Assessing Future Changes of Drought over South-Central United States in Supporting Regional Water Resource Planning

Rong Fu
Nelun Fernando, Lei Yin, Tong Ren, Ze Yang, Adam Bowerman

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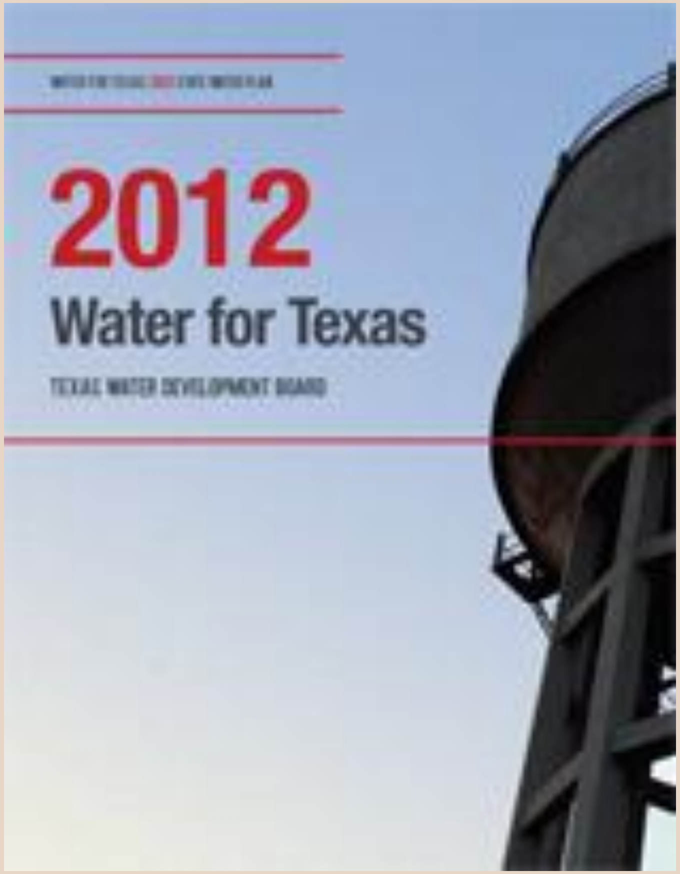
Projected drought impact in future

2012 Texas Water Plan:

- ***The economic loss would be $116 billion should a drought of the 1950s occur around 2060.***

- ***The capital cost of implementing strategies to mitigate such a potential economic loss would be $53 billion***

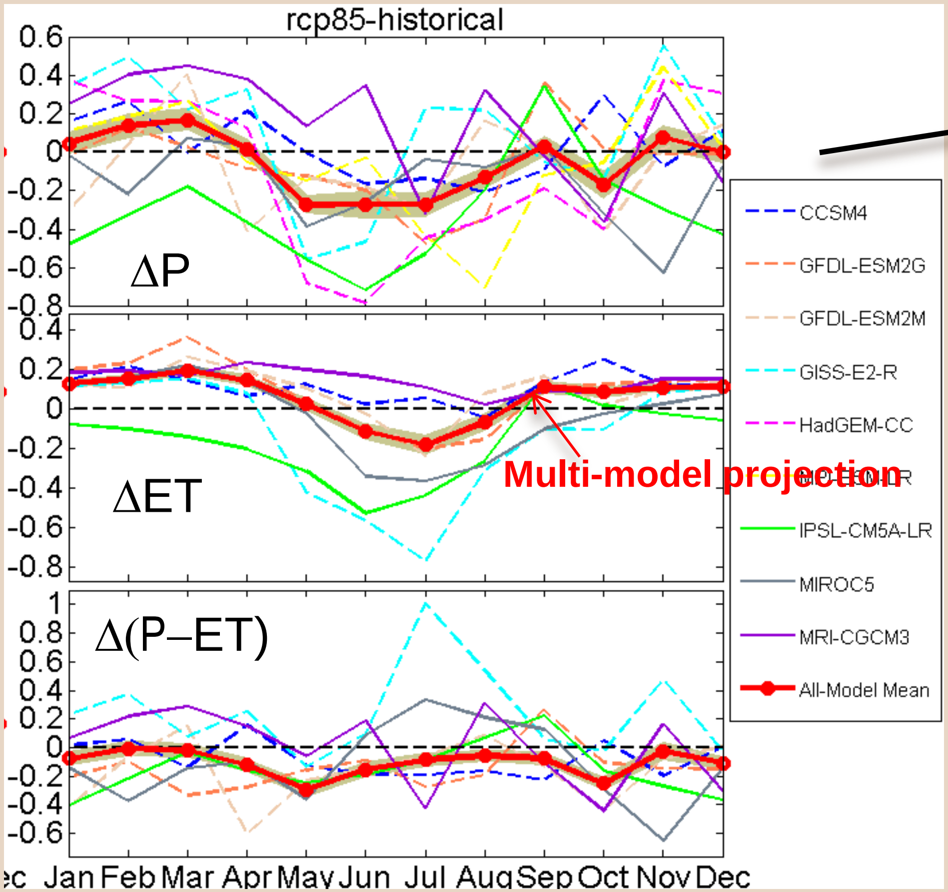
- ***However, large uncertainty in CMIP3 climate projections have in part hampered the use of climate projection for future water resource planning***

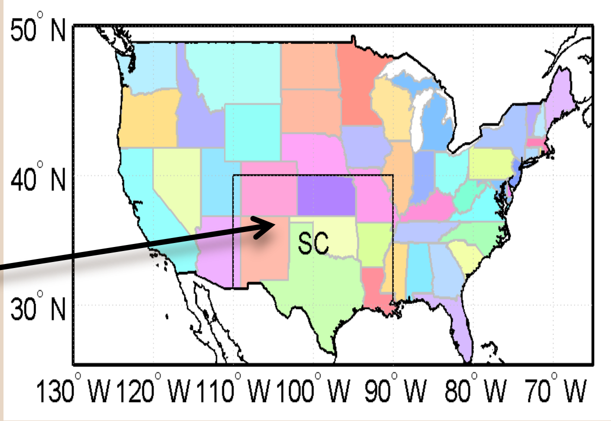


Cost of agriculture loss in 2011 drought: ~$7.62B

How about the projections by the CMIP5 Models?

