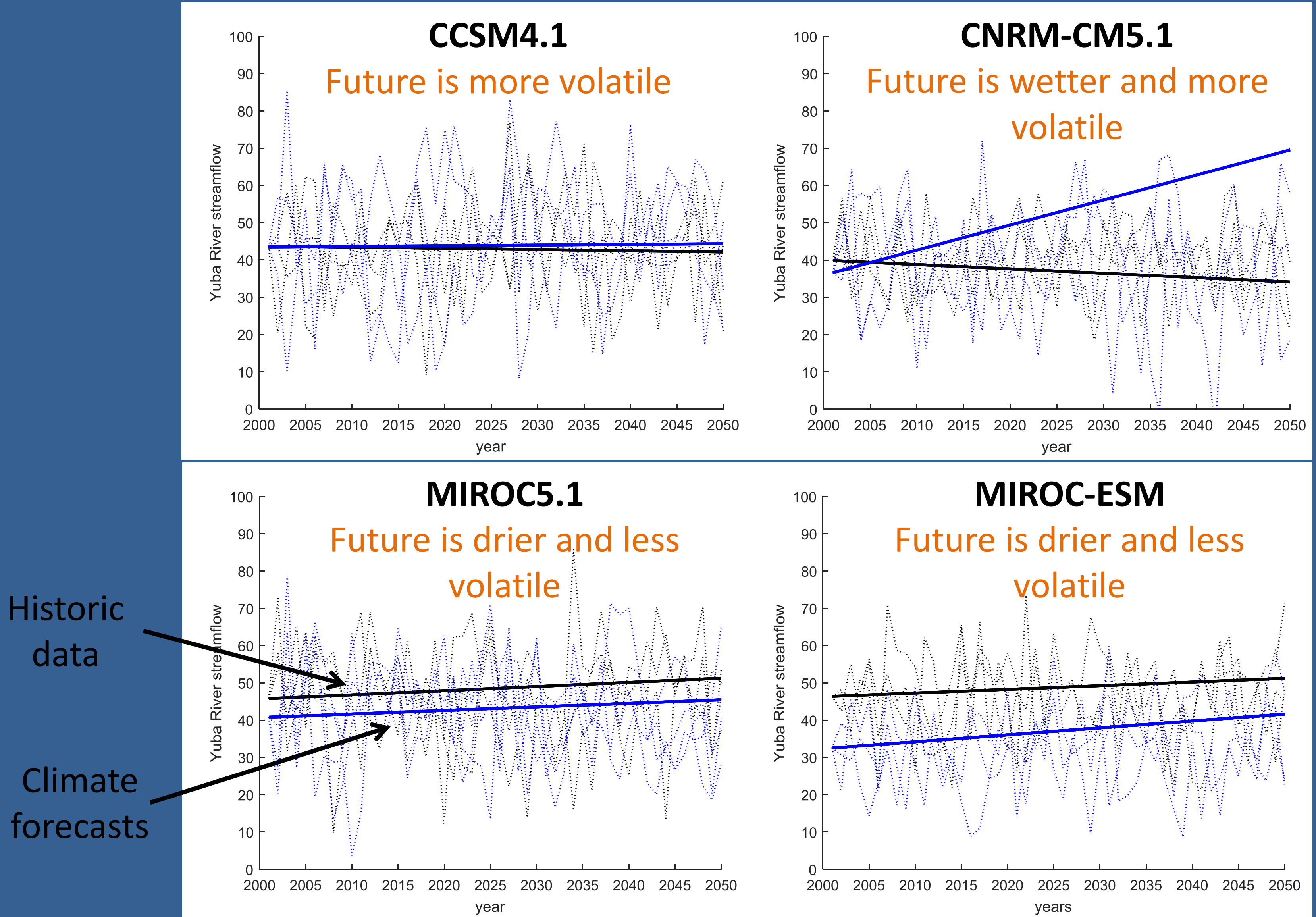


Table 2. Stochastic differential equation parameters for Yuba River streamflow

Climate scenario	**Climate model**	μ	$\overline{W}$	α	σ
1950-2000	CCSM4.1	-0.033	43.733	358.40	267.427
	CNRM-CM5.1	-0.117	39.849	368.035	208.052
	MIROC5.1	0.112	45.776	314.946	265.130
	MIROC-ESM	0.098	46.379	391.608	195.785
2001-2050 with moderate emission scenario	CCSM4.1	0.018	43.484	265.723	304.543
	CNRM-CM5.1	0.671	36.625	282.736	297.142
	MIROC5.1	0.095	40.799	287.533	257.950
	MIROC-ESM	0.186	32.519	297.348	190.450
2001-2050 with severe emission scenario	CCSM4.1	-0.077	50.453	359.187	260.836
	CNRM-CM5.1	0.260	43.326	239.034	202.044
	MIROC5.1	0.015	40.942	348.117	187.190
	MIROC-ESM	-0.193	45.274	394.581	205.313

