

Introduction to Hydrology loadings, climate change and extreme precipitation

**Probable Maximum Precipitation-20 years of Updating the
HMRs and What to Expect through 2100**

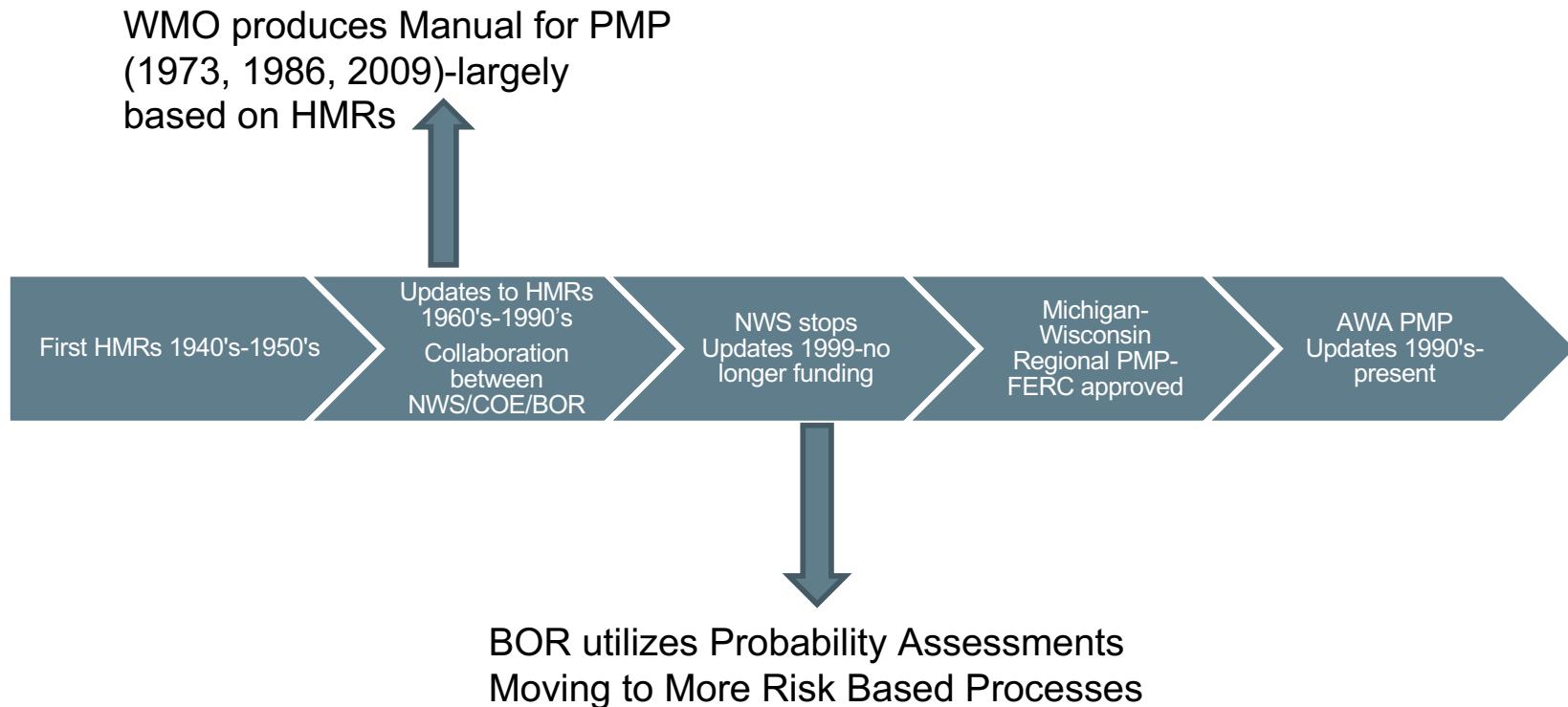
Applied Weather Associates (AWA)