Projected change during 2073-2099 relative to 1979-2005 for RCP8.5





The nine models used in the projections:

CCSM4(5), GFDL-ESM2G (1), GFDL-ESM2M(1), GISS-E2-R (5), HadGEM2-CC(1), MPI-ESM-LR (3), IPSL-CM5A-LR(4), MIROC5(3), MRI-CGCM3(1)

How can we determine the quality of the CMIP5 climate projection?

- ***Does the multi-models ensemble projection necessarily out-perform individual model projection over SC US?***
  - ***Gleckler et al. (2008), Pierce et al. (2009): An ensemble mean, especially a multi-model ensemble mean projection, can out-perform the best quality model because the former allows cancellation of offsetting errors in the individual global models.***
  - ***What should we do if majority of the models have similar biases?***

Datasets Used for Evaluation:

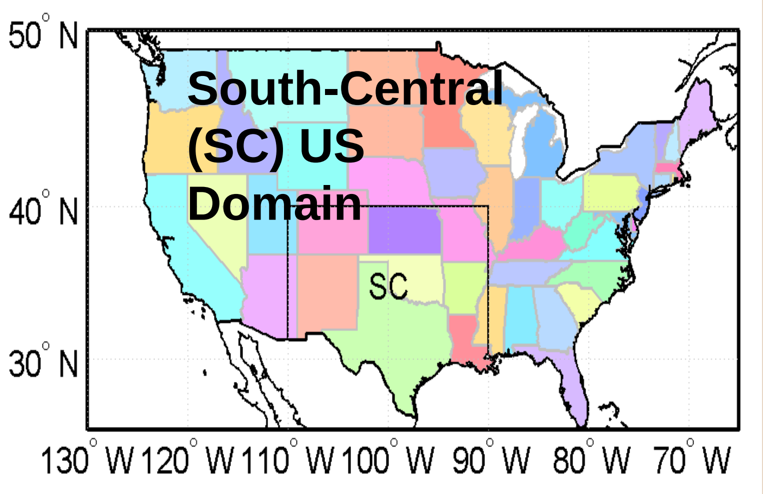
Datasets:

- *CPC US-Mexico daily rainfall (Higgins et al. 1996), 1°,*
- *GHCN daily Tmax,Tmin (Vose et al. 1992), 2.5°*
- *NLDAS (Rodell et al. 2004), ET, 1/8°, 1980-2007.*
- *ERSSTv3b SST (Smith et al. 2008), 2.0°, 1854-2005*
- *NCEP reanalysis (Kalney et al 1996; Kistler et al. 2001), 2.5°, 1948-present*

All the datasets and models are re-mapped to 2.5° spatial resolution

Periods:

- *1950-2005; meteorological data*
- *1900-2005: global SST warming related change*
- *1980-2005: surface energy/water balance.*



Criteria for our process-based model evaluation Metrics:

- ***Relevant to climate projection***
- ***Capture processes that control droughts over Texas***
- ***Can be compared to long-term observations***

Response to warming of the global sea surface temperature

Surface water budget and drought indices (influence soil moisture, vegetation)

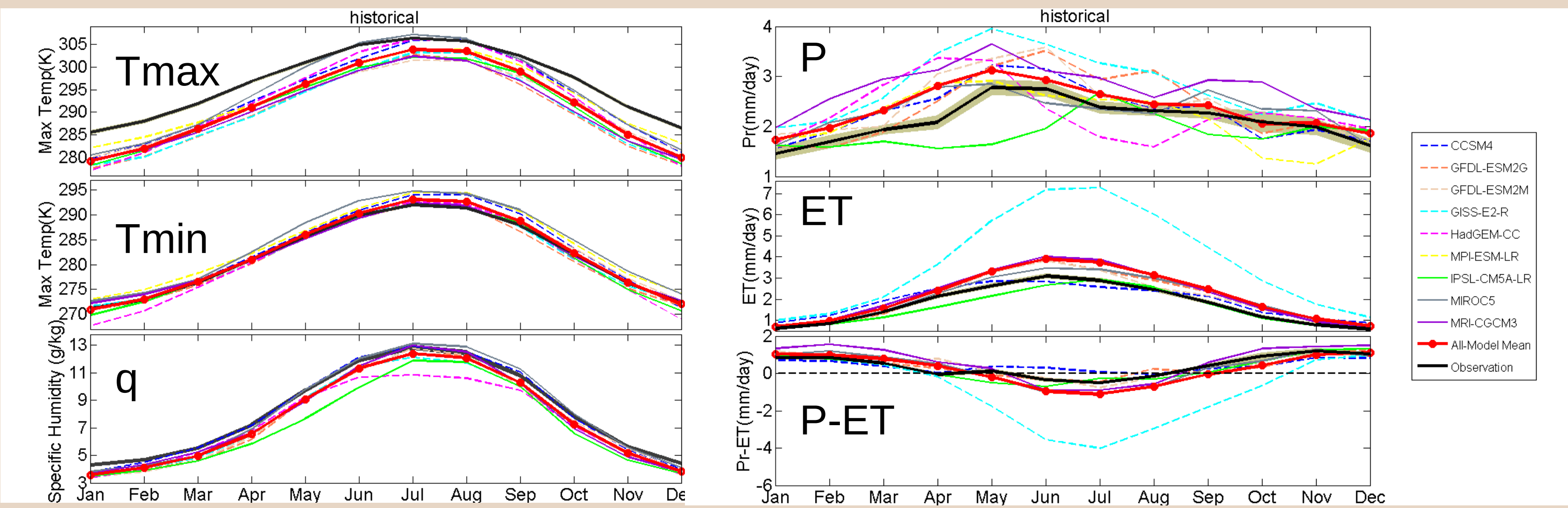
Surface meteorological conditions (influence CIN)

Large-scale circulation (UT high, LT winds)

Connection with ENSO

Evaluate seasonal cycles of climatic surface conditions:

