Investigating Dependability of Water Supply in a Changing Climate
Lessons from a Collaborative Case Study

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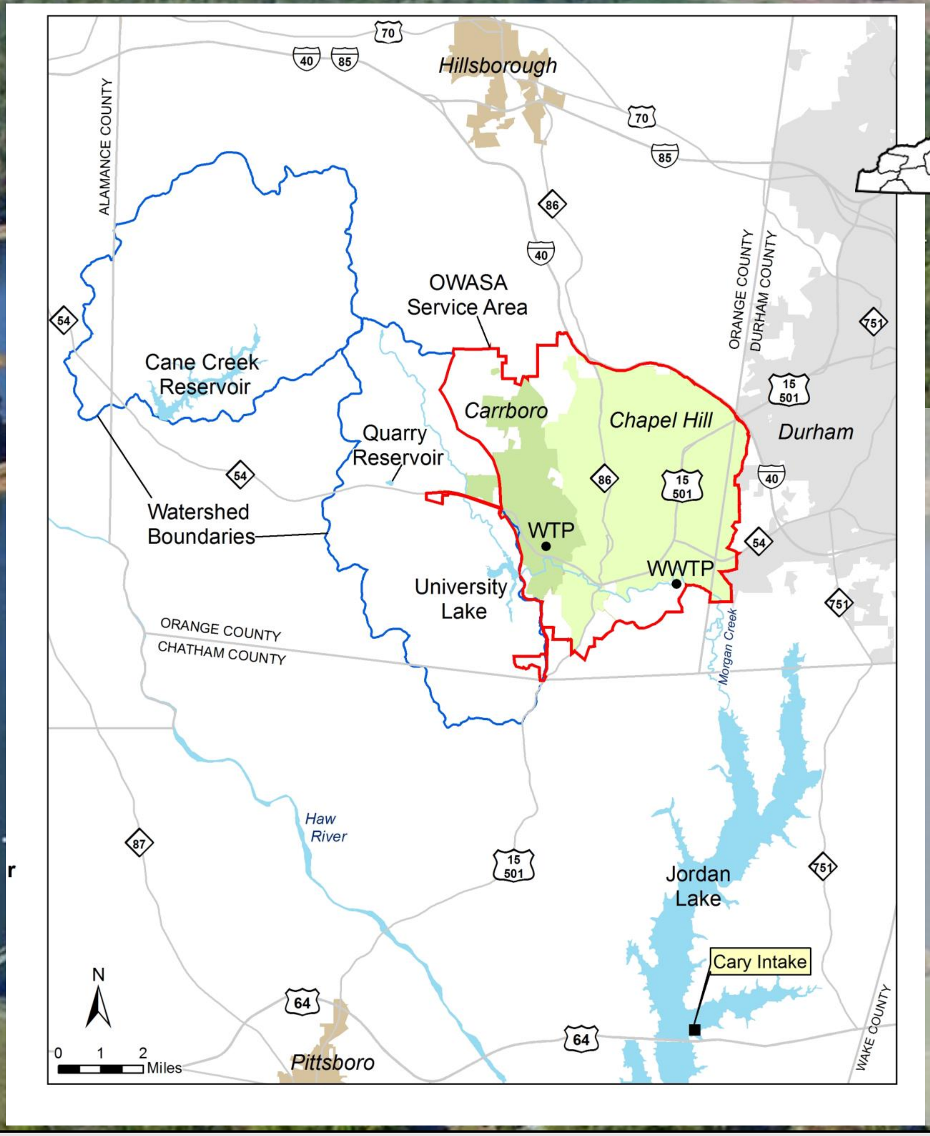
Ruth Rouse, Greg Carbone, Reed Palmer

Orange Water and Sewer Authority



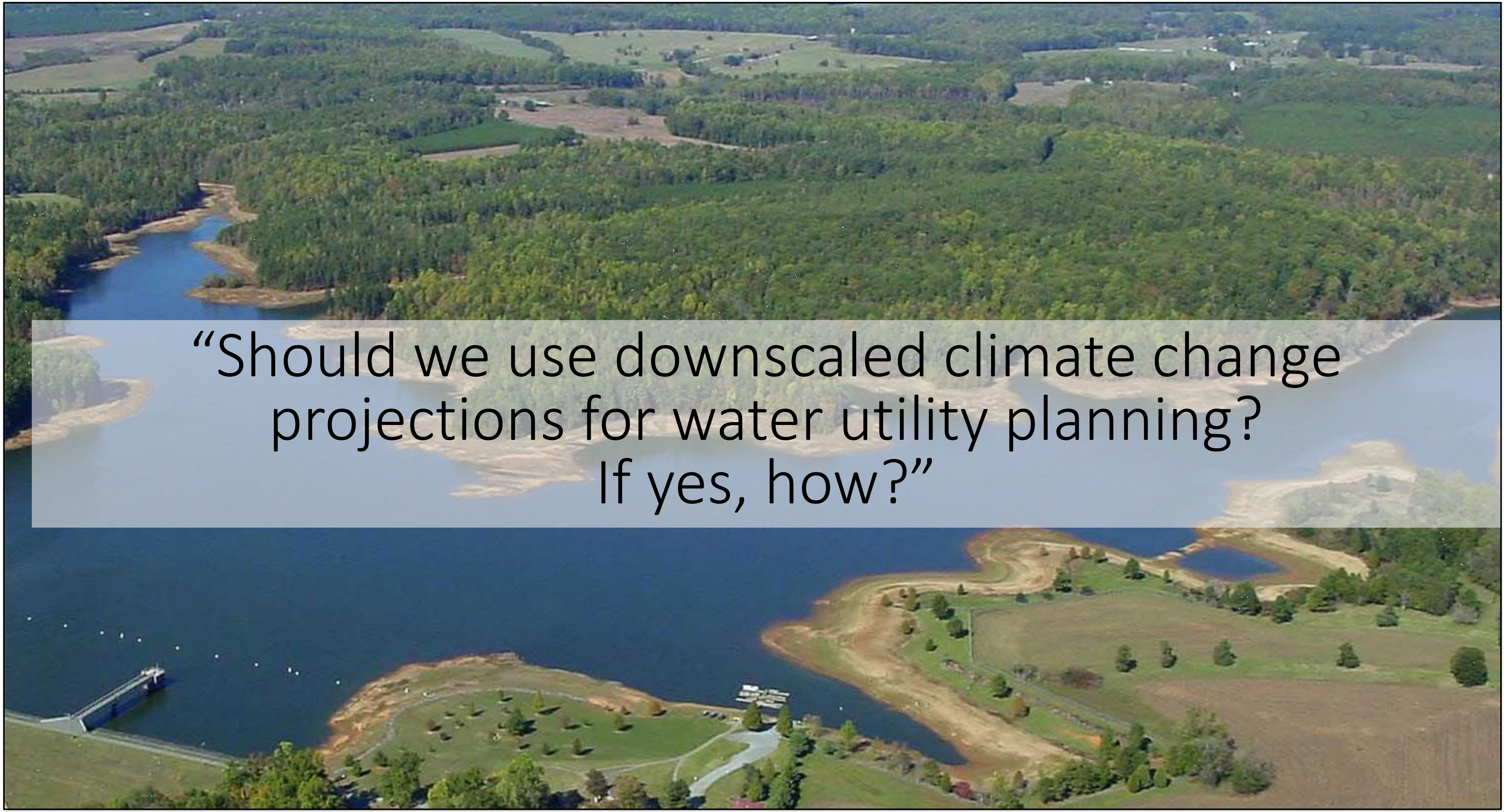
Current Capacity: 3.66 BG

Capacity in 2035: 4.85 BG

Demand in 2015: ~ 6.9 mgd

Allocation of 5% water supply pool of Jordan Lake

Long-range water supply plan update in 2016-2017



“Should we use downscaled climate change projections for water utility planning?
If yes, how?”

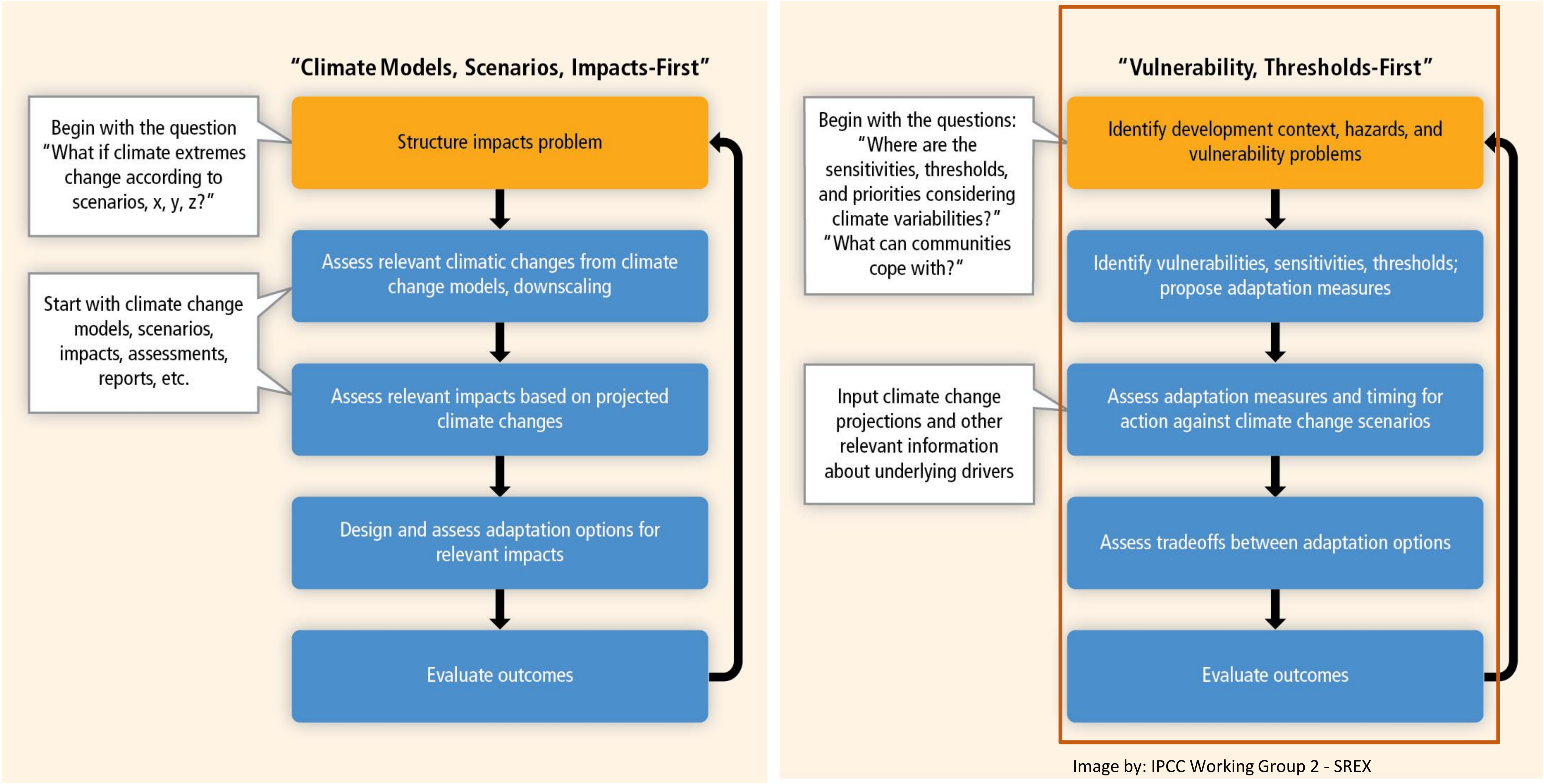
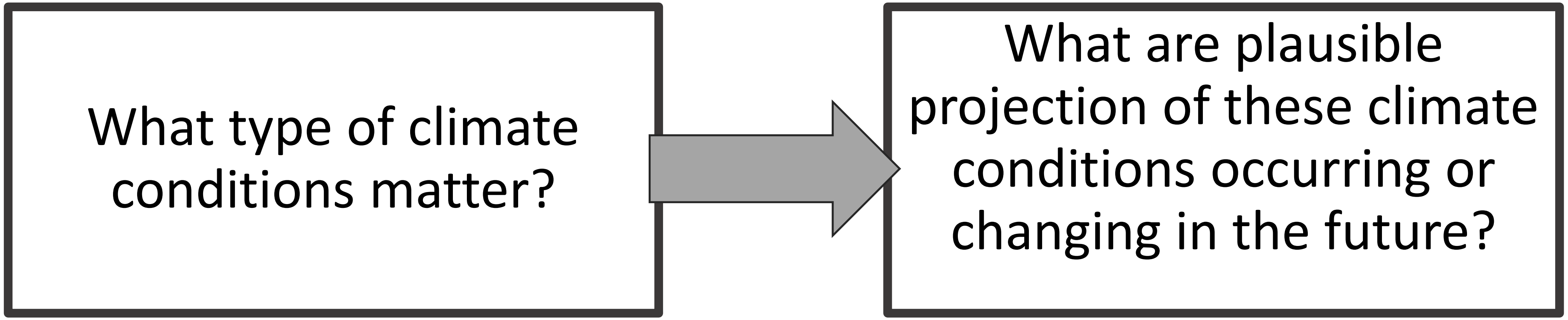


Image by: IPCC Working Group 2 - SREX



Decision-Centric Approach

What type of climate conditions matter?