Moderate GHG emissions

$$d(W - \mu t) = \alpha(\bar{W} + \mu t - W)dt + \sigma dz$$



CCSM4.1

Future is more volatile

CNRM-CM5.1

Future is wetter and more volatile

MIROC5.1

Future is drier and less volatile

MIROC-ESM

Future is drier and less volatile

Historic data

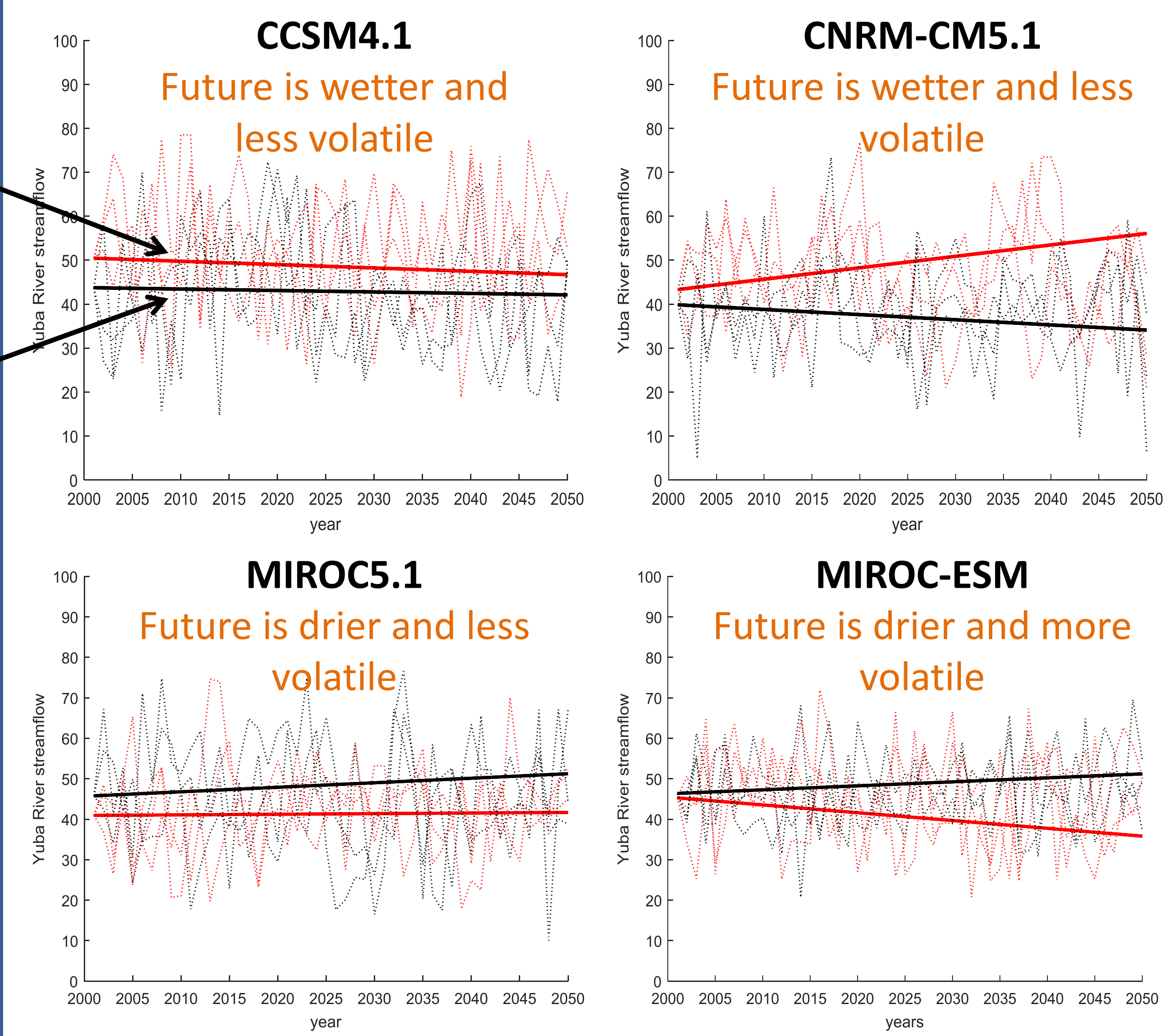
Climate forecasts

Severe GHG emissions

$$d(W - \mu t) = \alpha(\bar{W} + \mu t - W)dt + \sigma dz$$

Historic data