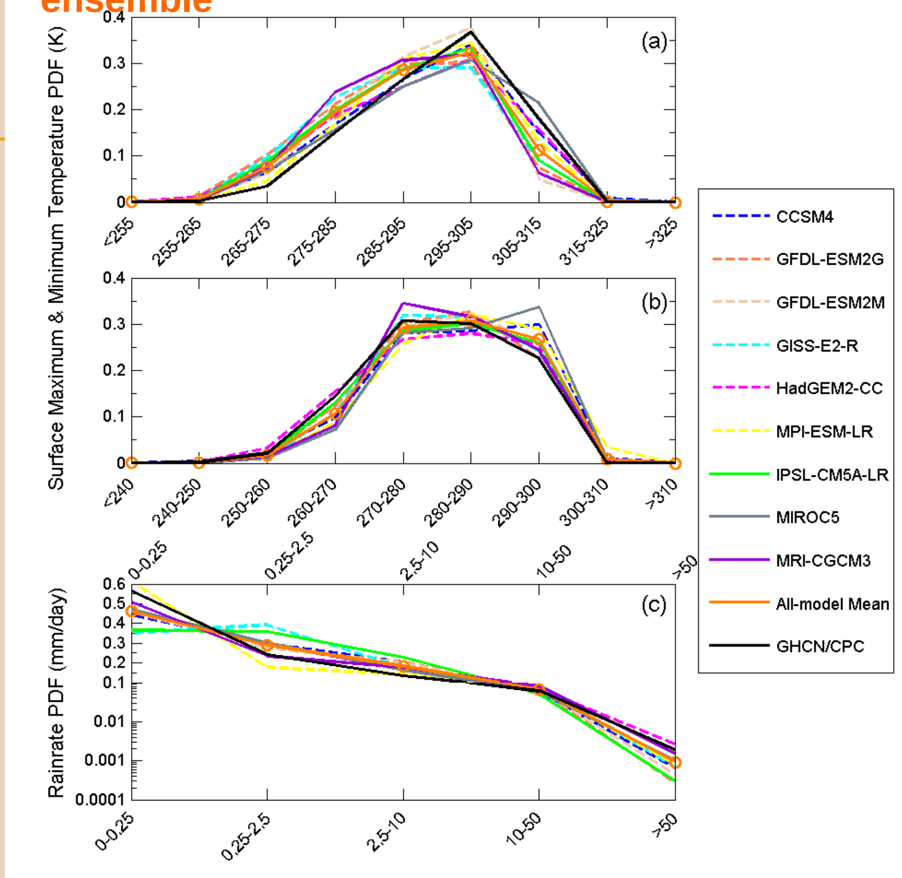
- ***Cold bias in daily maximum surface temperature (Tmax)***
- ***Overestimate Precipitation (P), Evapotranspiration (ET), esp. during spring & summer, overestimate net surface water loss in summer and fall.***
- ***Large discrepancies in seasonal rainfall***



Black line: observations, Bold Red line: multi-model ensemble mean

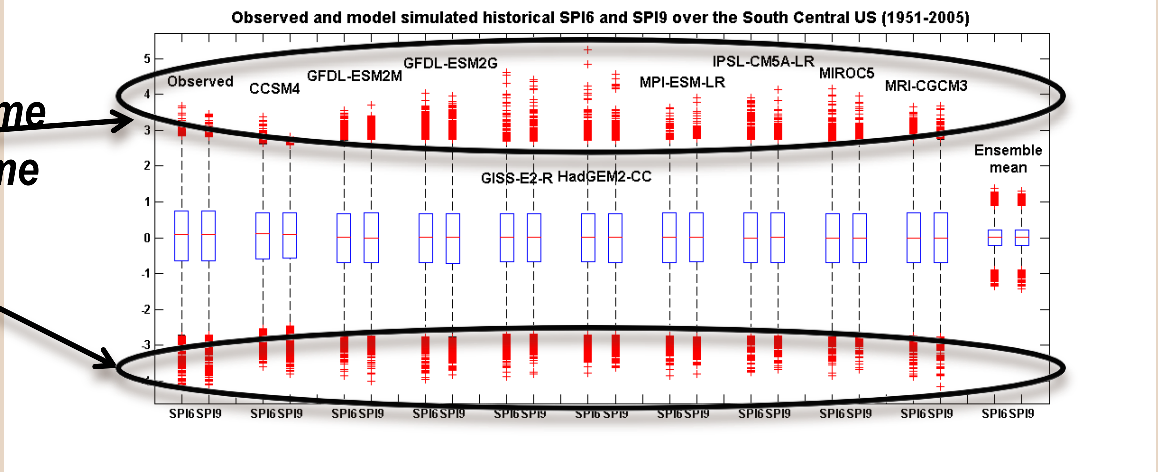
Probability distributions of Tmax, Tmin, P and drought indices (SPI6 and SPI9)

Black line: observation, Orange line: multi-model ensemble



- *Tmax: underestimate warmer Tmax and overestimate cooler Tmax*
- *Tmin: underestimate cooler Tmin, overestimate warmer Tmin (consistent with wet bias)*
- *P: underestimate non-rain and heavy rainrate, overestimate light rainrate*
- *SPI: reasonably realistic, but underestimate intensity of extreme drought and overestimate extreme wet anomalies.*