1. Planning-relevant metrics

1. 'Firm/Reliable Yield'

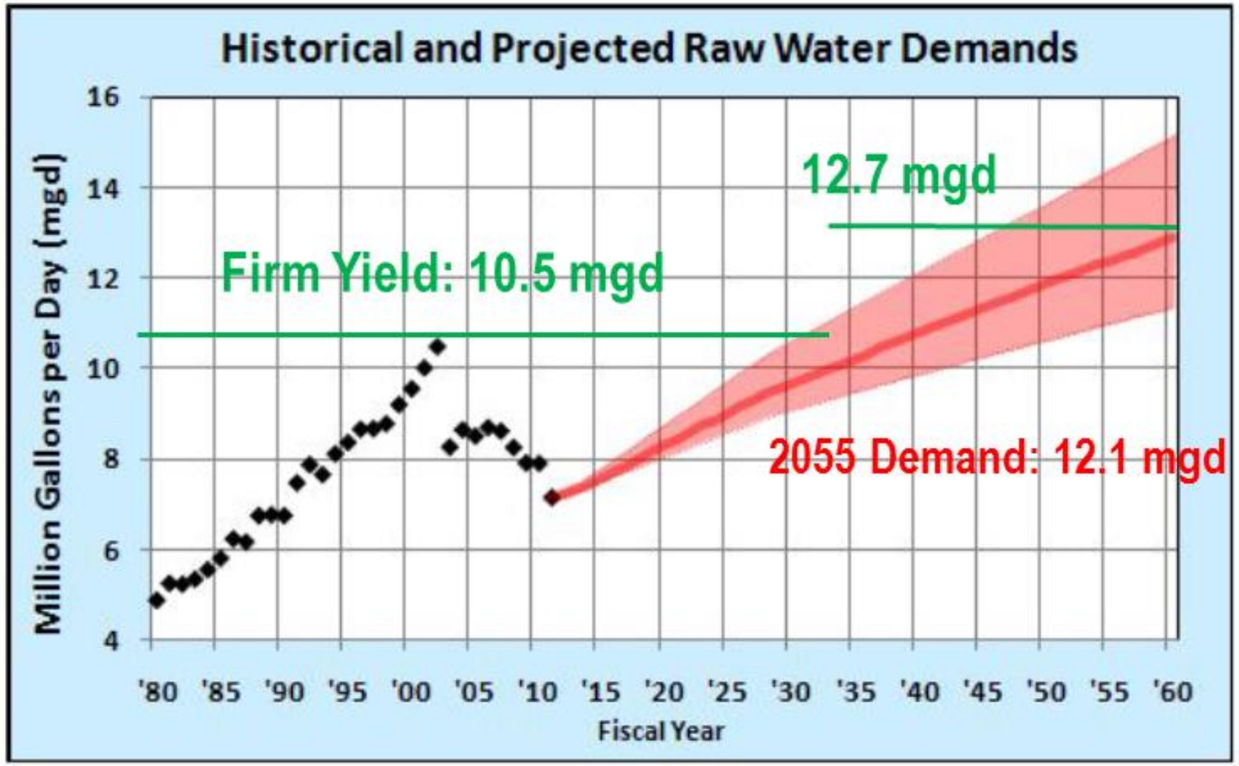
maximum quantity of water that could've been supplied daily throughout the 2002 drought-of-record, while reserving 20% emergency storage

current demand << firm yield

With expanded Quarry Reservoir in 2035,

proj. demand in 2055 < firm yield

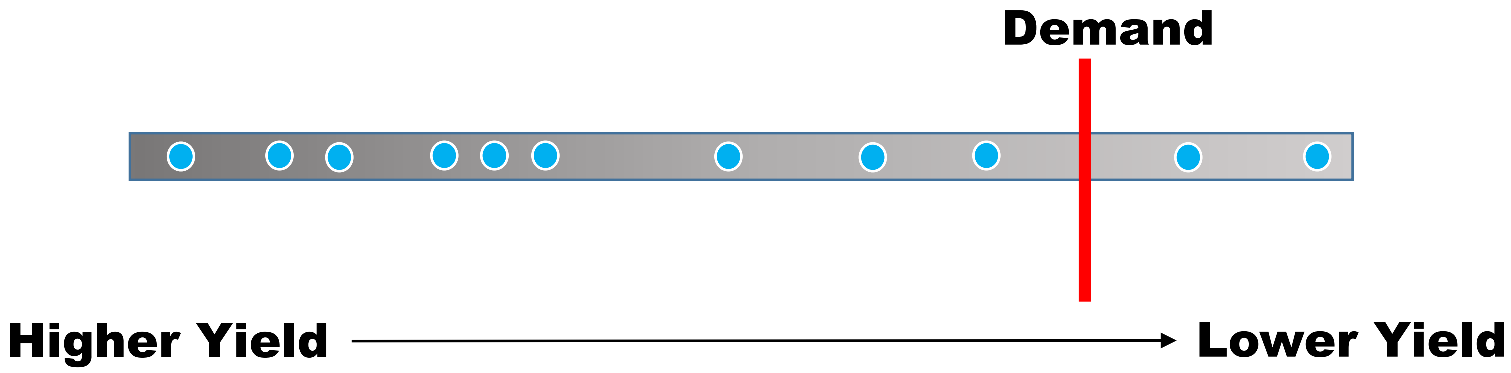
2. Reservoir Storage



Q: "How will climate change affect our firm yield through next 50 years?"

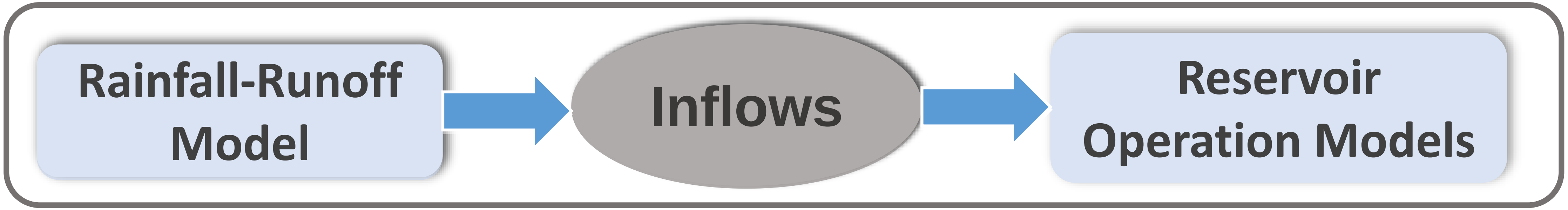
What type of climate conditions matter?

1. <u>Planning-relevant metrics and **their decision-relevant thresholds**</u>



What type of changes in climate matter?

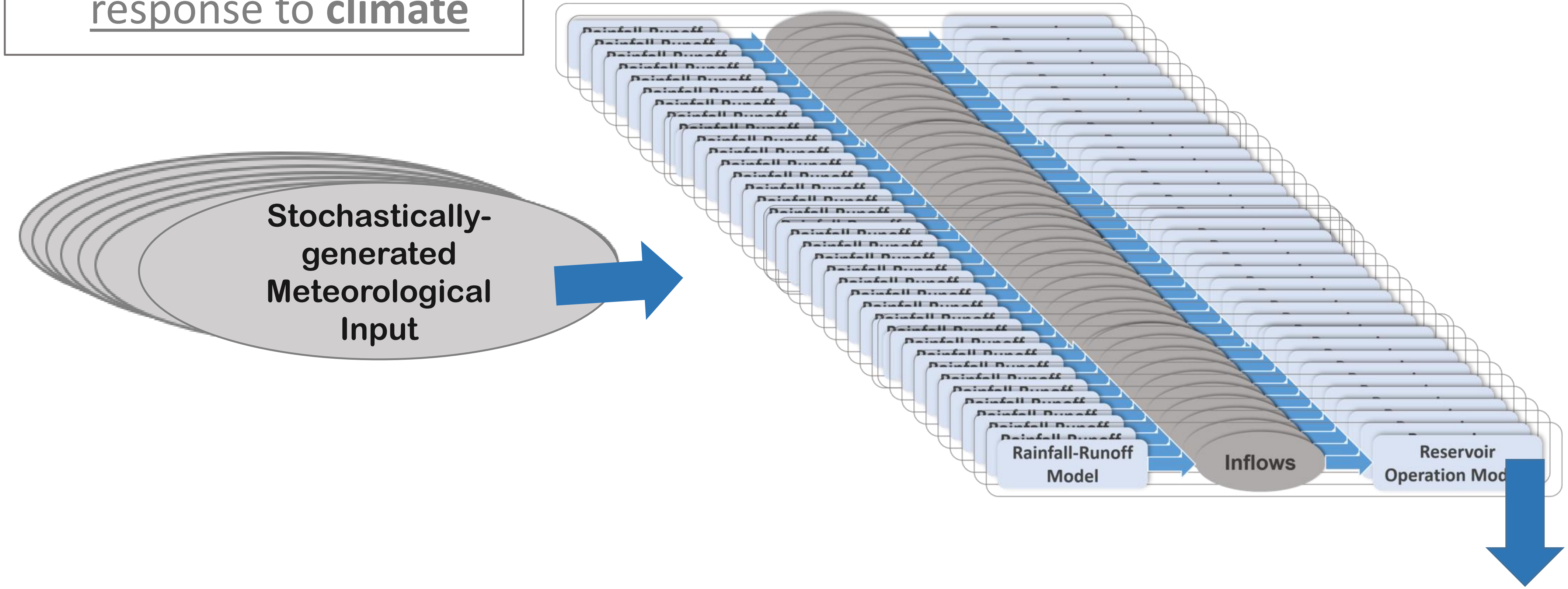
2. Model Set-up



Provided by
Reed Palmer
@Hazen & Sawyer

What type of changes in climate matter?