Bill Kappel

National Dam Safety Program Technical Seminar for 2023, Emmitsburg, MD



PMP Development History

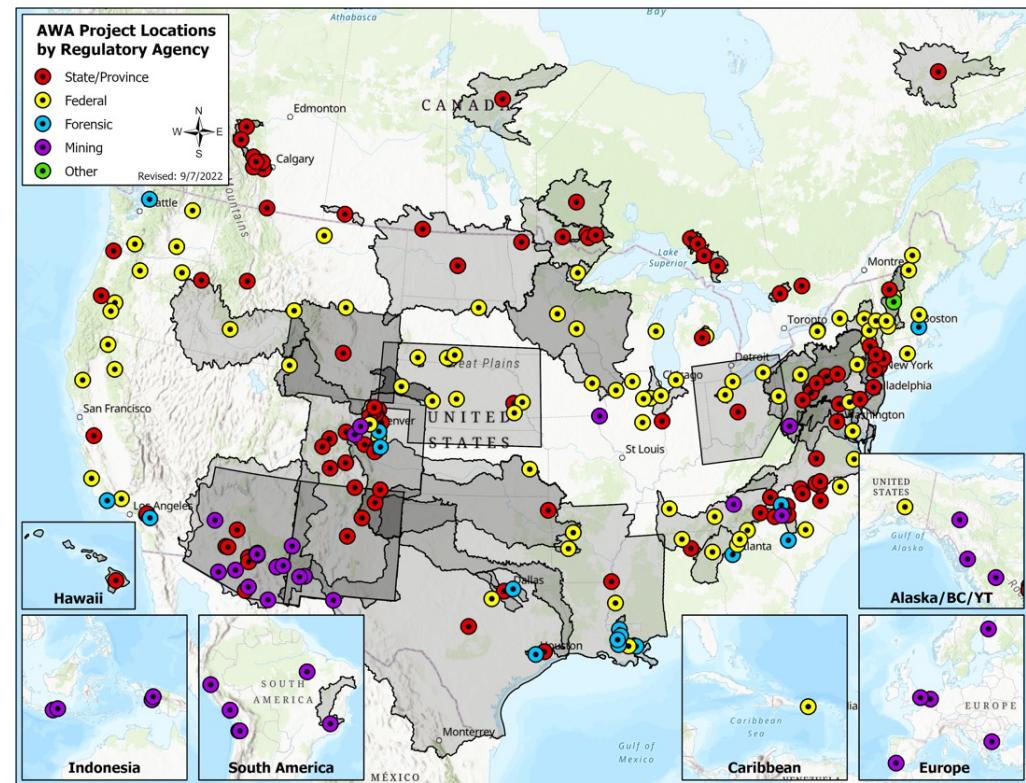


Overall PMP Development Today and What's Next

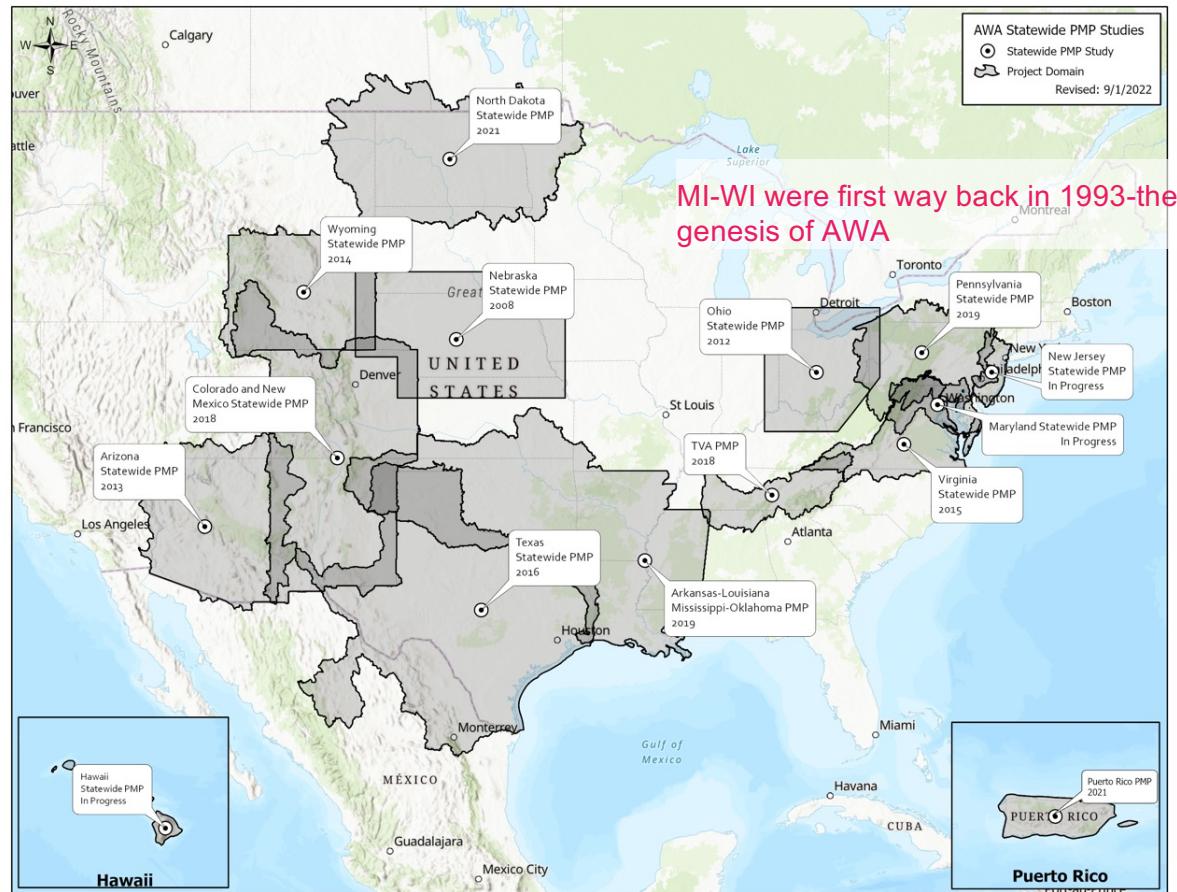
- Statewide studies a big part of the mix