Outliners >2.7σ

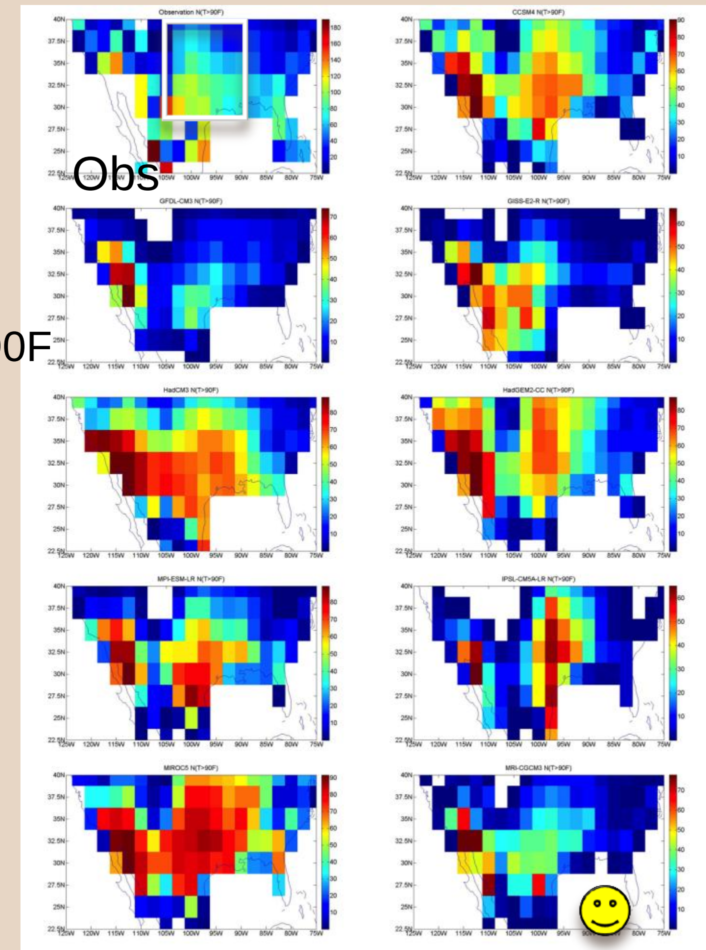


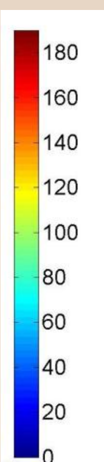
Number of days/yr when T_{max}>90F & 100F:

- ***Reverse the E-W gradient of extreme Tmax over Texas,***
- ***Most of models overestimate occurrence of extreme Tmax over the southeastern Great Plains,***
- ***Large inter-model discrepancies***

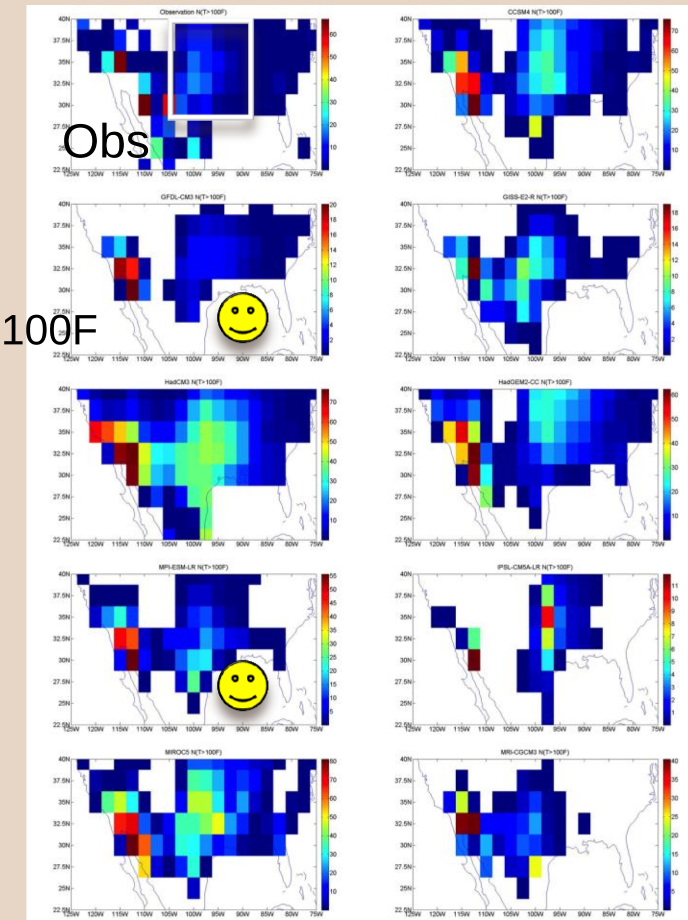
☺ highlight better models

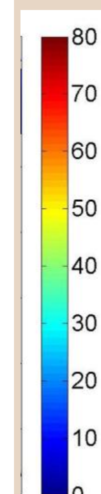
Tmax>90F





Tmax>100F





Evaluation of Large-scale atmospheric circulation:

- ***Most of the models underestimate the 500hPa ridge over central US in summer and strength of jet in spring (except for CCSM4).***
- ***Probably responsible for wet and cold biases in spring and summer.***