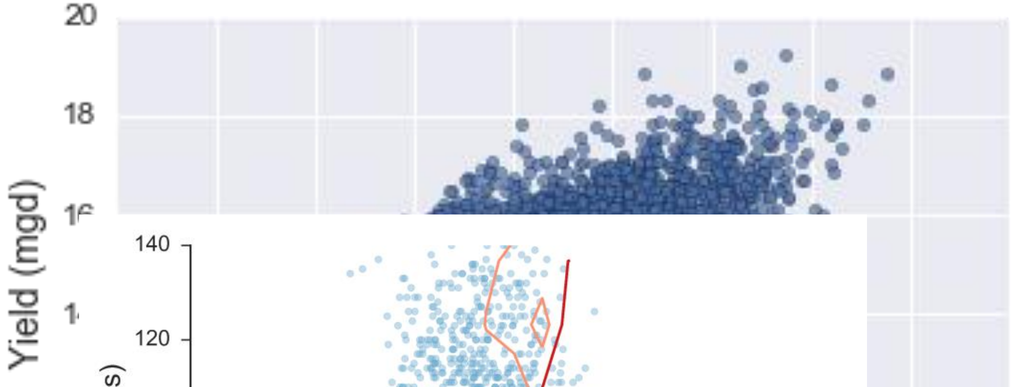
3. Simulating system response to **climate**

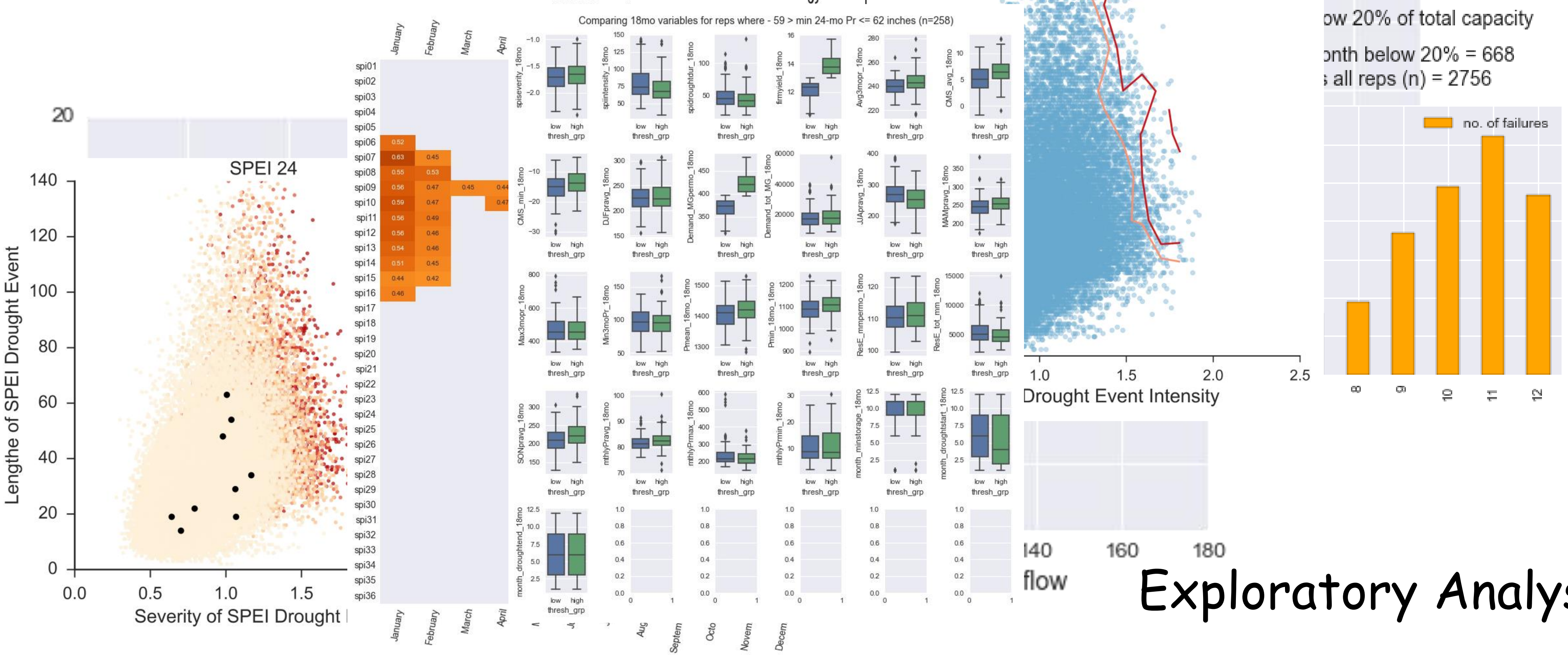


System Performance in a wide range of climate conditions

What type of changes in climate matter?

3. Identifying Key Climate Variables that Drive Reservoir Performance

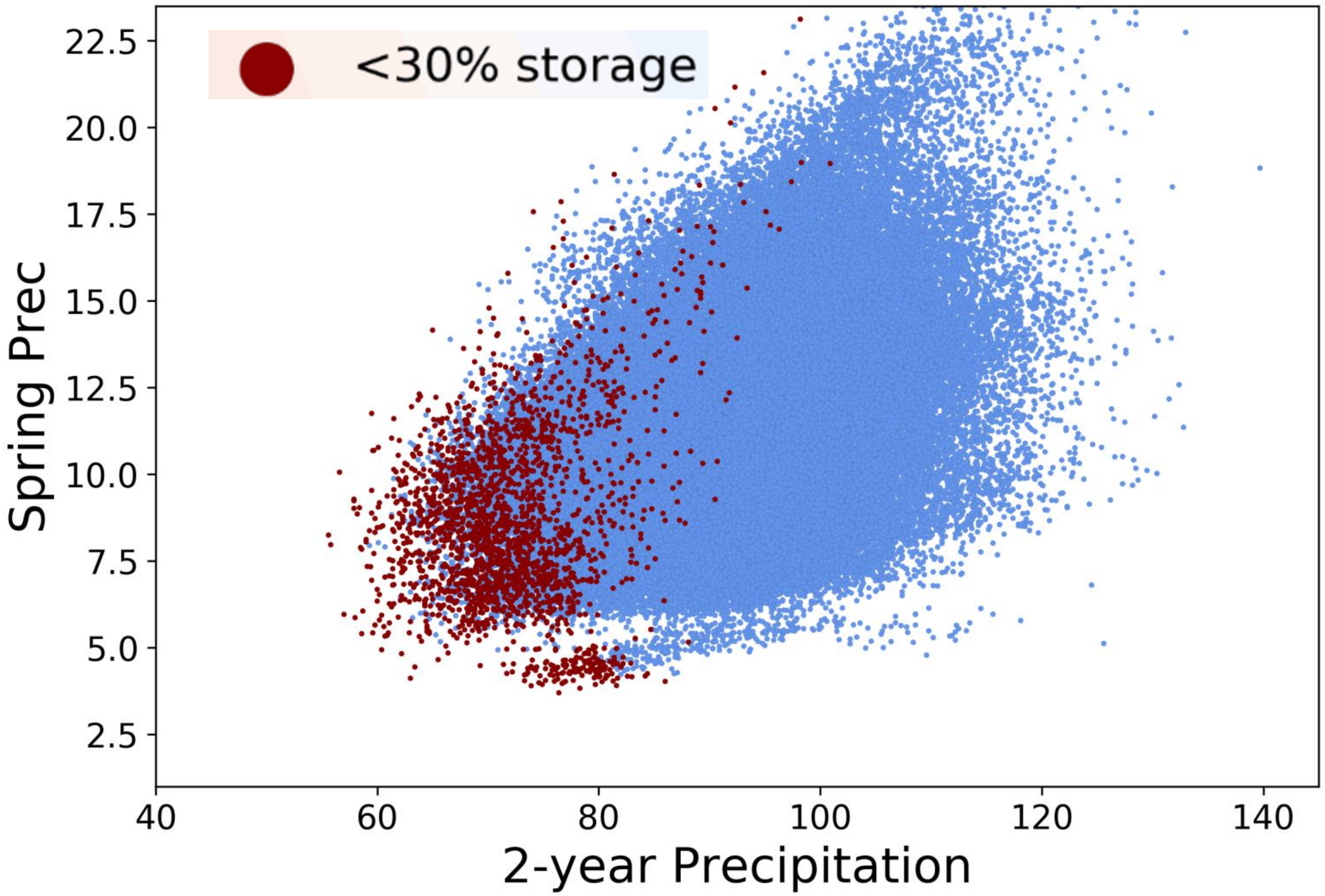




Exploratory Analysis!

What type of changes in climate matter?

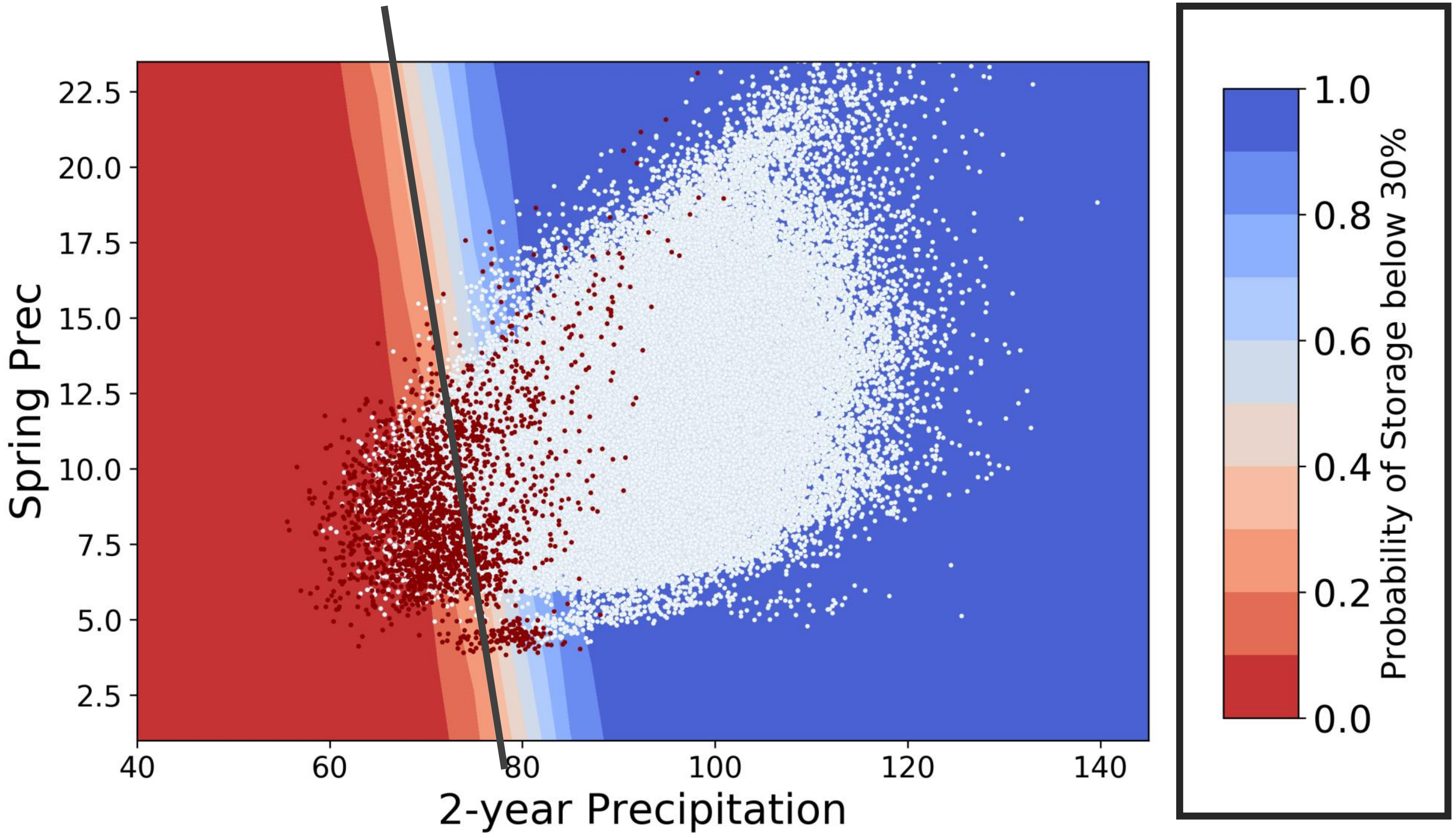
3. <u>Identifying Key Climate Variables that Drive Reservoir Performance</u>



What type of climate conditions matter?