- What's next

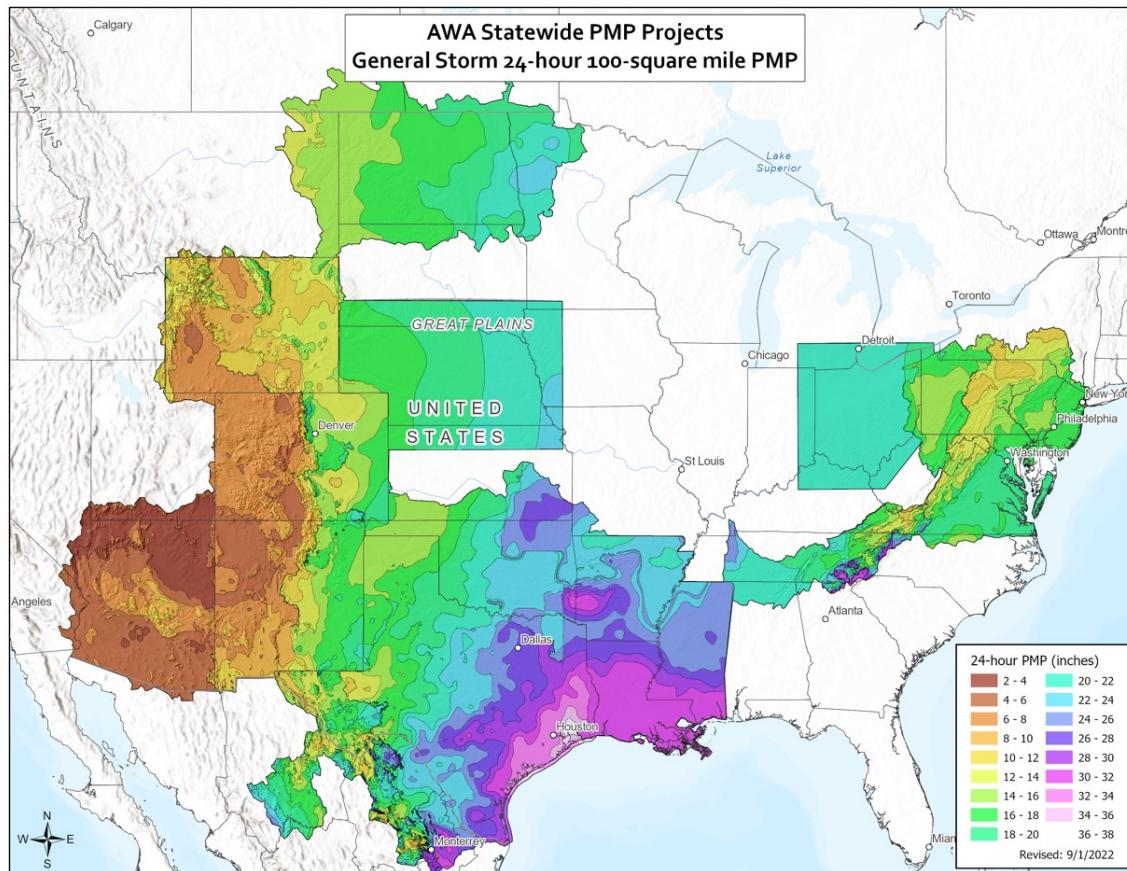
- PRECIP act
- Public-Private partnership
 - Updates
 - Storage
 - Access