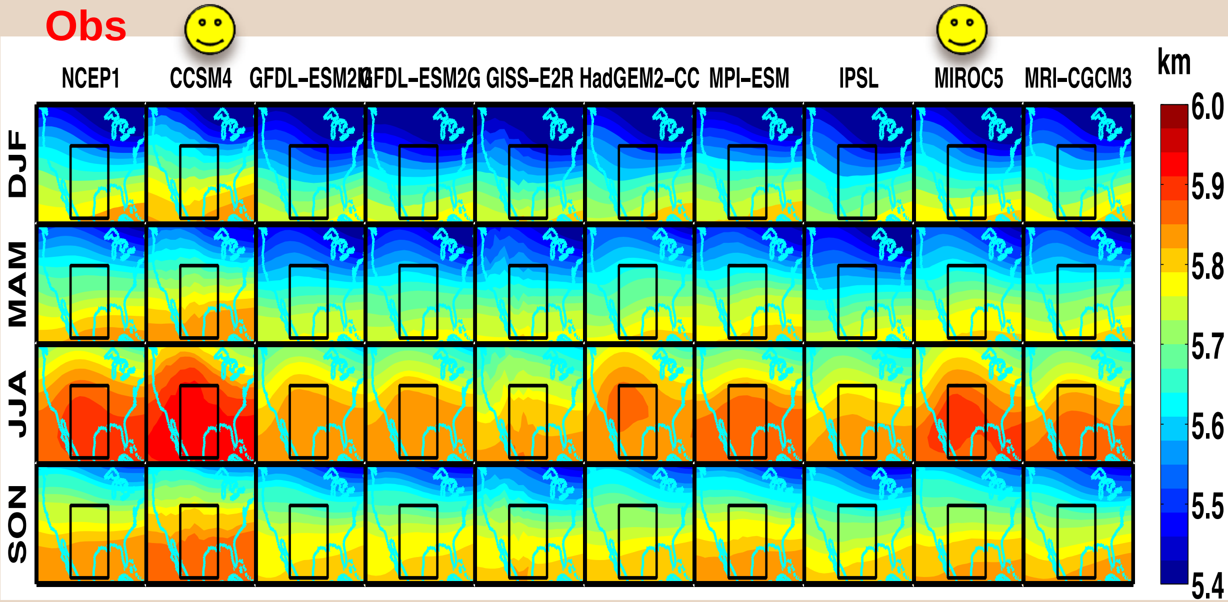


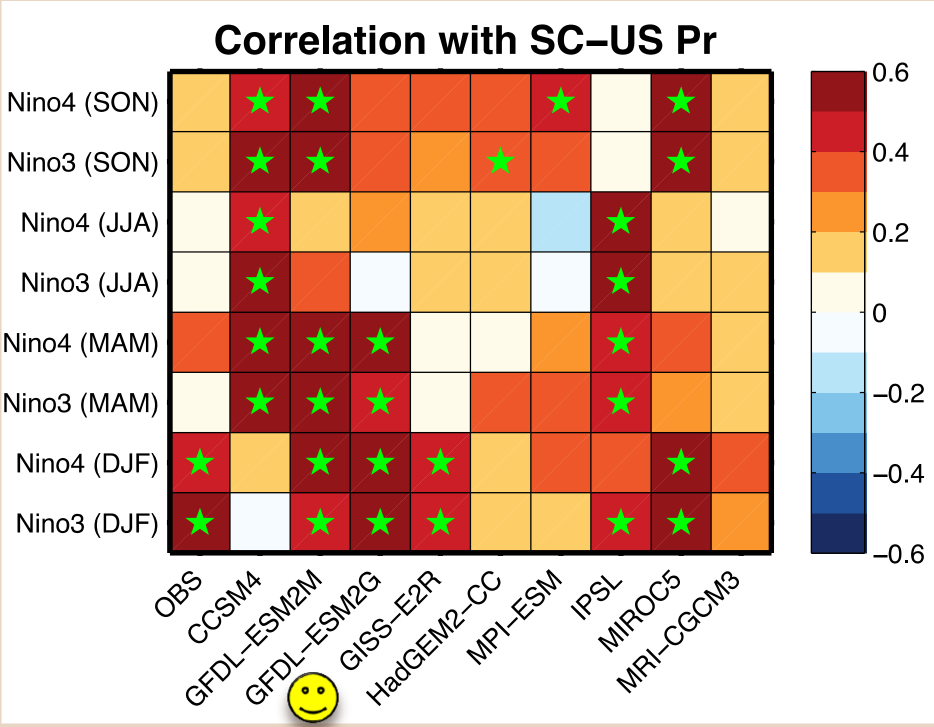
Figure 6: Comparison of the modeled Z500hPa pattern by each CMIP5 models with that of NCEP-CDAS1.

*Circles highlight better models

Correlation between SC US rainfall anomalies and Niño3 and Niño4 indices:

About 50% of the models

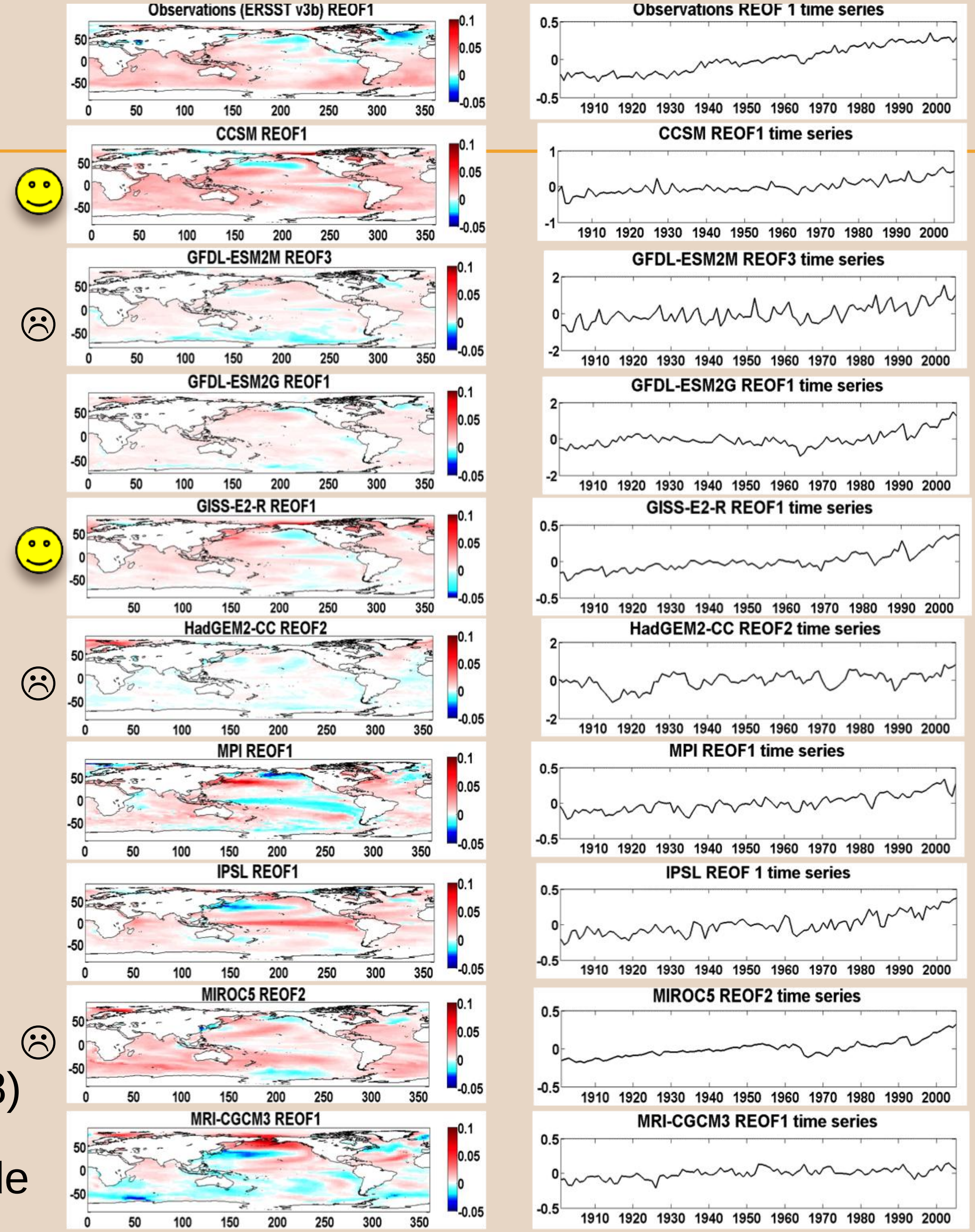
- ***underestimate correlation with ENSO in winter***
- ***overestimate ENSO connection in spring, summer and fall***
- ***Because of errors in ENSO tele-connection pattern.***



"Star" indicates significant correlation coefficient at 95% confidence level using student t-test.