4. Identifying Critical Climate Conditions

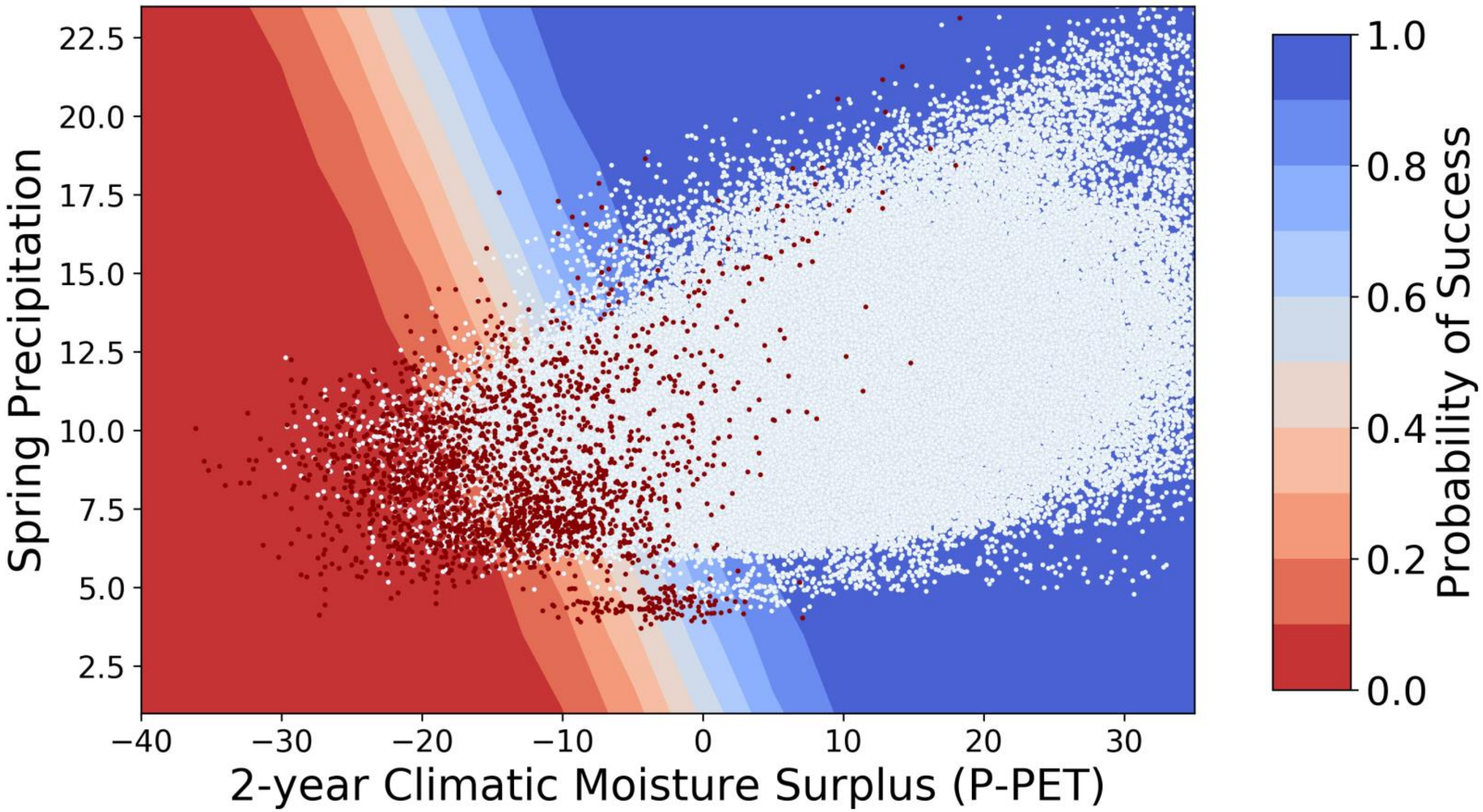
Logistic Regression



What type of climate conditions matter?

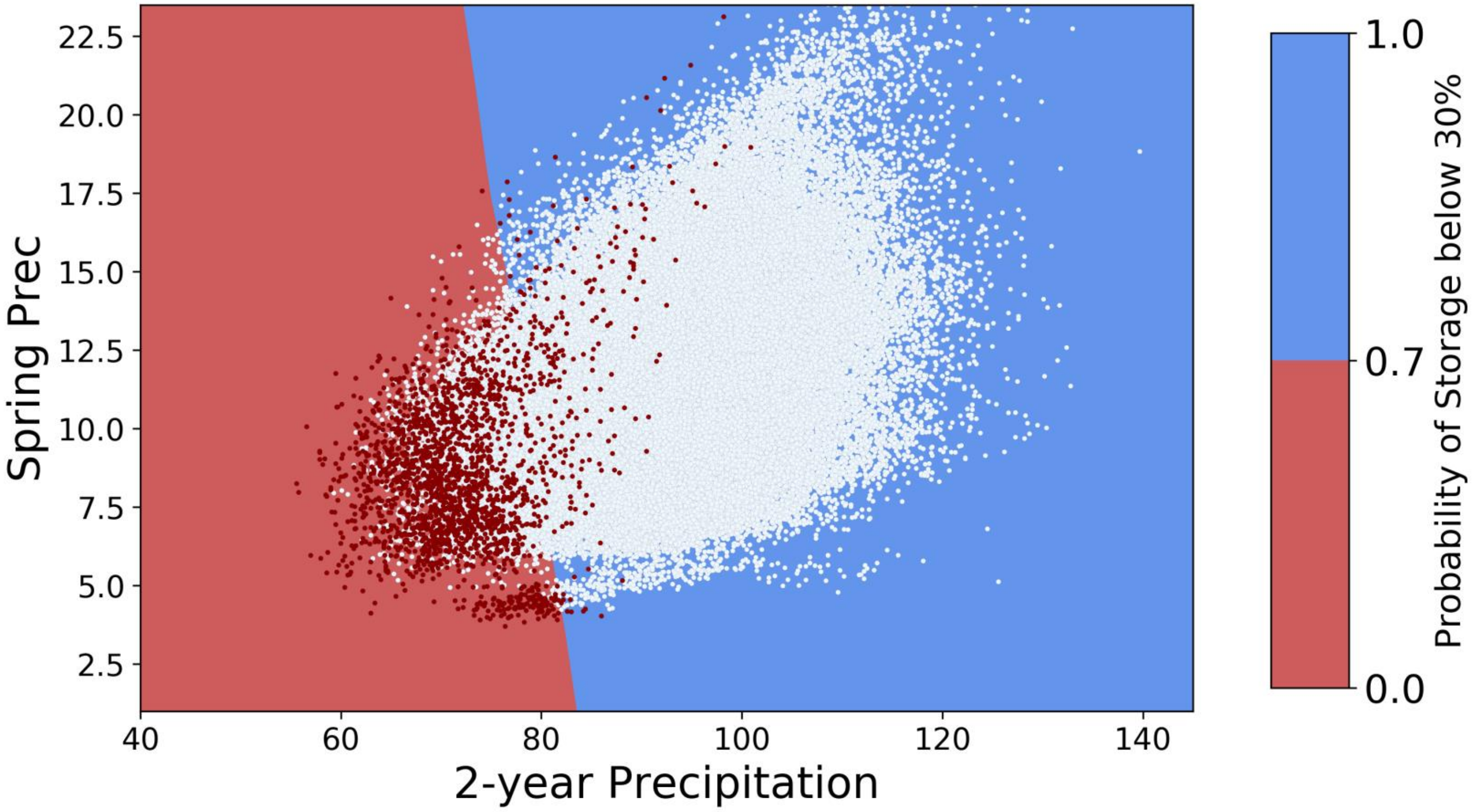
3. Identifying Key Climate Variables

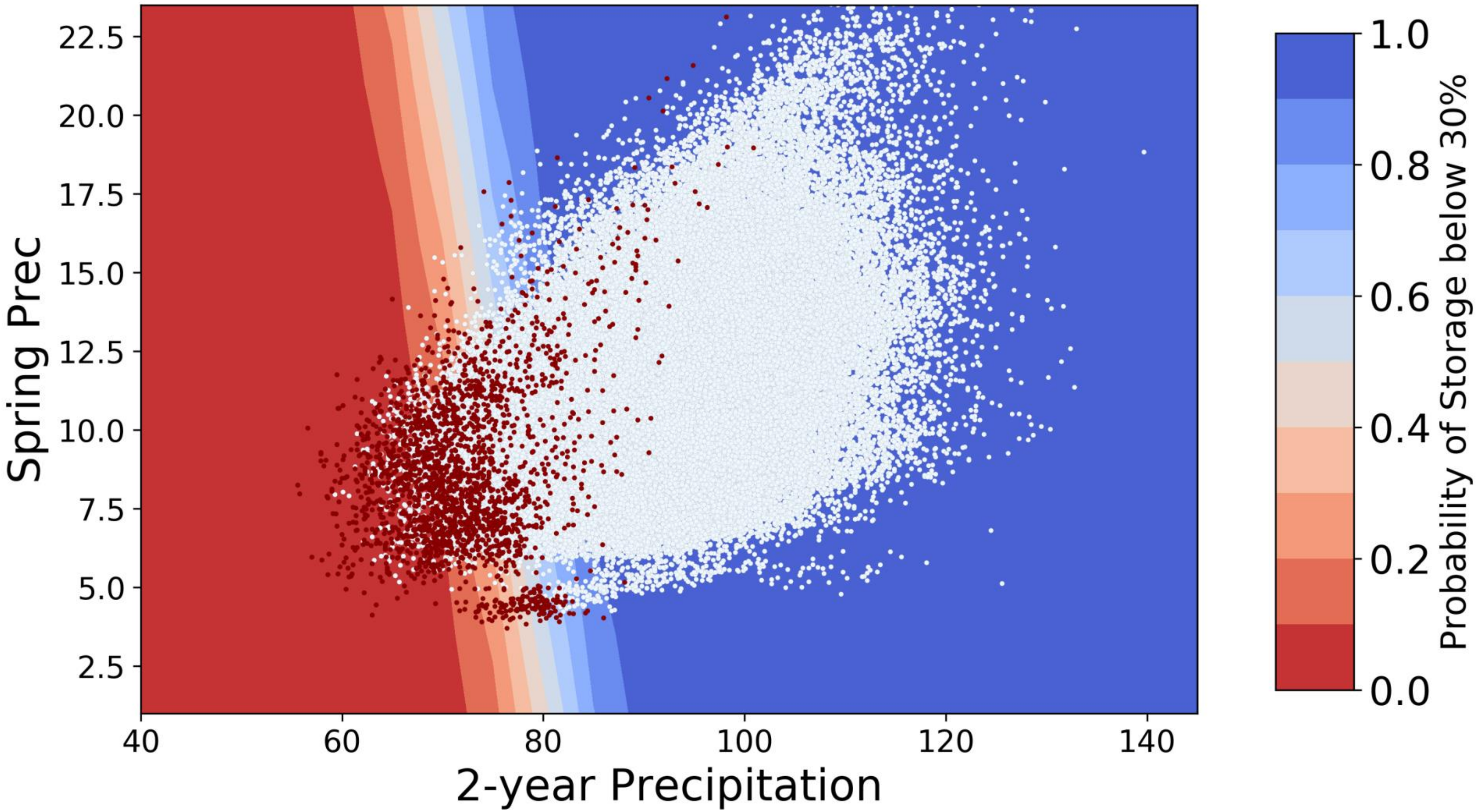
Incorporating Temperature….