Climate forecasts



CCSM4.1

Future is wetter and less volatile

CNRM-CM5.1

Future is wetter and less volatile

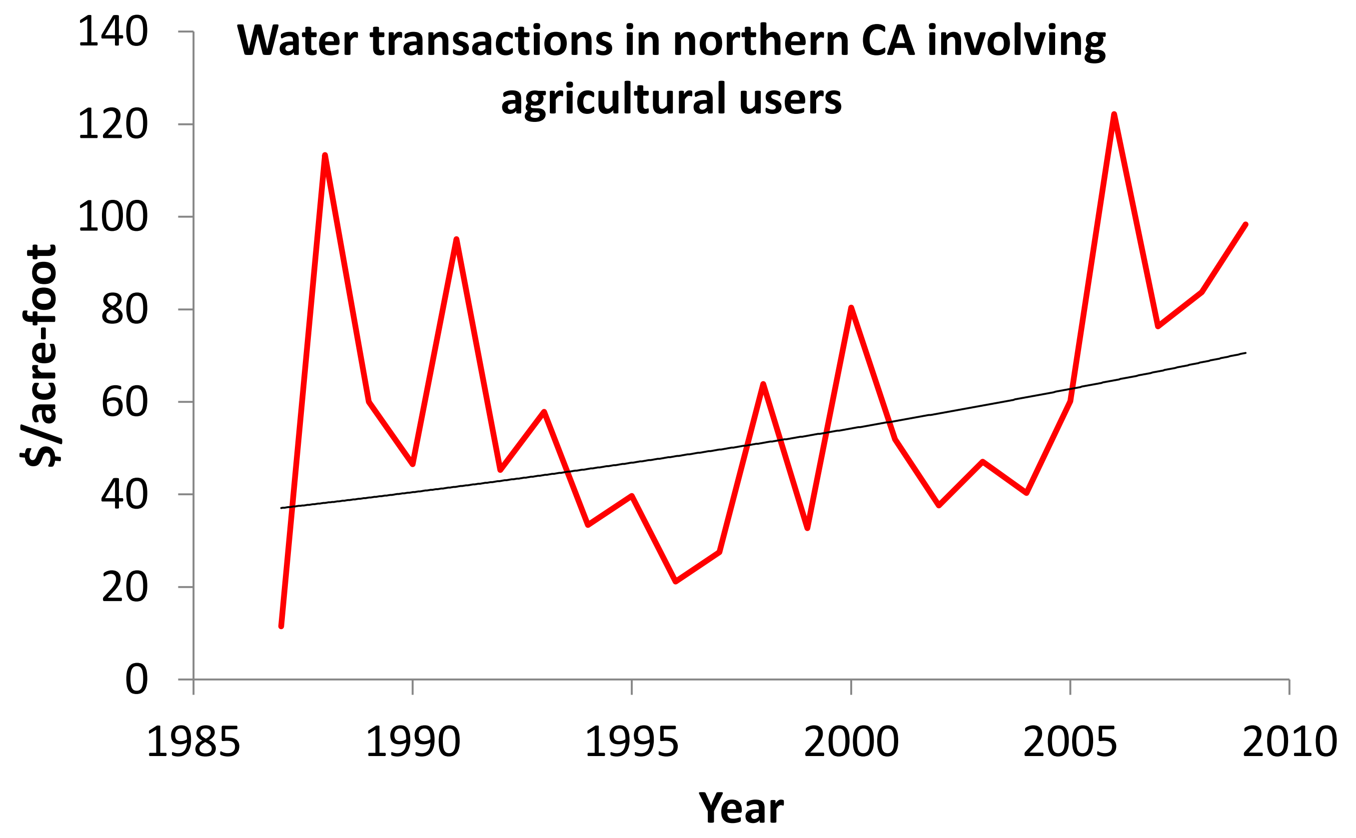
MIROC5.1

Future is drier and less volatile

MIROC-ESM

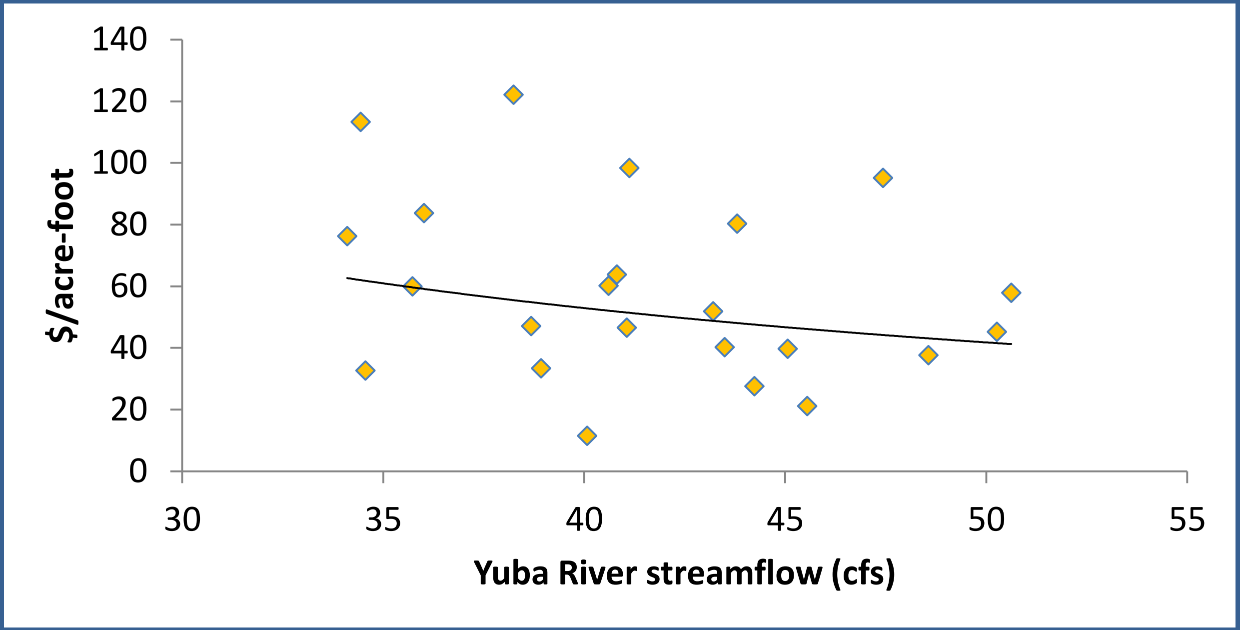
Future is drier and more volatile

Water market change and variability



Source: Water Transfer Level Dataset, U of California-Santa Barbara

Water market change and variability