Leading REOF of global SST variance during 1900-2005:

- ***Observation shows the global increase of sea surface temperature (SST) as the leading mode for SST variance (Schubert et al. 2008).***
- ***Few models realistically capture this global increase of SST mode (CCSM4 and MPI)***

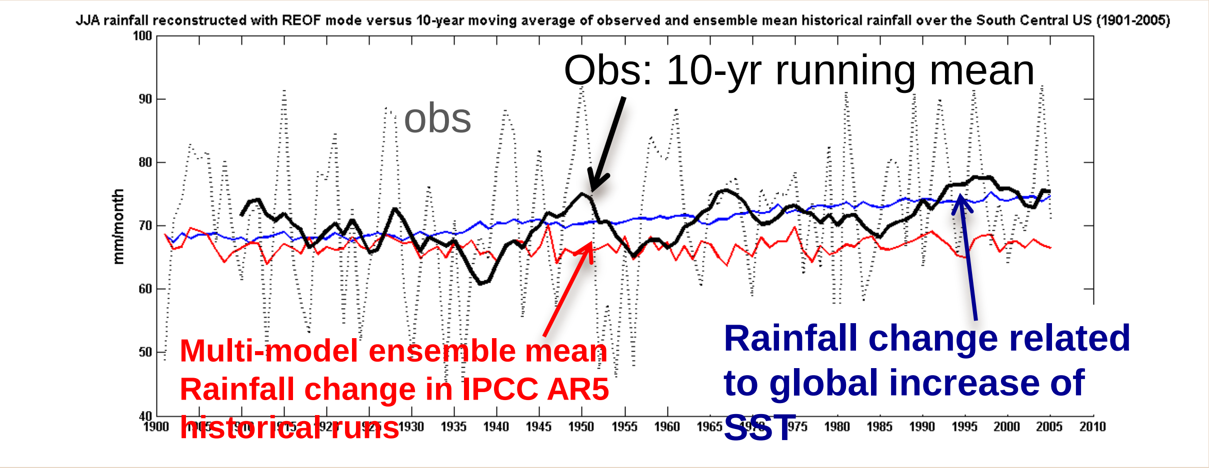


Method follow Schubert et al. 2008)

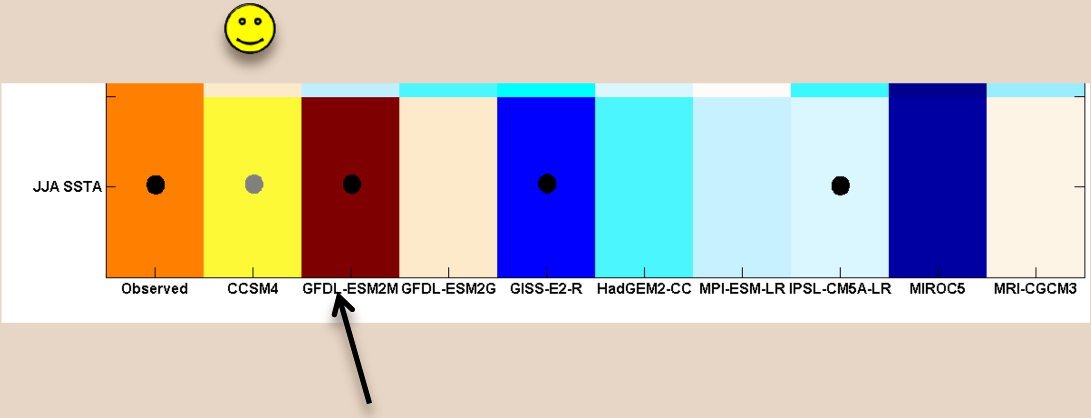
☹: Fail to capture the warming mode as the leading REOF mode

Modeled response of summer rainfall over SC US to the global SST warming mode:

- *Most of the models underestimate the change of summer rainfall over SC US associated with global increase of SST over the period of 1900-2005.*



- *Only CCSM4 captures the observed relationship between the increase of global SST mode and increase of summer rainfall over SC US.*