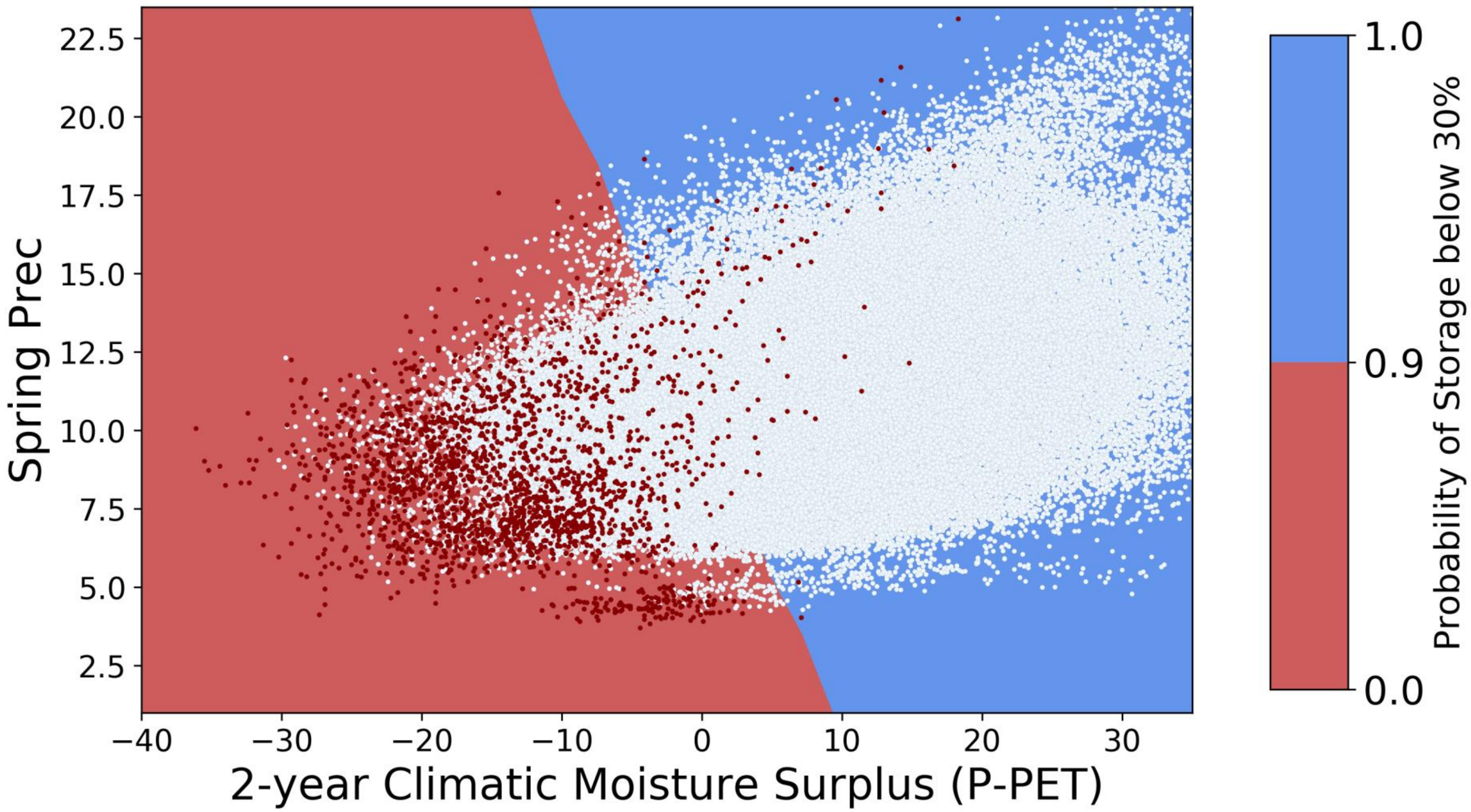


What type of climate conditions matter?

4. Defining **Critical Climate Exposure Space**

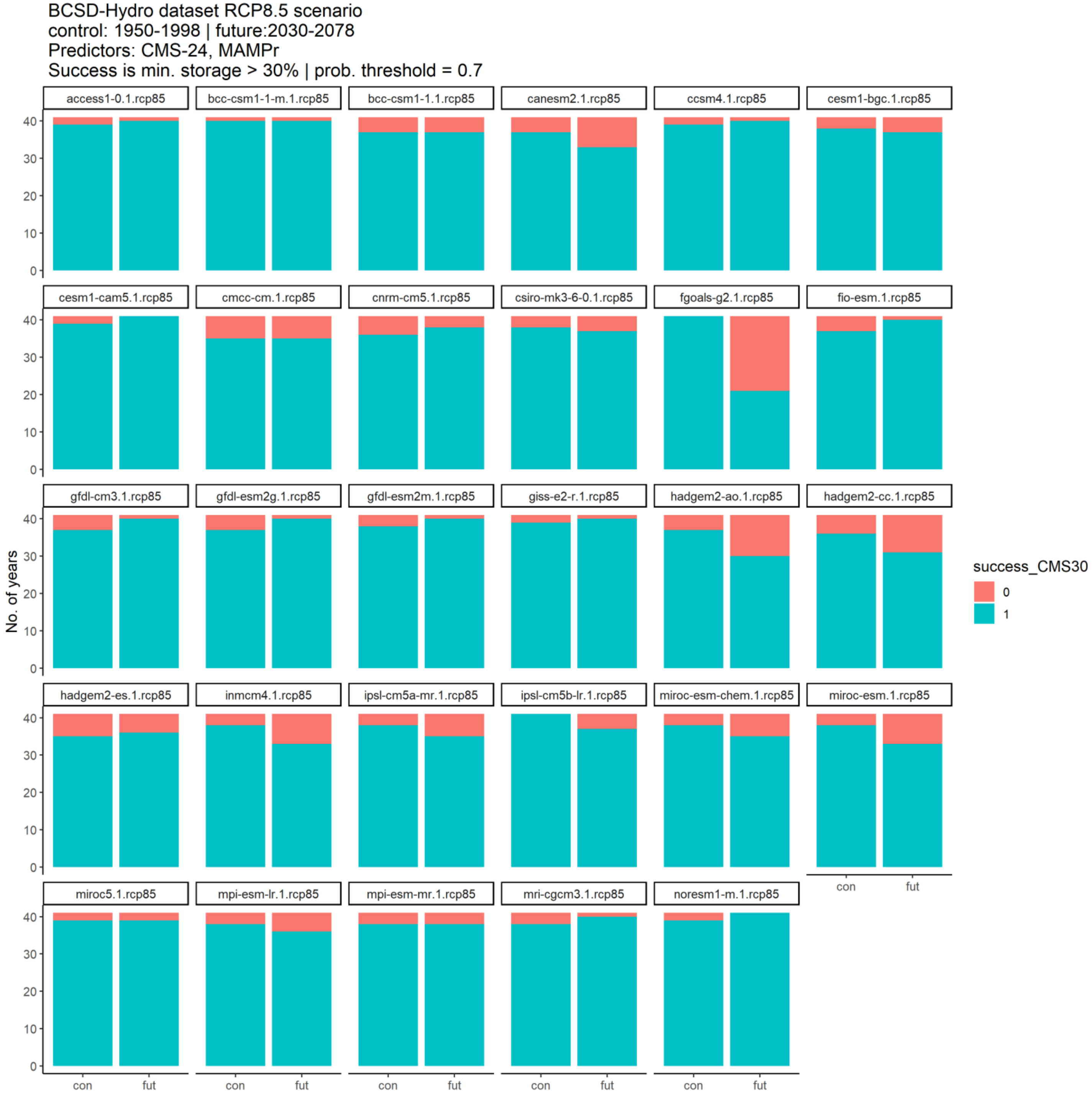



Spring Prec
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
40
60
80
100
120
140
2-year Precipitation
Probability of Storage below 30%
1.0
0.8
0.6
0.4
0.2
0.0



22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
Spring Prec
−40
−30
−20
−10
0
10
20
30
2-year Climatic Moisture Surplus (P-PET)
1.0
0.9
0.0
Probability of Storage below 30%

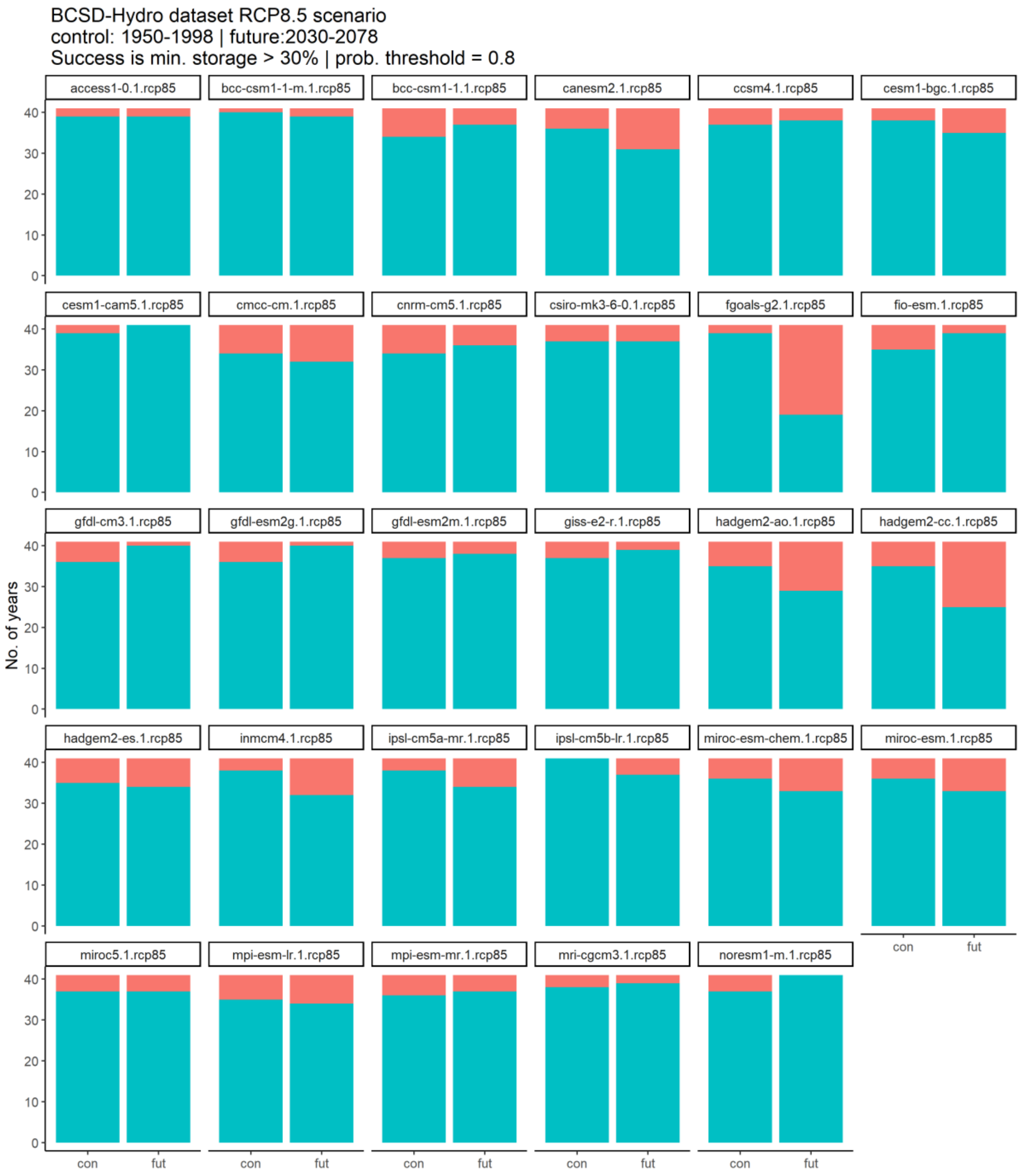
What are plausible projection of these climate conditions occurring or changing in the future?