- From demand equation: $\varphi(t) = P(t)^{\varepsilon}W(t)$

- Regression results indicate $\varepsilon = 0.945$ and

$$d\varphi = 0.152\varphi dt + 0.548\varphi dz$$

Solving for adaptation thresholds

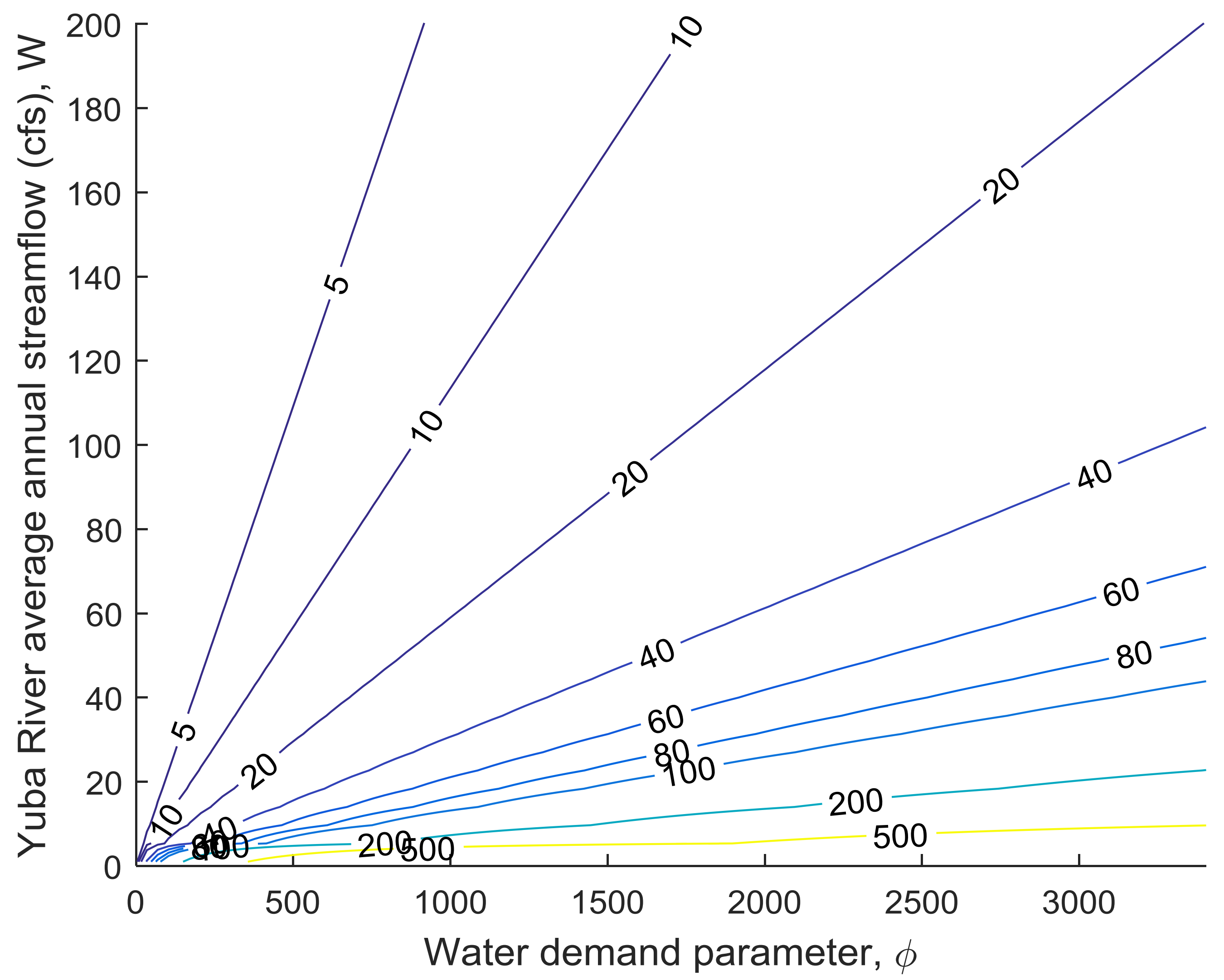
- No analytic solution so rewrite problem as system of variational inequalities
- Value function under the inefficient technology and the adaptation curve, $W^*(\varphi)$, satisfy