AWA Statewide Project Locations



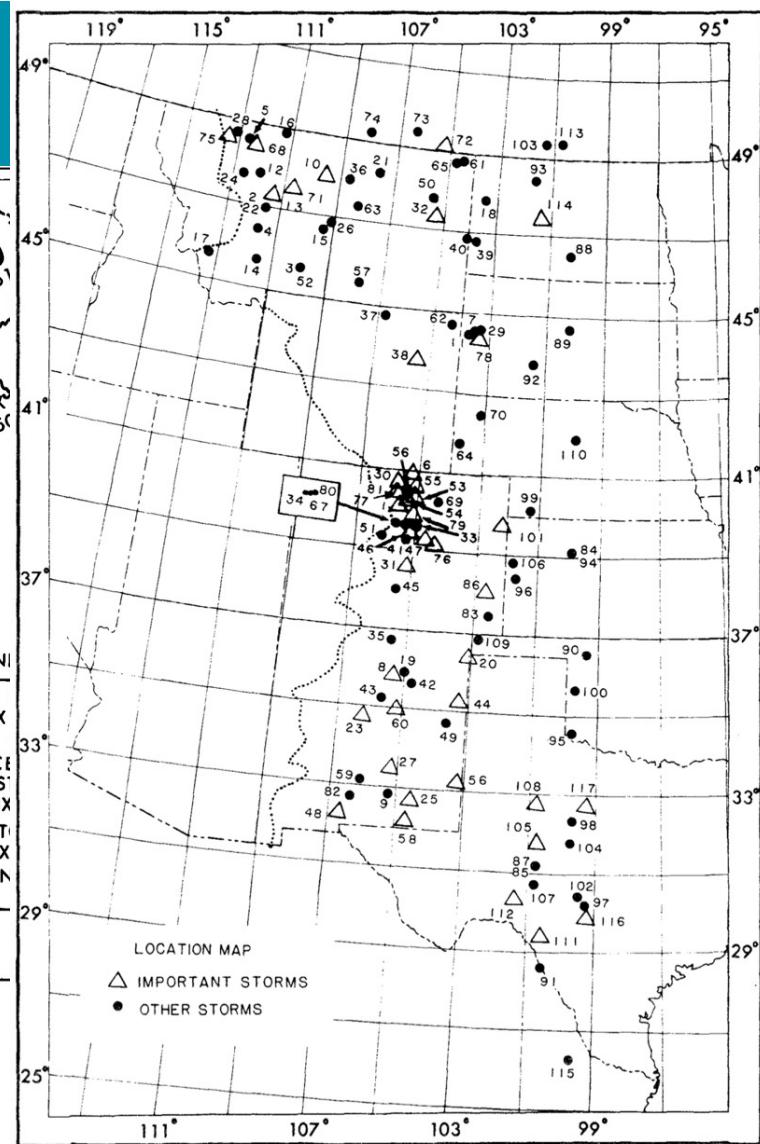
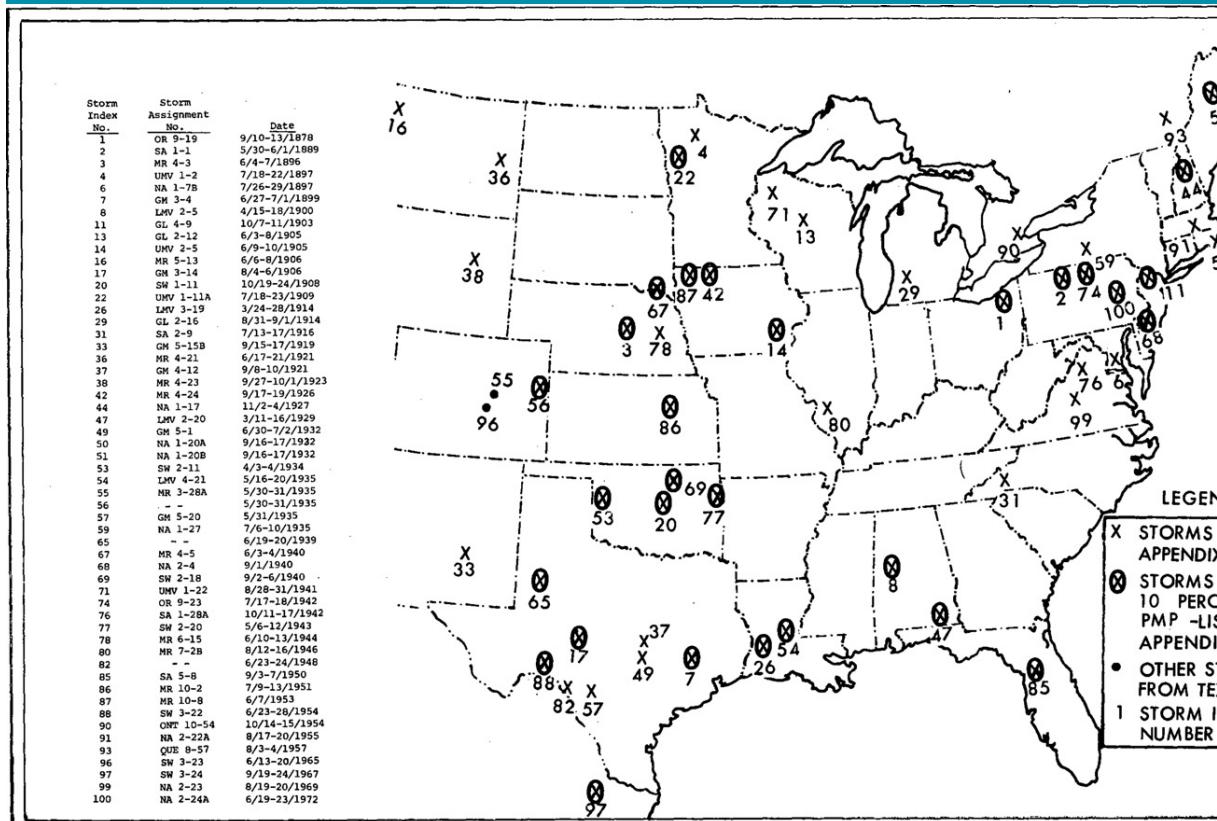
AWA Statewide PMP Depths All together