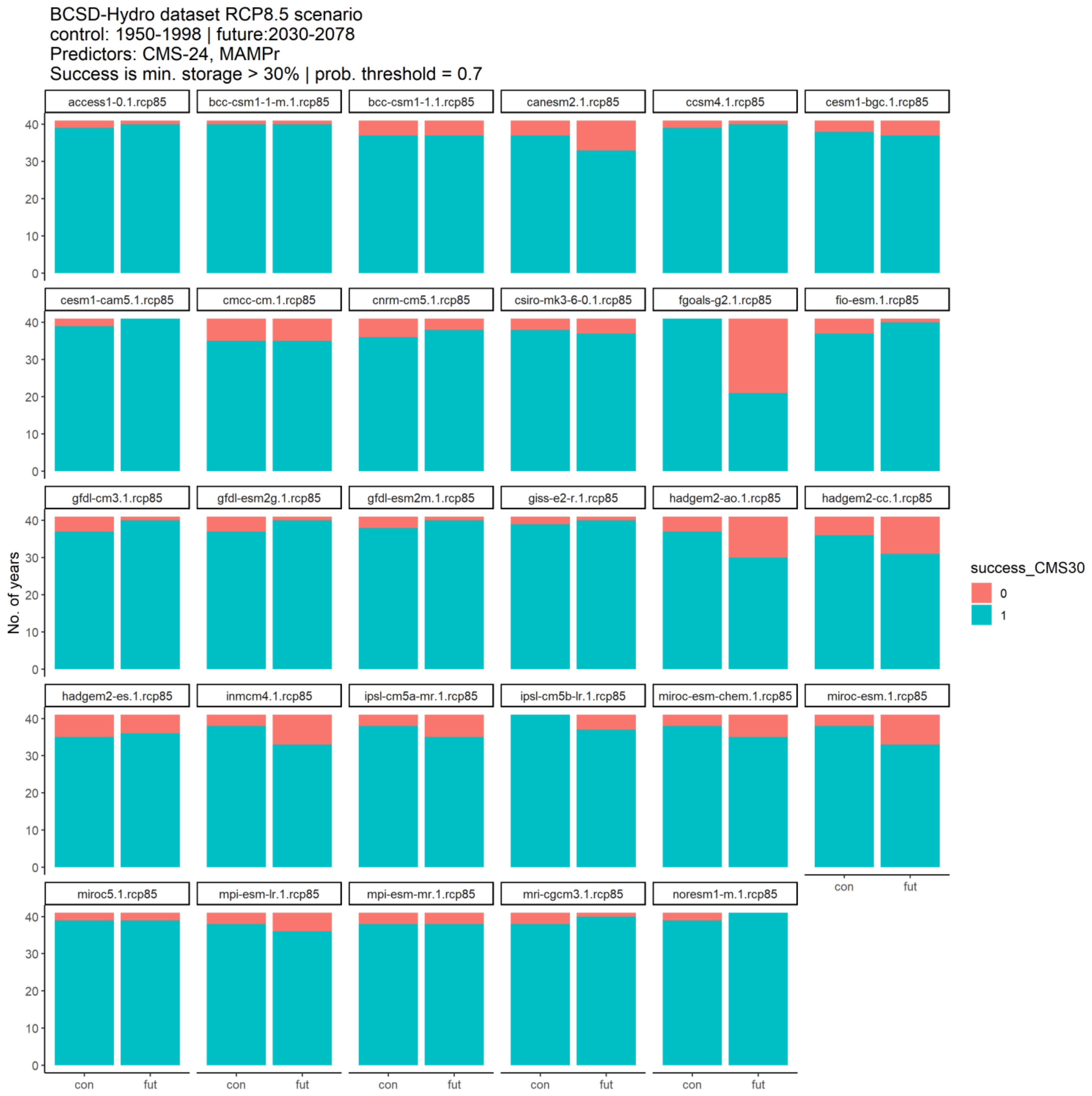

BCSD-Hydro dataset RCP8.5 scenario
control: 1950-1998 | future:2030-2078
Predictors: CMS-24, MAMPr
Success is min. storage > 30% | prob. threshold = 0.7
access1-0.1.rcp85
bcc-csm1-1-m.1.rcp85
bcc-csm1-1.1.rcp85
canesm2.1.rcp85
ccsm4.1.rcp85
cesm1-bgc.1.rcp85
cesm1-cam5.1.rcp85
cmcc-cm.1.rcp85
cnrm-cm5.1.rcp85
csiro-mk3-6-0.1.rcp85
fgoals-g2.1.rcp85
fio-esm.1.rcp85
gfdl-cm3.1.rcp85
gfdl-esm2g.1.rcp85
gfdl-esm2m.1.rcp85
giss-e2-r.1.rcp85
hadgem2-ao.1.rcp85
hadgem2-cc.1.rcp85
hadgem2-es.1.rcp85
inmcm4.1.rcp85
ipsl-cm5a-mr.1.rcp85
ipsl-cm5b-lr.1.rcp85
miroc-esm-chem.1.rcp85
miroc-esm.1.rcp85
miroc5.1.rcp85
mpi-esm-lr.1.rcp85
mpi-esm-mr.1.rcp85
mri-cgcm3.1.rcp85
noresm1-m.1.rcp85
No. of years
0
10
20
30
40
con
fut
success_CMS30
0
1

What are plausible projection of these climate conditions occurring or changing in the future?

1. Do Processing Decisions like Thresholds and Predictor Variables Matter?

i.e., do these choices significantly alter the main conclusions?


BCSD-Hydro dataset RCP8.5 scenario
control: 1950-1998 | future:2030-2078
Success is min. storage > 30% | prob. threshold = 0.8
access1-0.1.rcp85
bcc-csm1-1-m.1.rcp85
bcc-csm1-1.1.rcp85
canesm2.1.rcp85
ccsm4.1.rcp85
cesm1-bgc.1.rcp85
cesm1-cam5.1.rcp85
cmcc-cm.1.rcp85
cnrm-cm5.1.rcp85
csiro-mk3-6-0.1.rcp85
fgoals-g2.1.rcp85
fio-esm.1.rcp85
gfdl-cm3.1.rcp85
gfdl-esm2g.1.rcp85
gfdl-esm2m.1.rcp85
giss-e2-r.1.rcp85
hadgem2-ao.1.rcp85
hadgem2-cc.1.rcp85
hadgem2-es.1.rcp85
inmcm4.1.rcp85
ipsl-cm5a-mr.1.rcp85
ipsl-cm5b-lr.1.rcp85
miroc-esm-chem.1.rcp85
miroc-esm.1.rcp85
miroc5.1.rcp85
mpi-esm-lr.1.rcp85
mpi-esm-mr.1.rcp85
mri-cgcm3.1.rcp85
noresm1-m.1.rcp85
No. of years
0
10
20
30
40
con
fut


BCSD-Hydro dataset RCP8.5 scenario
control: 1950-1998 | future:2030-2078
Predictors: CMS-24, MAMPr
Success is min. storage > 30% | prob. threshold = 0.7
access1-0.1.rcp85
bcc-csm1-1-m.1.rcp85
bcc-csm1-1.1.rcp85
canesm2.1.rcp85
ccsm4.1.rcp85
cesm1-bgc.1.rcp85
cesm1-cam5.1.rcp85
cmcc-cm.1.rcp85
cnrm-cm5.1.rcp85
csiro-mk3-6-0.1.rcp85
fgoals-g2.1.rcp85
fio-esm.1.rcp85
gfdl-cm3.1.rcp85
gfdl-esm2g.1.rcp85
gfdl-esm2m.1.rcp85
giss-e2-r.1.rcp85
hadgem2-ao.1.rcp85
hadgem2-cc.1.rcp85
hadgem2-es.1.rcp85
inmcm4.1.rcp85
ipsl-cm5a-mr.1.rcp85
ipsl-cm5b-lr.1.rcp85
miroc-esm-chem.1.rcp85
miroc-esm.1.rcp85
miroc5.1.rcp85
mpi-esm-lr.1.rcp85
mpi-esm-mr.1.rcp85
mri-cgcm3.1.rcp85
noresm1-m.1.rcp85
No. of years
0
10
20
30
40
con
fut
success_CMS30
0
1

BCSD-Hydro dataset RCP8.5 scenario
control: 1950-1998 | future:2030-2078
Success is min. storage > 30% | prob. threshold = 0.8
No. of years
success_(
0
1
con
fut

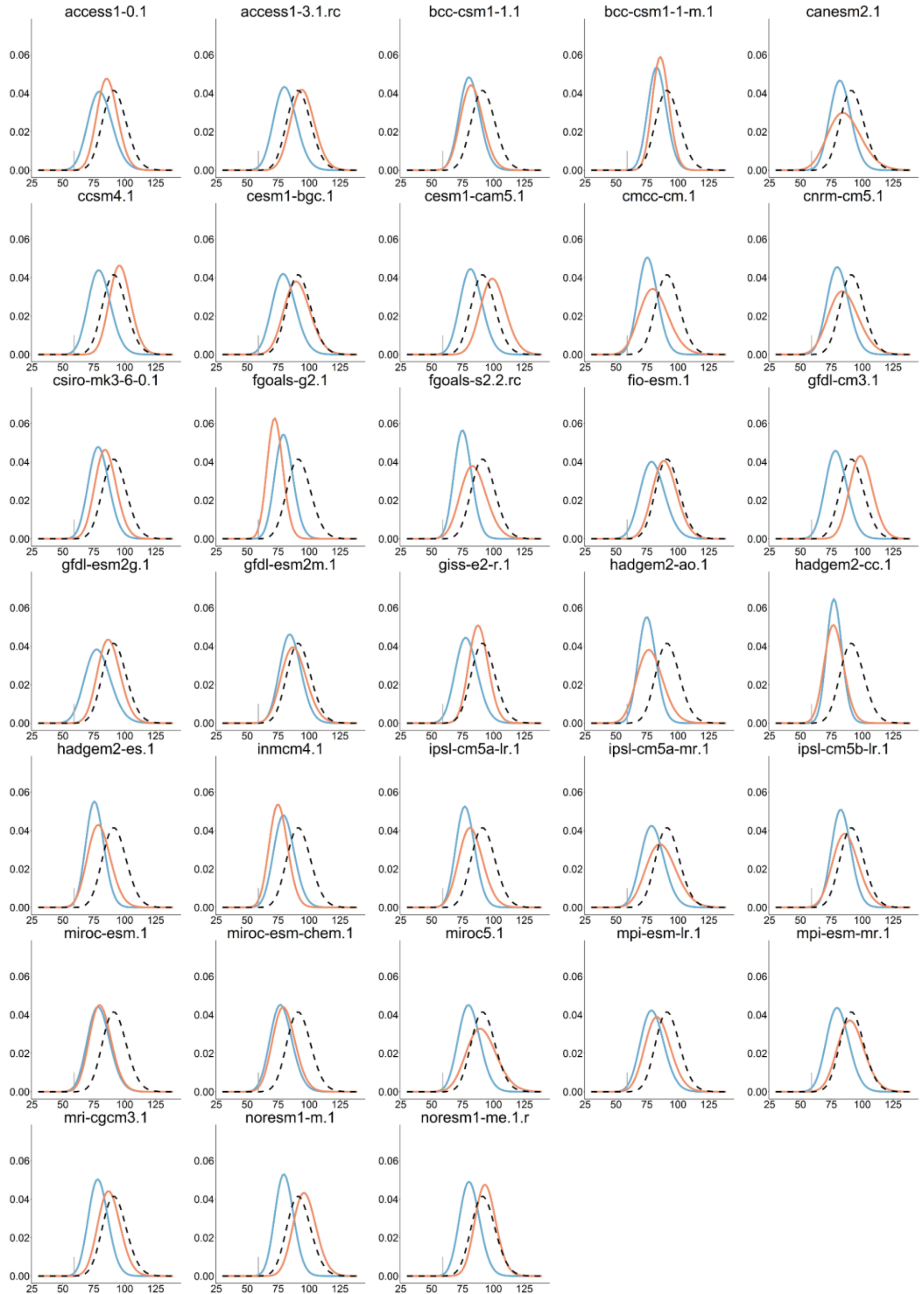
BCSD-Hydro dataset RCP8.5 scenario
control: 1950-1998 | future:2030-2078
Success is min. storage > 30% | prob. threshold = 0.8
No. of years
success_CMS3
0
1
con
fut