$$\rho V_I \geq \Pi_I + \frac{\partial V_I}{\partial t} + a(\varphi, t)\frac{\partial V_I}{\partial \varphi} + \alpha(W, t)\frac{\partial V_I}{\partial W} + \frac{b(\varphi, t)^2}{2}\frac{\partial^2 V_I}{\partial \varphi^2} + \frac{\sigma(W, t)^2}{2}\frac{\partial^2 V_I}{\partial W^2} + b\sigma\delta\frac{\partial^2 V_I}{\partial \varphi \partial W}$$

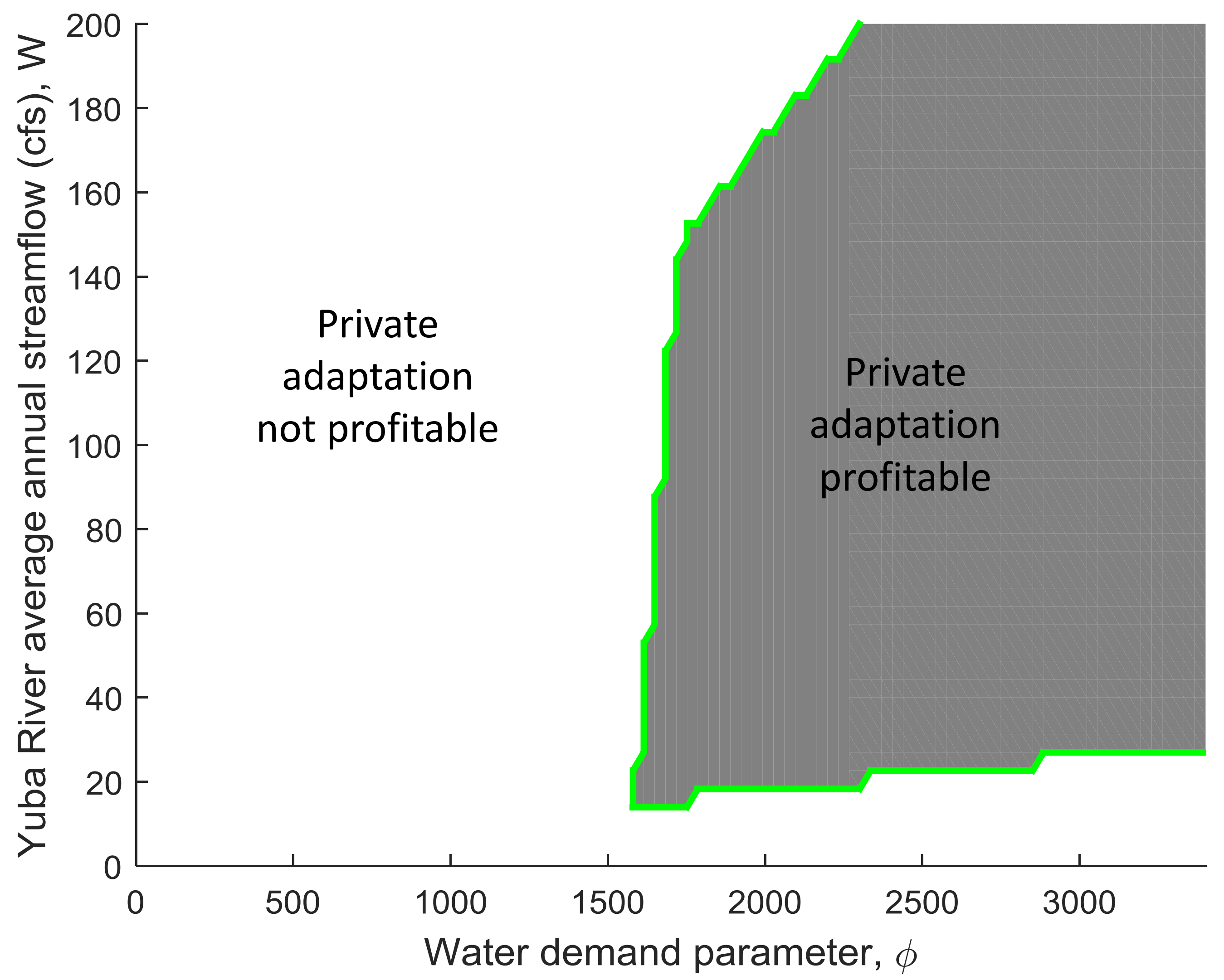
$$V_I(W, \varphi) \geq V_E(W, \varphi) - K$$