Warming mode is not the leading REOF

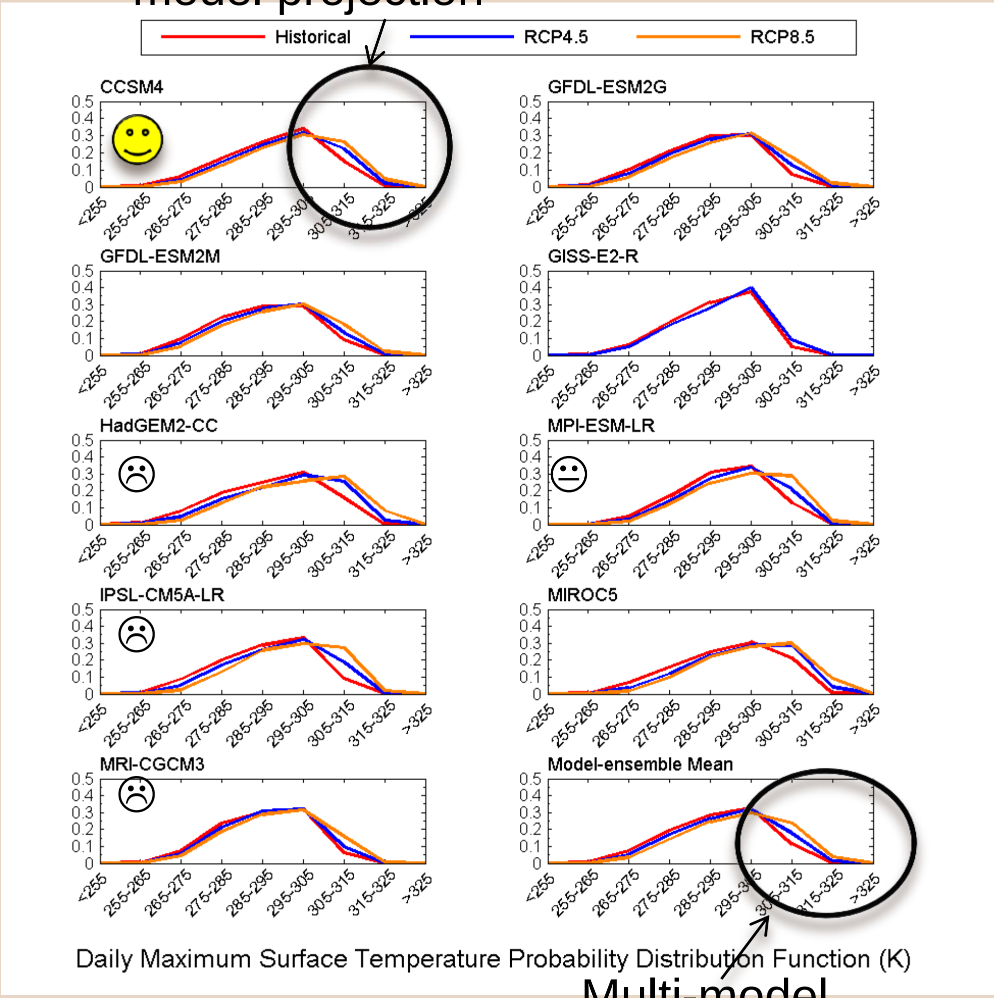
- ***CCSM4 appears to be the best performing model for the SC US region, mainly because of it qualitatively captures the observed SC US rainfall response to the global SST warming mode and large-scale circulation pattern.***

- ***HadGEM2-CC, IPSL and MRI appear to be least reliable models for the SC US due to their large uncertainties in***
  - ***Global SST warming mode and its relationship with SC US rainfall change***
  - ***Connection between ENSO and SC US rainfall anomalous***
  - ***Rainfall seasonality***

Projected change of Tmax during 2073-2099 relative to 1979-2005:

- *Models consistently project a disproportional increase of occurrence of high Tmax (>90F - 108F) by*
    - *25-50% under low emission (but unlikely RCP4.5) scenario (CO_2 reaches 650 ppm by 2100)*
    - *50-100% under high emission (business as usual, RCP8.5) scenario (CO_2 reaches 1350ppm by 2100)*
- *Less reliable models tend to project stronger increases of Tmax.*