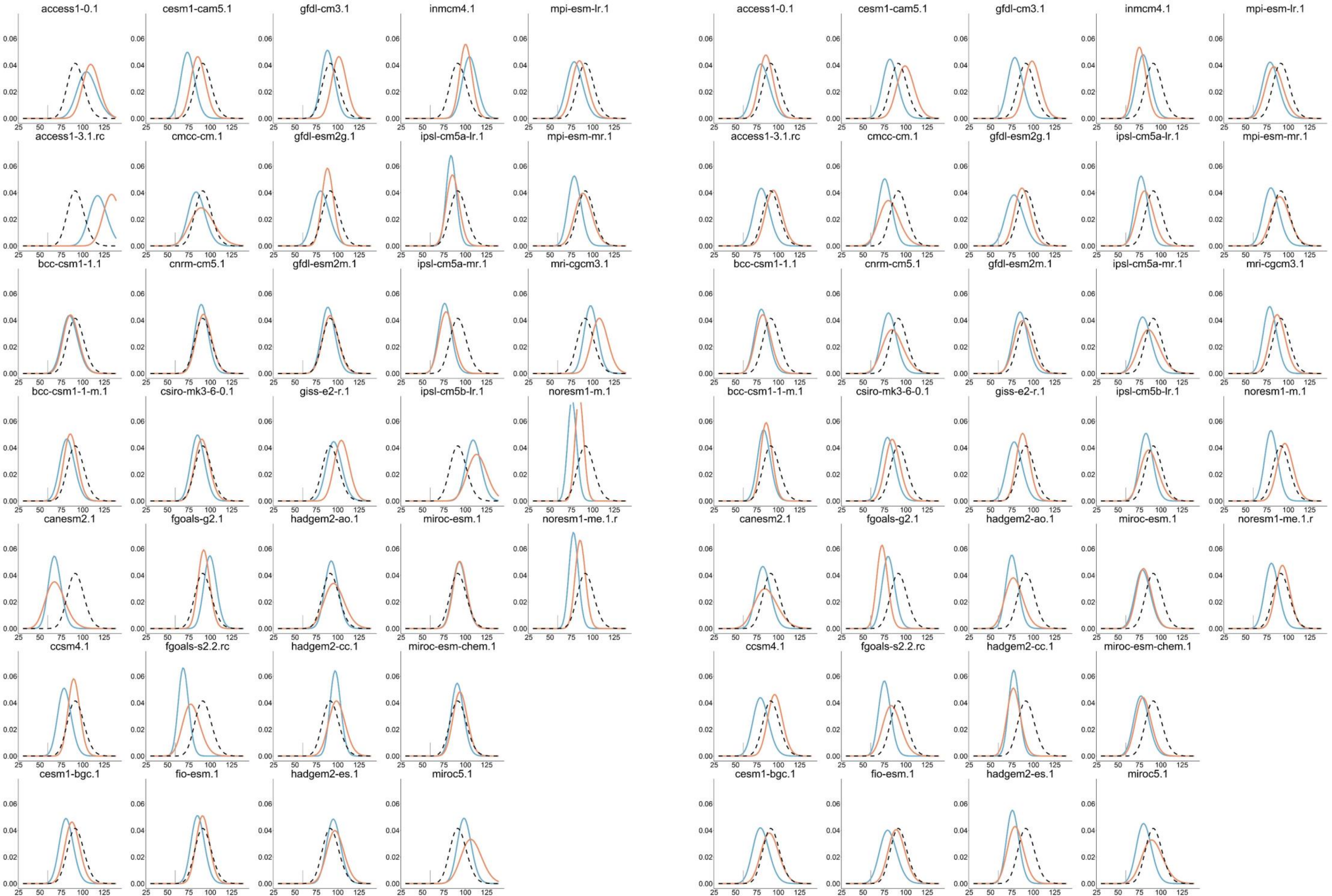
What are plausible projection of these climate conditions occurring or changing in the future?

2. How well do climate models simulate multi-year persistent dry periods?

What are plausible projection of these climate conditions occurring or changing in the future?

How well do climate models simulate multi-year persistent dry periods?



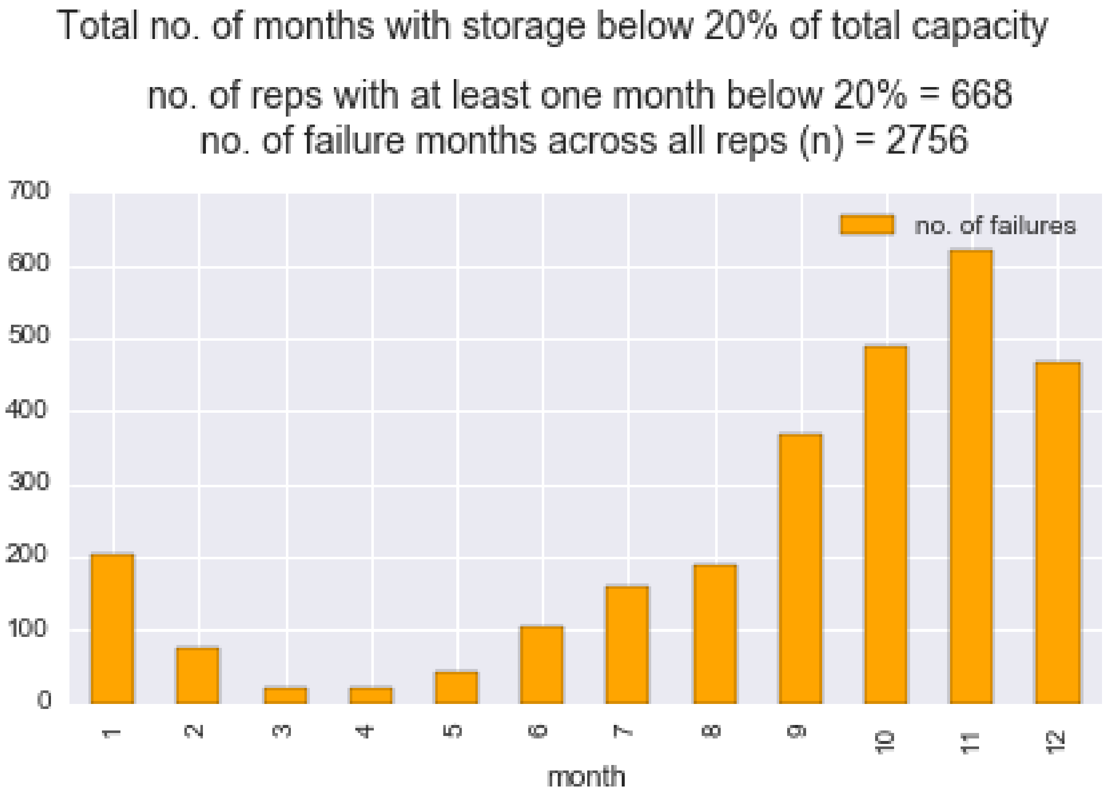

access1-0.1
cesm1-cam5.1
gfdl-cm3.1
inmcm4.1
mpi-esm-lr.1
access1-3.1.rc
cmcc-cm.1
gfdl-esm2g.1
ipsl-cm5a-lr.1
mpi-esm-mr.1
bcc-csm1-1.1
cnrm-cm5.1
gfdl-esm2m.1
ipsl-cm5a-mr.1
mri-cgcm3.1
bcc-csm1-1-m.1
csiro-mk3-6-0.1
giss-e2-r.1
ipsl-cm5b-lr.1
noresm1-m.1
canesm2.1
fgoals-g2.1
hadgem2-ao.1
miroc-esm.1
noresm1-me.1.r
ccsm4.1
fgoals-s2.2.rc
hadgem2-cc.1
miroc-esm-chem.1
cesm1-bgc.1
fio-esm.1
hadgem2-es.1
miroc5.1
access1-0.1
cesm1-cam5.1
gfdl-cm3.1
inmcm4.1
mpi-esm-lr.1
access1-3.1.rc
cmcc-cm.1
gfdl-esm2g.1
ipsl-cm5a-lr.1
mpi-esm-mr.1
bcc-csm1-1.1
cnrm-cm5.1
gfdl-esm2m.1
ipsl-cm5a-mr.1
mri-cgcm3.1
bcc-csm1-1-m.1
csiro-mk3-6-0.1
giss-e2-r.1
ipsl-cm5b-lr.1
noresm1-m.1
canesm2.1
fgoals-g2.1
hadgem2-ao.1
miroc-esm.1
noresm1-me.1.r
ccsm4.1
fgoals-s2.2.rc
hadgem2-cc.1
miroc-esm-chem.1
cesm1-bgc.1
fio-esm.1
hadgem2-es.1
miroc5.1

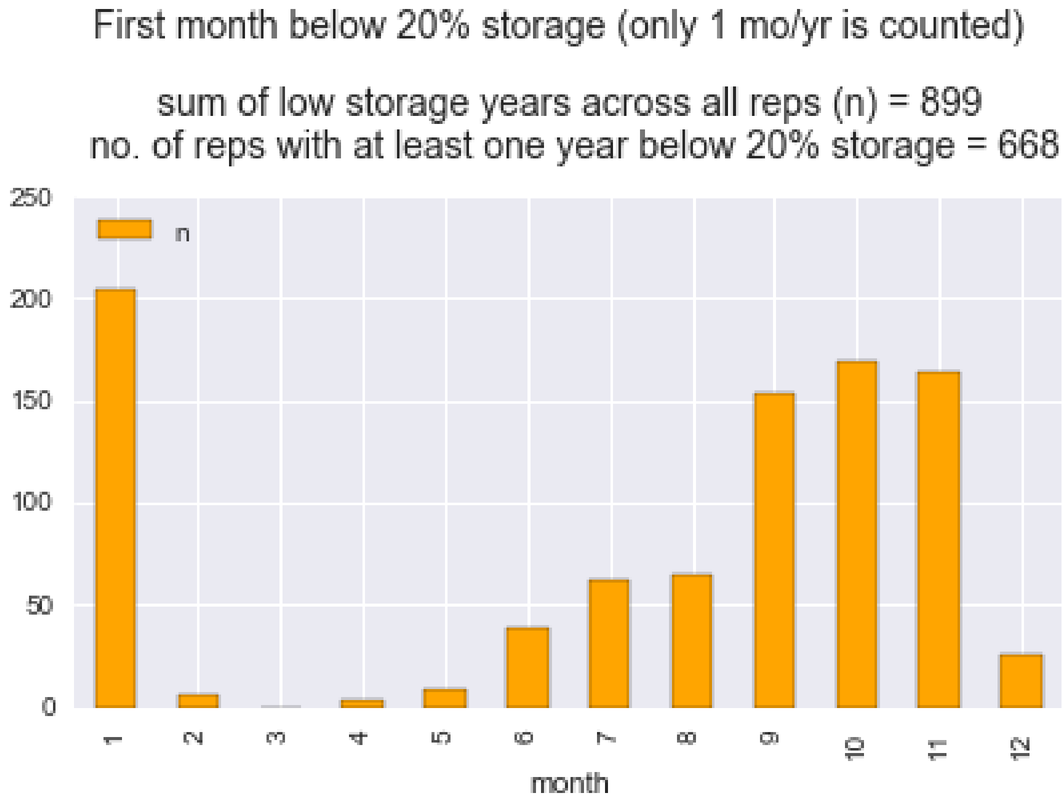
- Focusing on OWASA’s planning context and system first
- Focusing climate change analysis on conditions that threaten water supply dependability
- Making transparent the analysis of future projections
- Focusing on decision-relevance of uncertainty in climate projections