- If 1st condition holds as an equality, it is optimal to delay private adaptation
- If 2nd condition holds as an equality, it is optimal to immediately adapt
- Approximate value functions V_I and V_E in MATLAB using collocation methods (Miranda and Fackler 2002)

Relevant state space

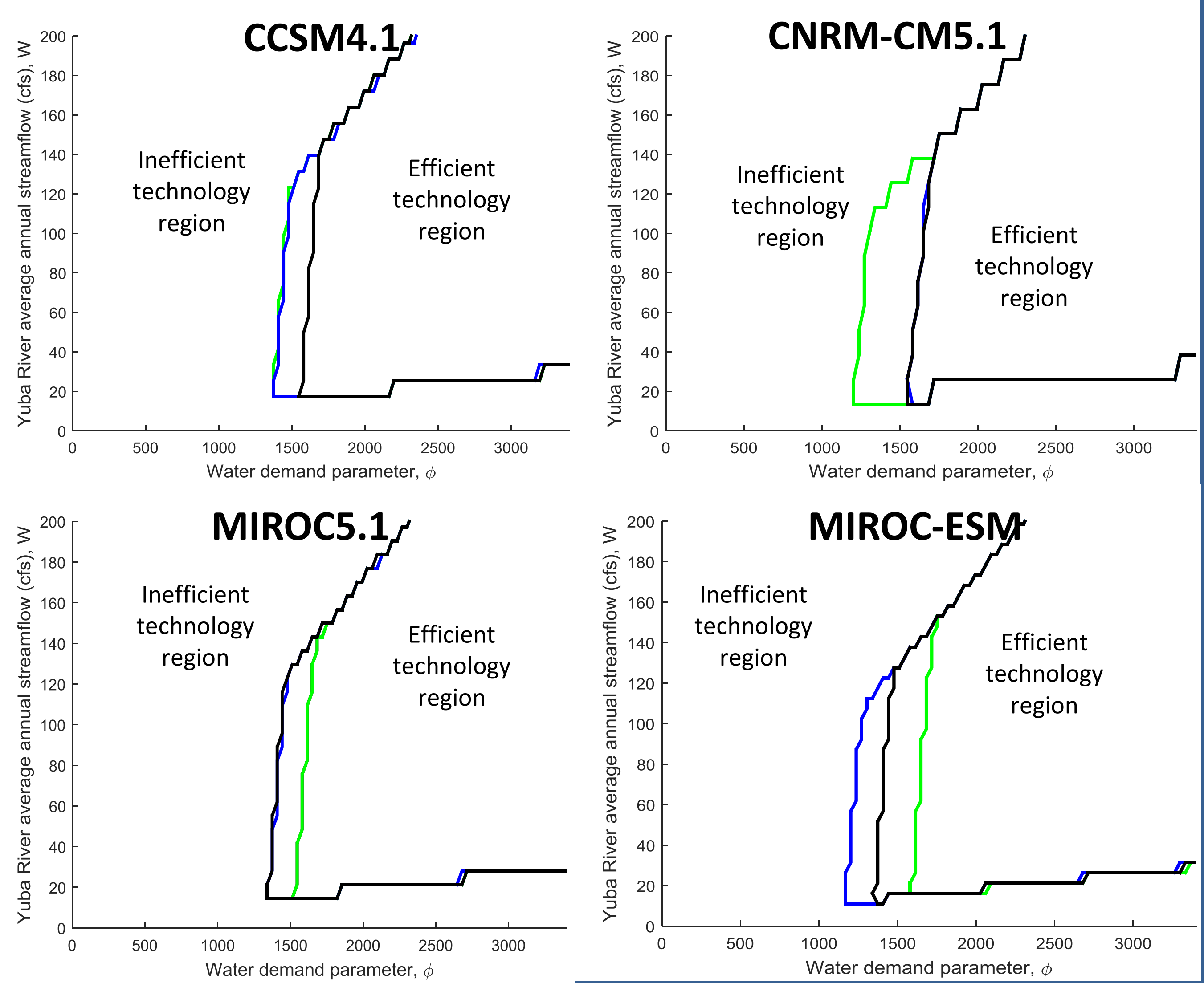


Adaptation threshold



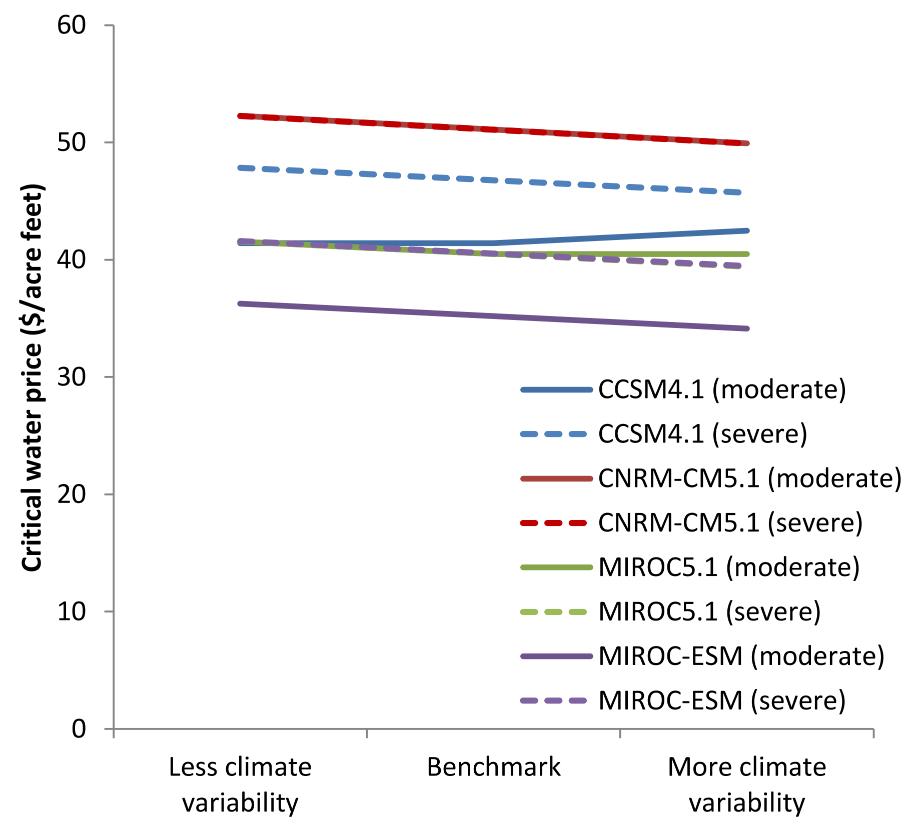
Do climate forecasts influence adaptation? YES

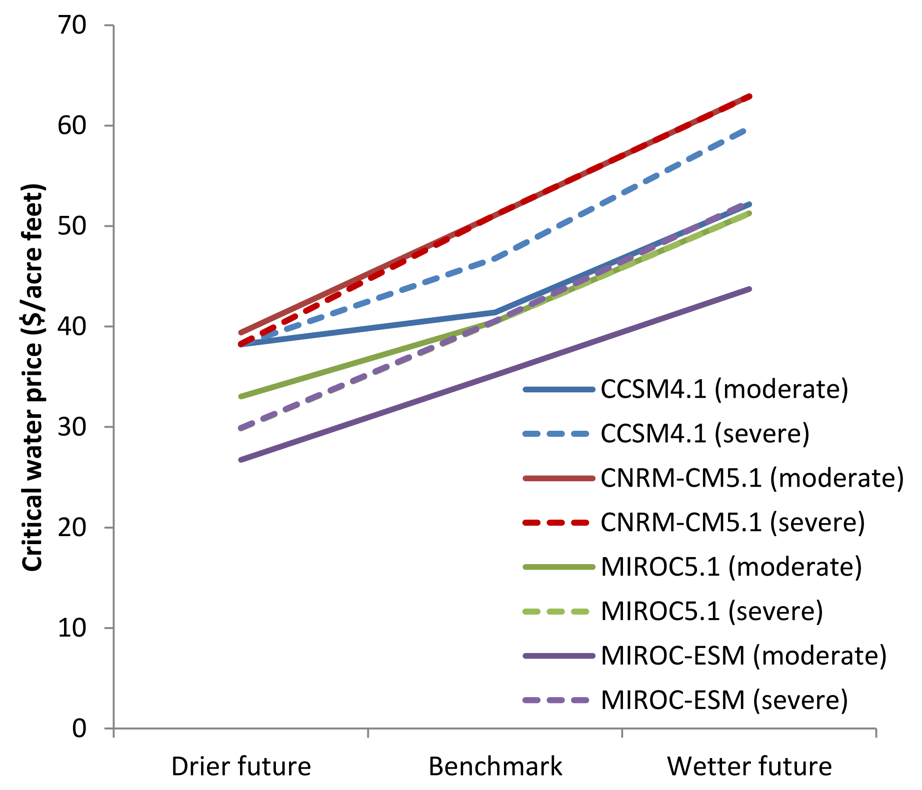
Historic data
Moderate forecasts
Severe forecasts