Best performing model projection

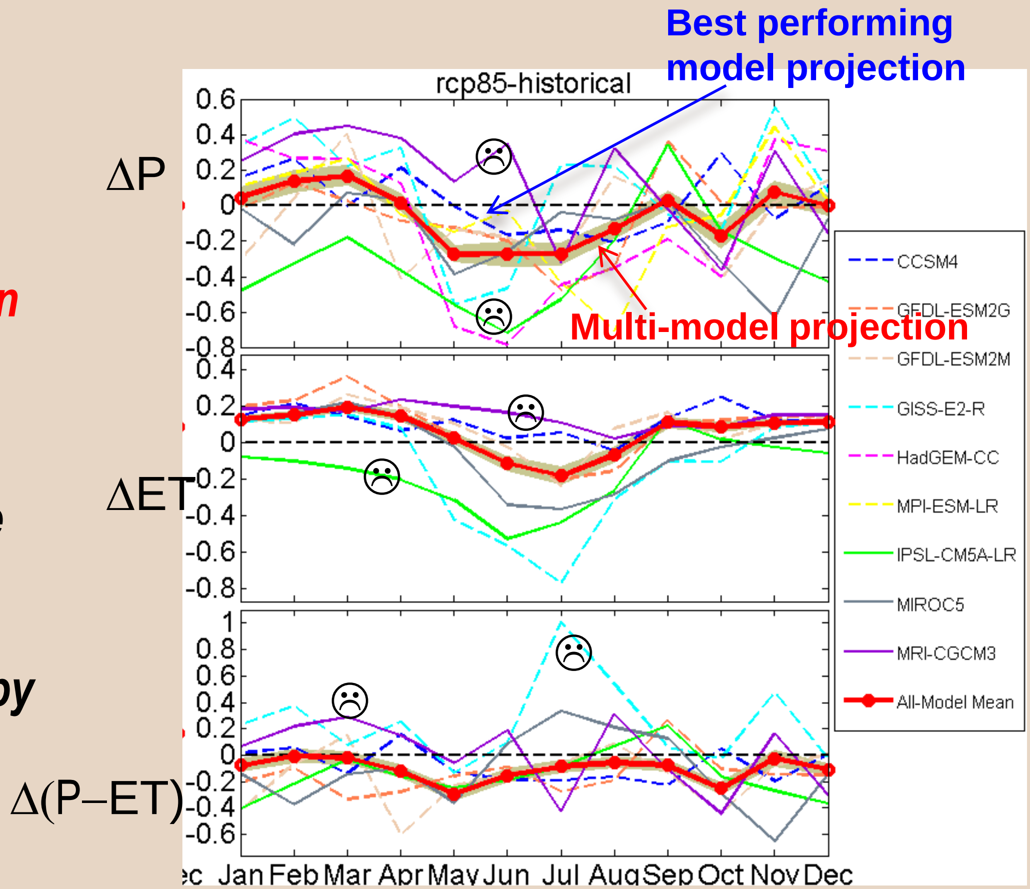


Multi-model ensemble projection

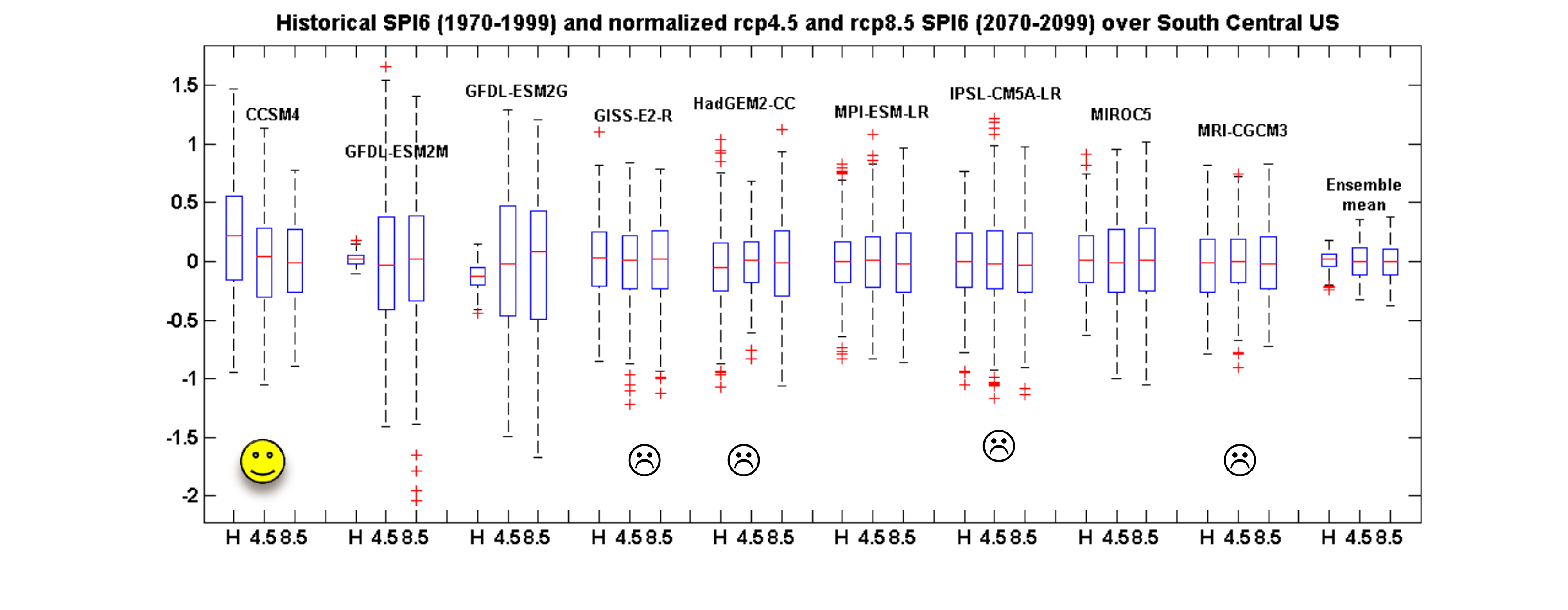
Projected change of surface net water flux in 2073-2099 relative to 1979-2005:

Under the high emission (RCP8.5) scenario:

- ***Both multi-models and best performing model project net drying, by ~20% of P-ET in spring and summer, despite differences in details.***
- ***Increase of rainfall (P) and ET during winter and spring, decrease of rainfall and ET in summer.***
- ***Net drying in spring is dominated by increase of ET, whereas drying in summer is dominated by decrease of P.***
- ***Outliners in projections tends to be the poor performing models.***



Projected change of drought index (SPI6)



Conclusions:

The 9 CMIP5 climate models we evaluated

- *Share common wet and cold biases, due to underestimate mid-tropospheric ridge in summer, the upper-level wind and westerly low-level winds in spring. Most of the models cannot adequately capture the variations of SC US rainfall with ENSO and the increase of global SST.*

- *Consistently project ~20% decrease of net P-ET (dry) in spring-summer by 2073-2099 relative to 1979-2005, under the RCP8.5, despite differences in details. However, the projections of extreme droughts and wet anomalies are still highly uncertain.*

- *Large ensemble numbers are needed to assess future changes of probability of extreme droughts (Deser et al. 2012).*

- *Communicate capability and uncertainty of the climate projections is an useful first step for supporting water resource planning.*

Ranking the models using our process-based metrics:

Response to increase of the global sea surface temperature

Surface conditions

Surface water budget and drought indices

Large-scale circulation

Connection with ENSO

Table 2: Ranking of model performance for SC US regional climate change

Variables	Models								
	CCSM4	GFDL-ESM2G	GFDL-ESM2M	GISS-E2-R	HadGEM2	MPI	IPSL	MIROC5	MRI
				Tier-1: Forced variability or change					
				Correlation with global SST warming:					
a_{GW}	1	3	1	3	2	3	3	3	3
GW_{SST}	2	1	3	1	3	2	2	3	2
Subtotal	1.5	2	2	2	2.5	2.5	2.5	3	2.5
				Seasonal cycle:					
Tmax	1	2	2	2	1	2	3	1	2
Tmin	2	1	1	1	3	1	3	2	1
q	1	1	2	1	3	1	3	1	1
Subtotal	1.3	1.3	1.7	1.3	2.3	1.3	3	1.3	1.3
PD_{Tmax}	3	3	3	3	3	3	3	3	2
PD_{RR}	2	2	2	2	2	2	2	2	1
P	1	3	3	2	3	1	2	2	3
ET	3	2	2	3	2	2	2	2	2
SPI6	2	2	2	2	2	2	2	2	2
SPI9	2	2	2	2	2	2	2	2	2
Subtotal	2.2	2.3	2.3	2.3	2.3	2	2.2	2.2	2
Z500	2	3	3	3	2	2	3	2	3
U850	1	2	2	2	2	1	1	2	2
V850	2	2	2	2	1	2	2	2	2
Subtotal	1.7	2.3	2.3	23	1.7	1.7	2	2	2.3
				Tier-2: natural variability					
$r_{p,Niño3}$	3	2	2	1	3	3	3	2	3
SZ500, Niño3	2	2	2	3	3	3	3	3	3
$r_{p,Niño4}$	3	2	2	1	3	3	3	2	3
SZ500, Niño4	2	2	2	3	3	3	3	2	3
Subtotal	2.5	2	2	2	3	3	3	2.3	3