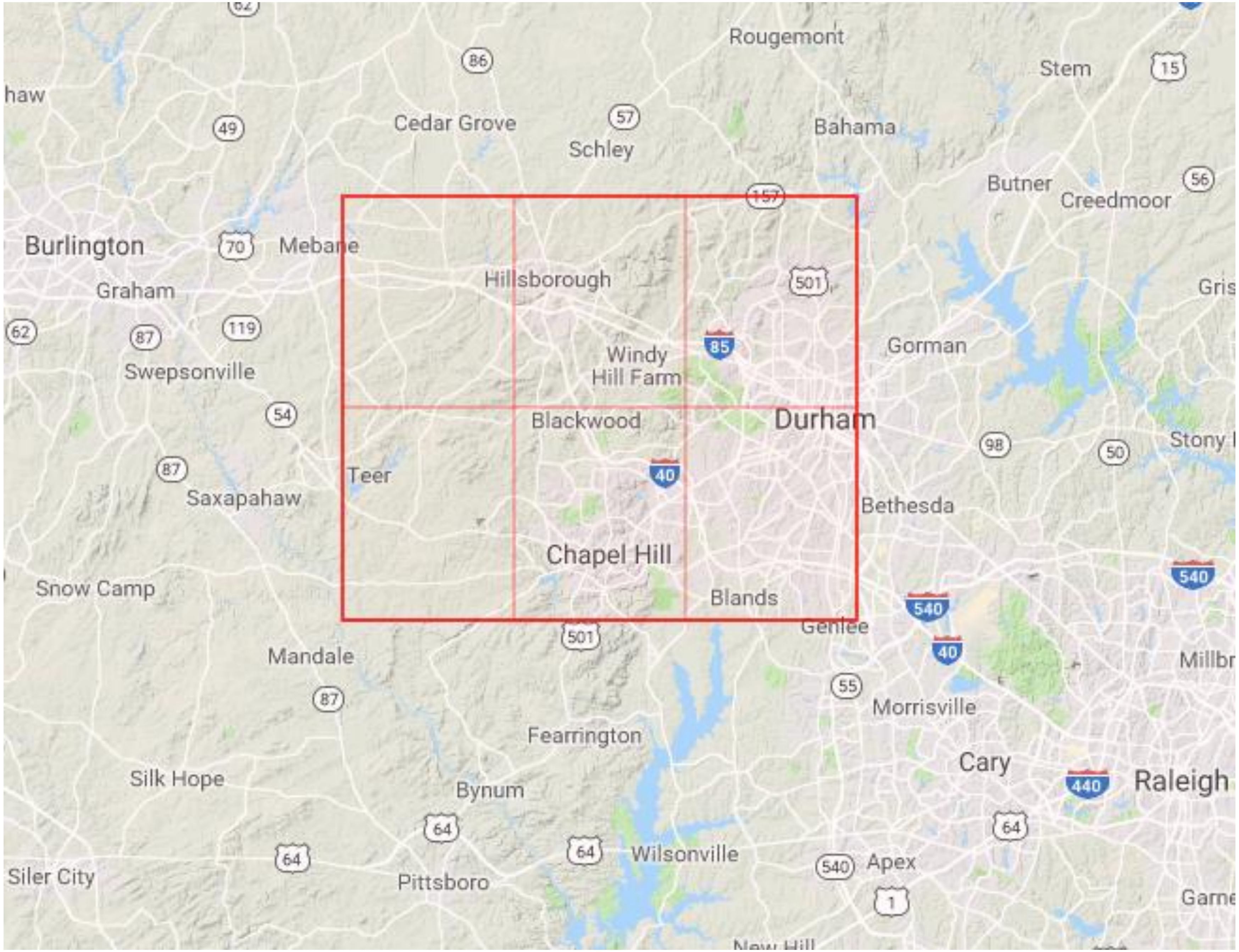
……… **how have these influenced the usability of climate change information?**

Thoughts so far…

Thank you!


Total no. of months with storage below 20% of total capacity
no. of reps with at least one month below 20% = 668
no. of failure months across all reps (n) = 2756
no. of failures
month
0
100
200
300
400
500
600
700
1
2
3
4
5
6
7
8
9
10
11
12


First month below 20% storage (only 1 mo/yr is counted)
sum of low storage years across all reps (n) = 899
no. of reps with at least one year below 20% storage = 668
n
month
0
50
100
150
200
250
1
2
3
4
5
6
7
8
9
10
11
12



Rougemont
Stem
Cedar Grove
Schley
Bahama
Butner
Creedmoor
Burlington
Mebane
Hillsborough
Graham
Swepsonville
Windy Hill Farm
Gorman
Blackwood
Durham
Teer
Saxapahaw
Bethesda
Chapel Hill
Snow Camp
Blands
Genlee
Mandale
Morrisville
Fearrington
Cary
Raleigh
Silk Hope
Bynum
Wilsonville
Apex
Siler City
Pittsboro

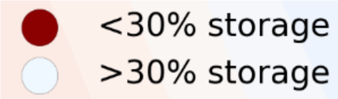
The form of the logistic regression model is given by Equation 1, where p_i represents the probability that performance in the i^{th} SOW is classified as a success and X_i represents a vector of covariates (in this case, streamflow and demand characteristics) describing the i^{th} SOW:

1) $$\ln\left(\frac{p_i}{1-p_i}\right) = \mathbf{X_i^T}\beta.$$

The coefficients, β, on the covariates are estimated using Maximum Likelihood Estimation.

To determine which streamflow and demand characteristics are most important in explaining successes and failures, we can compare the McFadden's pseudo-R^2 values associated with different models that include different covariates. McFadden's pseudo-R^2, $R^2_{McFadden}$, is given by Equation 2:

2) $$R^2_{McFadden} = 1 - \frac{\ln \hat{L}(M_{Full})}{\ln \hat{L}(M_{Intercept})}$$

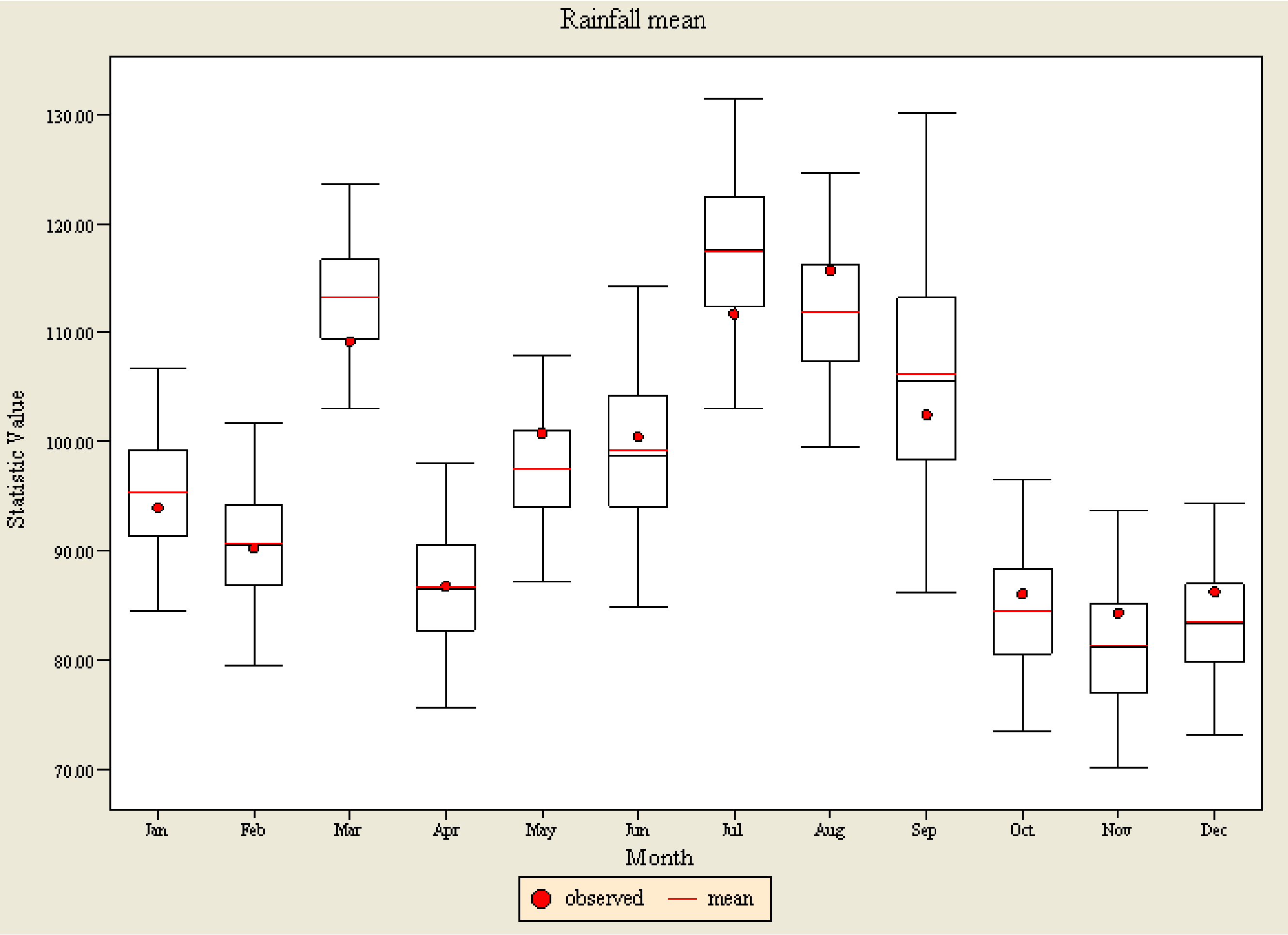

<30% storage
>30% storage

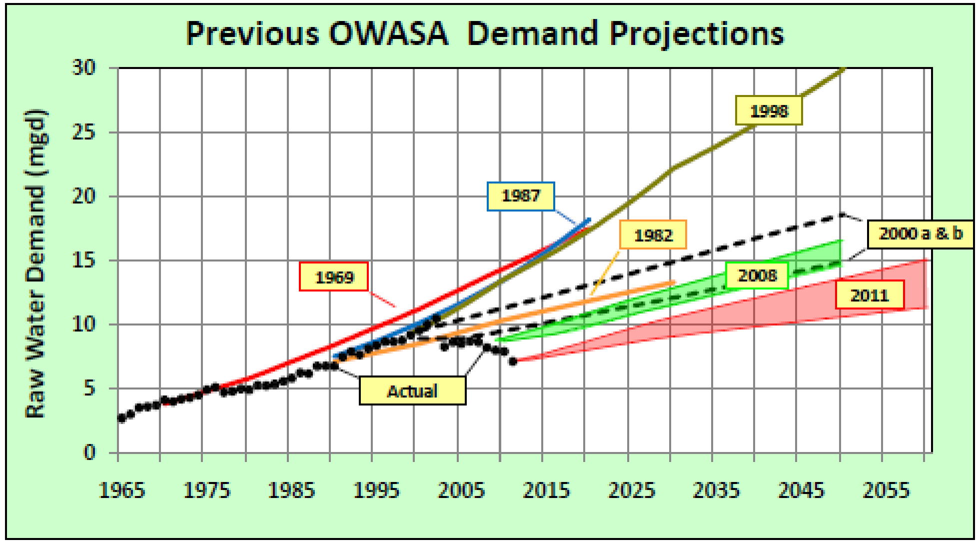

BCSD-Hydro dataset
RCP8.5 scenario | control: 1950-1998 future:2030-2078
access1-0.1.rcp85
bcc-csm1-1-m.1.rcp85
bcc-csm1-1.1.rcp85
canesm2.1.rcp85
ccsm4.1.rcp85
cesm1-bgc.1.rcp85
cesm1-cam5.1.rcp85
cmcc-cm.1.rcp85
cnrm-cm5.1.rcp85
csiro-mk3-6-0.1.rcp85
fgoals-g2.1.rcp85
fio-esm.1.rcp85
gfdl-cm3.1.rcp85
gfdl-esm2g.1.rcp85
gfdl-esm2m.1.rcp85
giss-e2-r.1.rcp85
hadgem2-ao.1.rcp85
hadgem2-cc.1.rcp85
hadgem2-es.1.rcp85
inmcm4.1.rcp85
ipsl-cm5a-mr.1.rcp85
ipsl-cm5b-lr.1.rcp85
miroc-esm-chem.1.rcp85
miroc-esm.1.rcp85
miroc5.1.rcp85
mpi-esm-lr.1.rcp85
mpi-esm-mr.1.rcp85
mri-cgcm3.1.rcp85
noresm1-m.1.rcp85
0
10
20
30
40
con
fut
scen
success_CMS30
0
1

Stochastic Data Generation

Stochastic Climate Library (SCL)

- 1st order autoregressive annual model and monthly method of fragments model; cross-correlation preserved
- Model trained on observed records of P, Tmax, Reservoir Evaporation
- <u>5000 synthetic monthly time series</u>





Previous OWASA Demand Projections
Raw Water Demand (mgd)
30
25
20
15
10
5
0
1965
1975
1985
1995
2005
2015
2025
2035
2045
2055
1998
1987
1982
1969
2000 a & b
2008
2011
Actual

Current Yield: 10.5 mgd

Future Yield: 12.7 mgd