Does more climate variability delay adaptation? NO

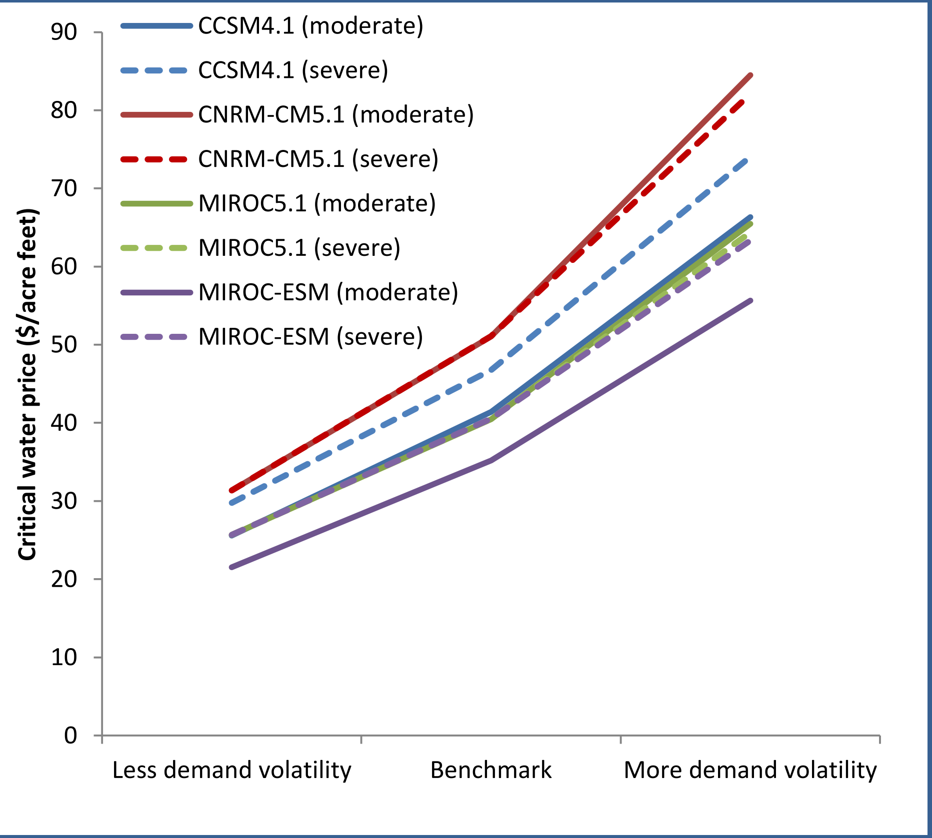
If streamflow is 40 cfs…

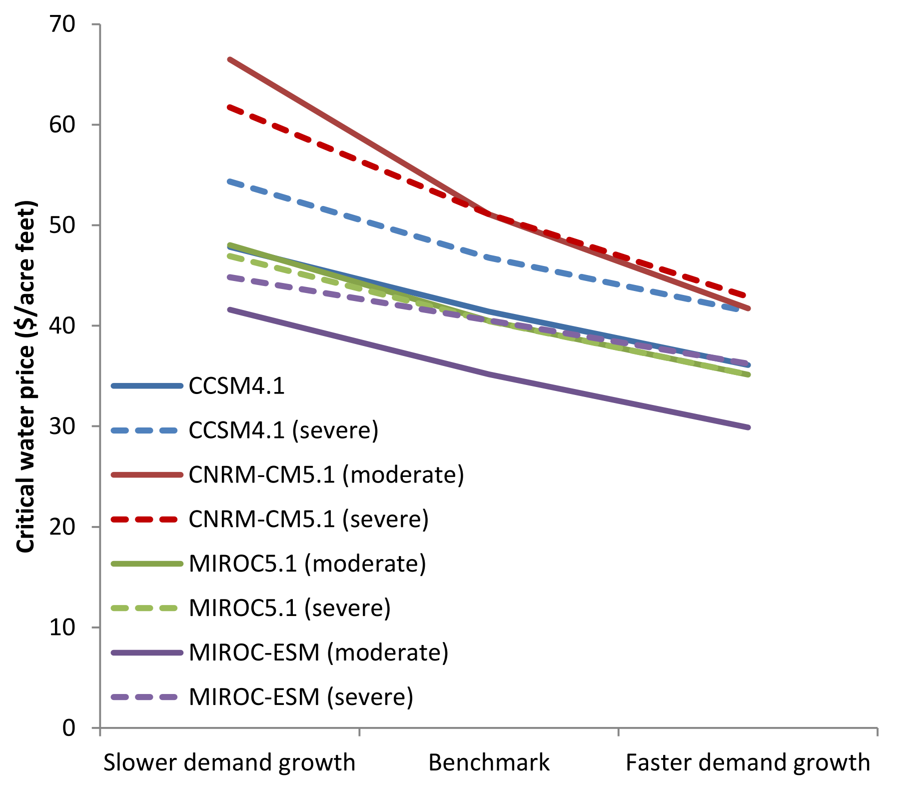




How important is market variability? **VERY**

If streamflow is 40 cfs…





Take-home points

- Climate forecasts matter but uncertainty over GHG emissions may not
- More climate variability doesn’t necessarily delay adaptation
- Market sources of variability are just as important (if not more so) than climate variability

Future work

- Value of climate forecast information
- Applications to other adaptation investments in other locations
- Trend stationary versus difference stationary
- Dueling irreversibilities