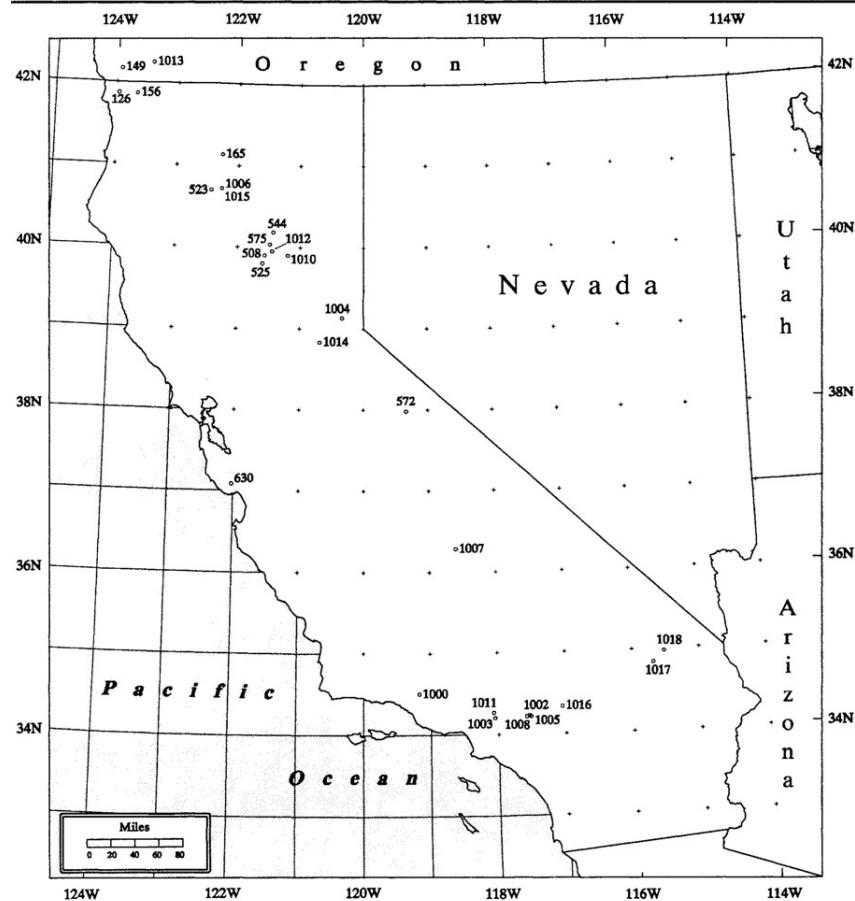
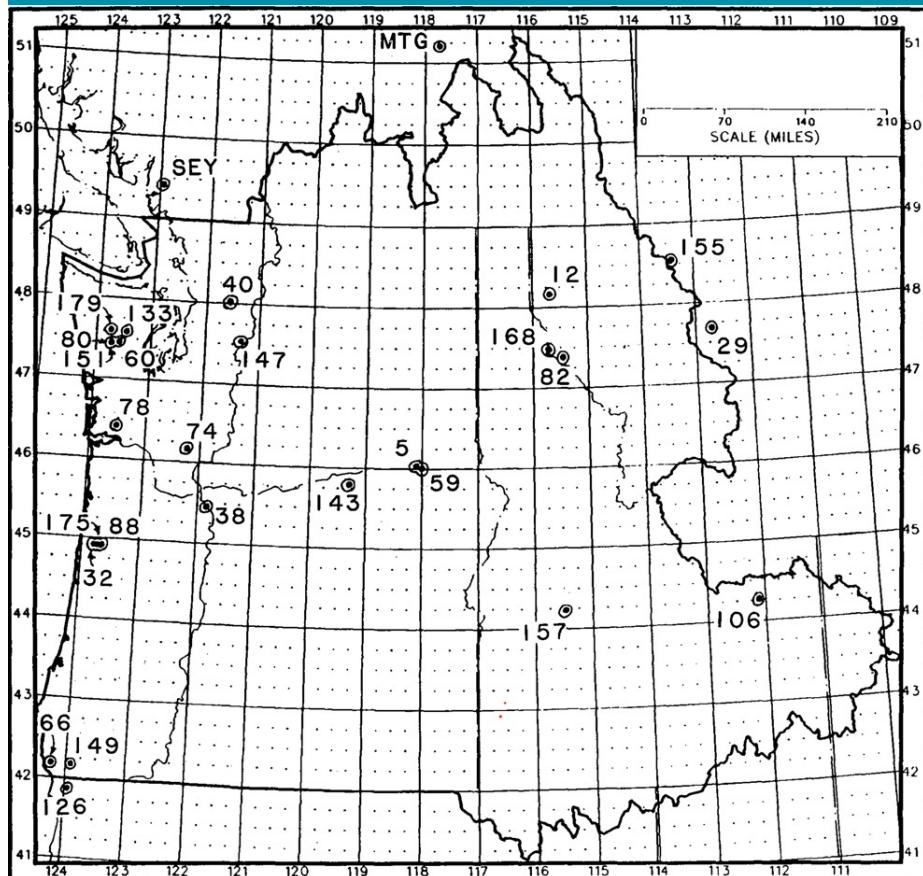
AWA Statewide Progress Improvements

- Continual updates to the storm database
- PMP by storm type and season
- Meteorological analyses of many other aspects
- Storm based temporal patterns
- Storm based spatial patterns
- Input for probabilistic assessments

HMR Storm Database

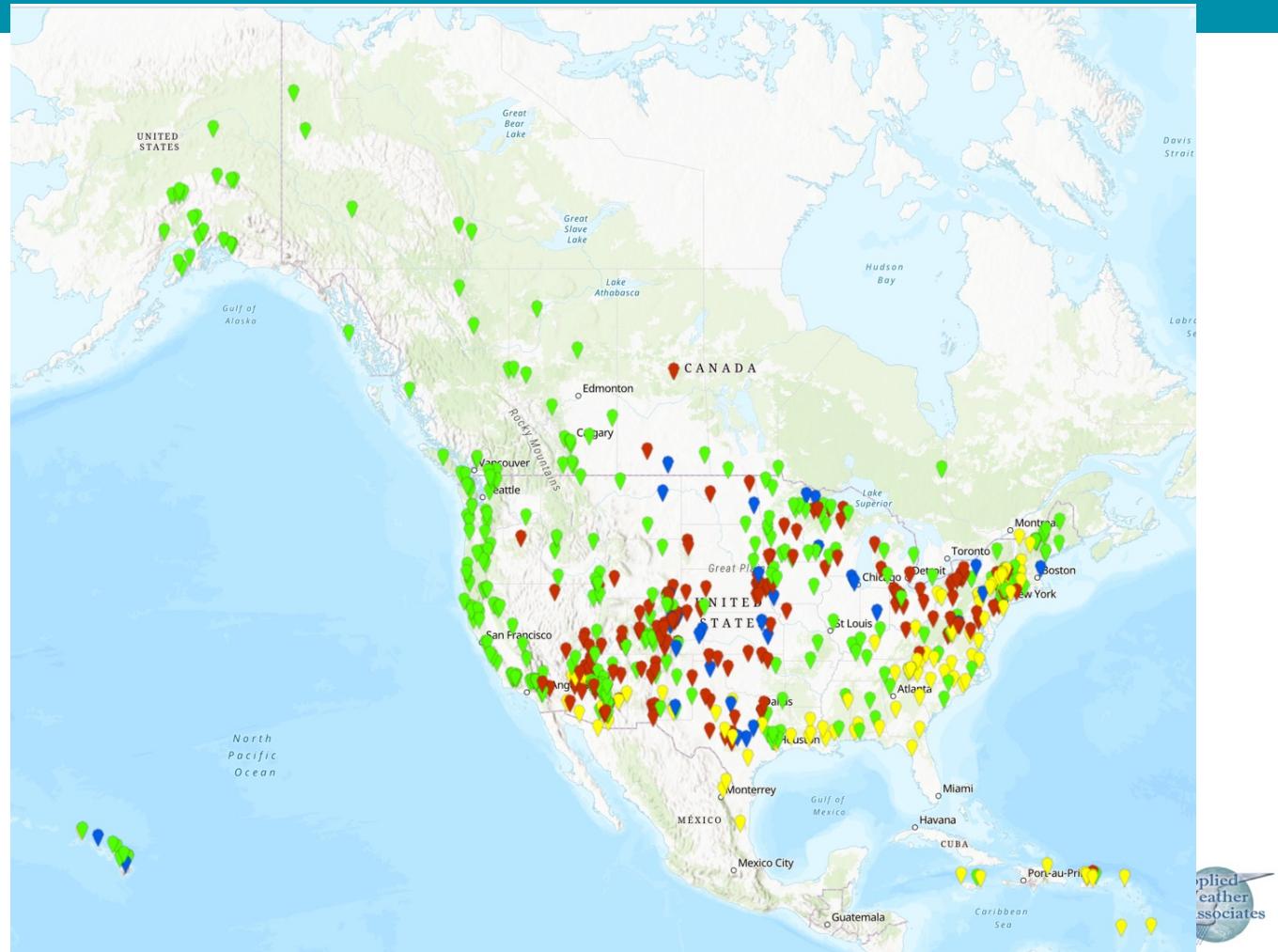


HMR Storm Database

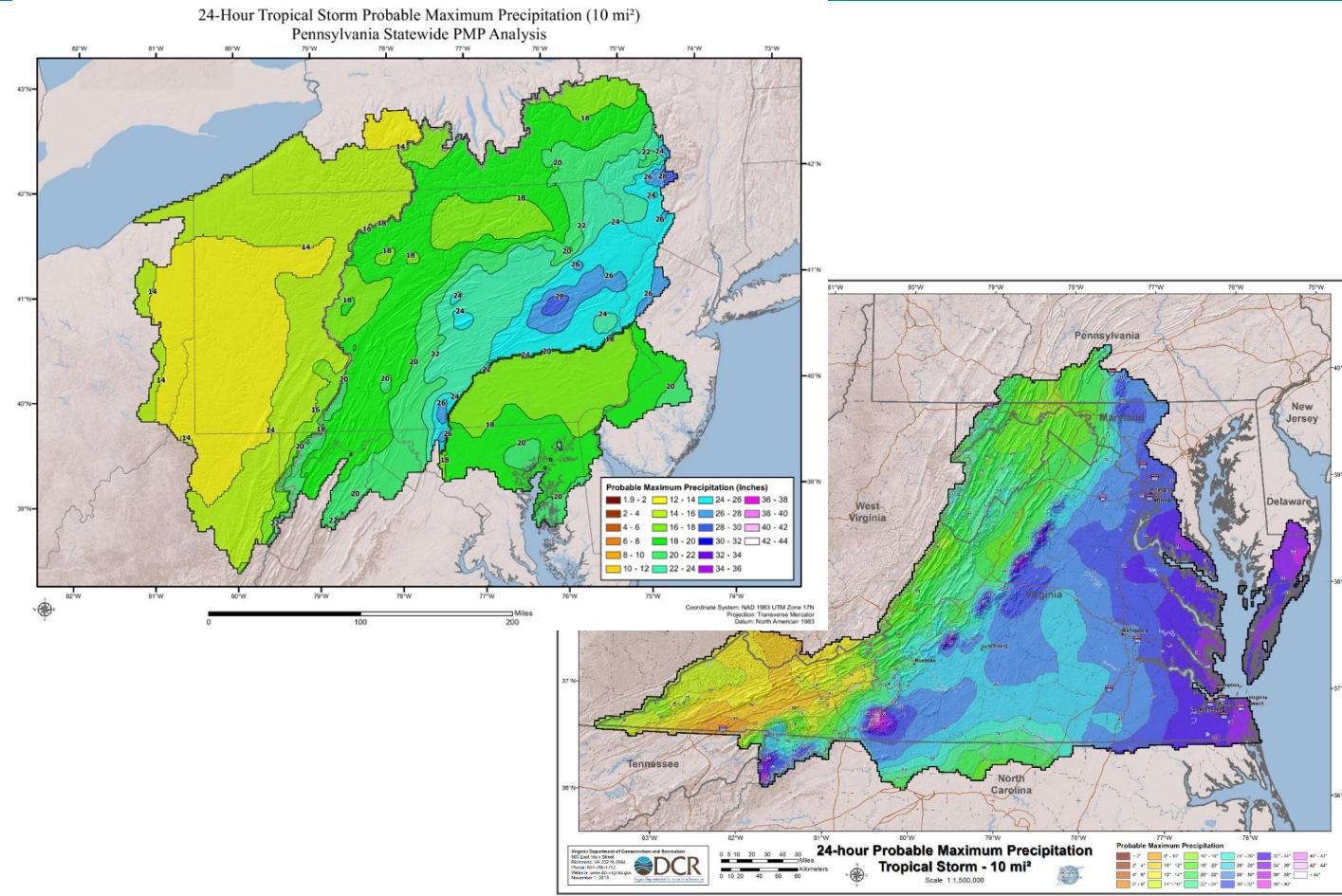


AWA SPAS Storm Database

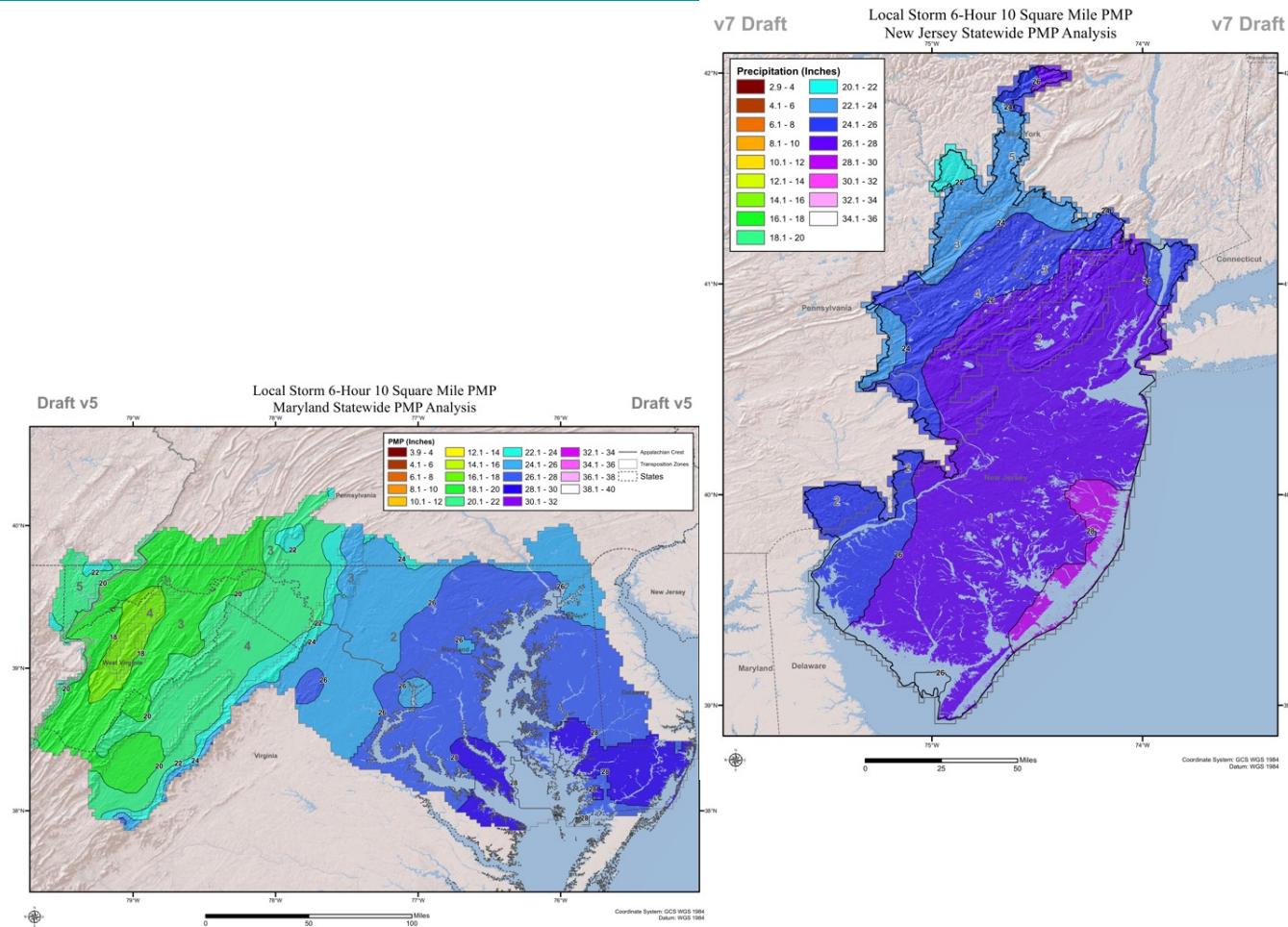
- Nearly 1000 storms analyzed
- Provide numerous outputs
 - For PMP
 - Hydro Calibration
 - Temporal/Spatial
 - ARFs



AWA Statewide Output Examples-East



AWA Statewide Output Examples-East



Statewide Projects-Now and What's Next

- Huge amounts of data/results over time
- Web interface for all studies for consistency
- No need desktop GIS
 - Corrects version control
 - Incorporate updates and improvements for all states
 - Include new storms
 - Include updated methods/climate data
- Provide consolidated support and maintenance
- Continually updated storm database

AWA Web PMP Tool Example

CO-NM REPS Basin PMP Tool | New Mexico OSE | Applied Weather Associates | Colorado DWR | New Mexico OSE

Basin PMP Estimation Web Application

Colorado-New Mexico Deterministic Regional Probable Maximum Precipitation Study

TERMS AND CONDITIONS

(DRAFT Version - NOT FOR OFFICIAL USE)

This tool was prepared by Applied Weather Associates, LLC (AWA). The results and conclusions provided by this tool are based upon open-source professional judgment using currently available data. Therefore, neither AWA nor any person acting on behalf of AWA can: (a) make any representations, warranties or guarantees as to the accuracy of the information provided by this tool; or (b) assume any liability relating to use of any information provided by this tool.

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INSTRUCTIONS

- Click "Add Drainage Basin Layer" icon to add a polygon layer representing the drainage basin from the Input tab.
- The File tab allows for adding layers in the Shapefile (.zip), KML, or CSV formats.
- Click the "Run Basin PMP Tool" icon to run the Basin PMP geoprocessing tool. In the Input tab, select the basin layer added in Step 1 and click Run.
- The geoprocessing service will run which may take several minutes. In the Output tab progress messages will be displayed while the process runs.
- Once complete, the result items will be listed in the Output tab:
 - For each storm type, there will be a point layer (e.g., "Local Storm PMP depths" representing the basin area-size and controlling storm duration points. This table can be expanded by clicking the magnifying glass icon).
 - There is also a "Depth-Duration Table". The table is used to provide input for the "Depth-Duration Chart" tool described in the next step.
 - For each output layer, the user may click the "... icon to access additional operations including:
 - Zoom to layer
 - Download as a .csv
 - Export the layer as a Feature Collection, or GeoJSON
 - Save to My Content if you would like to add it to your ArcGIS organization
 - View the Attribute Table

INSTRUCTIONS

- Click "Add Drainage Basin Layer" icon to add a polygon layer representing the drainage basin outline to be used for PMP estimation.
- The File tab allows for adding layers in the Shapefile (.zip), KML, or CSV formats.
- Click the "Run Basin PMP Tool" icon to run the Basin PMP geoprocessing tool. In the Input tab, select the basin layer added in Step 1 and click Run.
- The geoprocessing service will run which may take several minutes. In the Output tab progress messages will be displayed while the process runs.
- Once complete, the result items will be listed in the Output tab:
 - For each storm type, there will be a point layer (e.g., "Local Storm PMP depths" representing the basin area-size and controlling storm duration points for each analysis point over the basin. The points occur at as spatial interval of 30 seconds over the basin).
 - There is also a "Depth-Duration Table". The table is used to provide input for the "Depth-Duration Chart" tool described in the next step.
 - For each output layer, the user may click the "... icon to access additional operations including:
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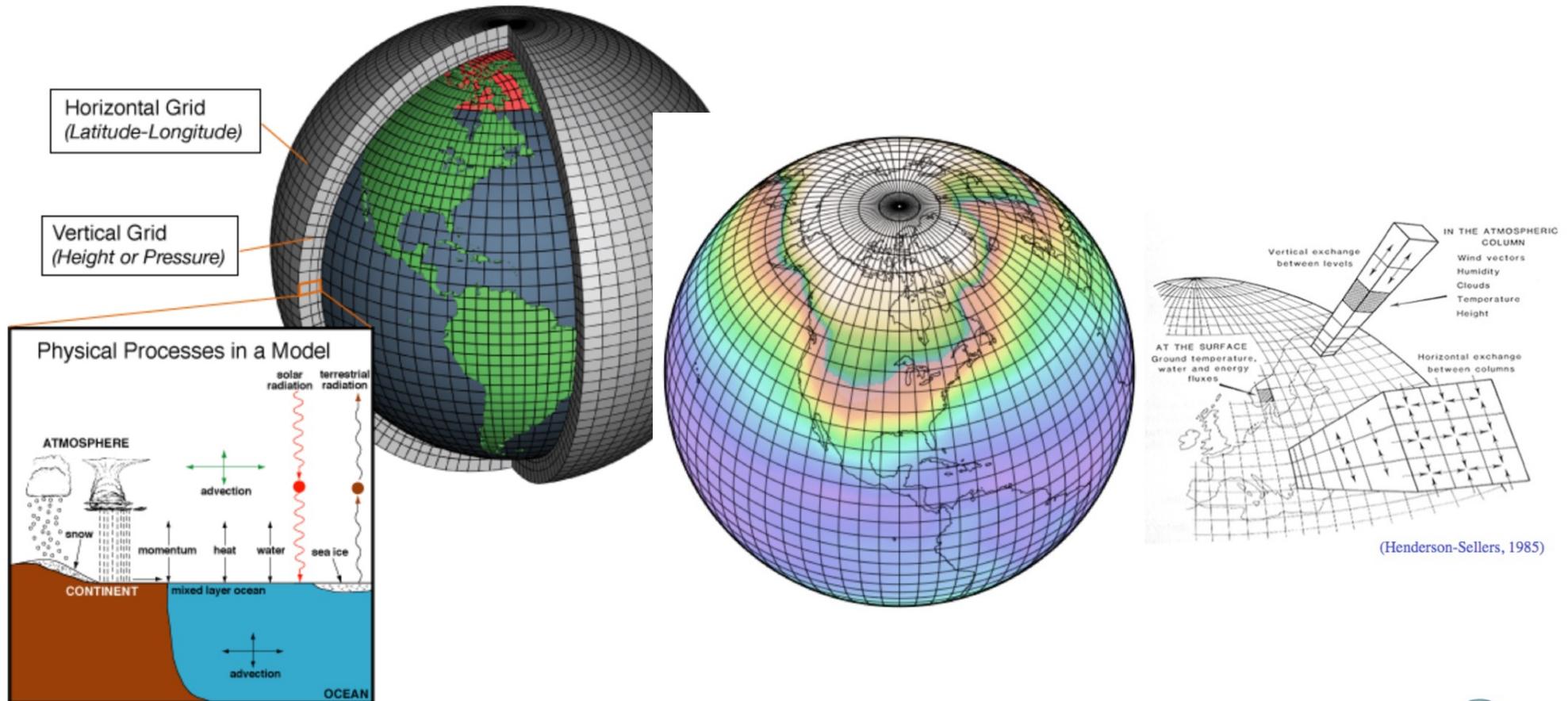


Climate Change, PMP, and Dam Safety

- So what's next? Does PMP change in a changing climate?



Global Climate Model-General Circulation Model



Climate Model Background

- Global Models are downscaled using Regional Climate Models
 - To better replicate local climate/topography
 - To better capture local meteorological conditions
- Two types of downscaling
 - Statistical
 - Dynamic

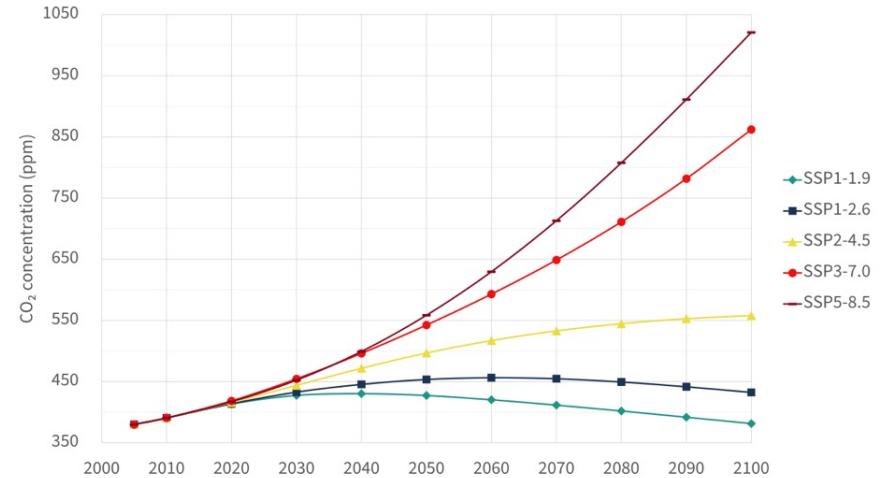
Climate Model Background

- Various research groups conduct climate change modeling
 - Share data via CMIP6 group
- Shared Socioeconomic Pathway (SSP)
 - SSP account for unknown future GHG emissions
- SSP scenarios used as boundary conditions for CMIP6 GCMs
 - Commonly use SSP 4.5 and 8.5

CMIP6 Climate Model Projections

- The **SSP 4.5** intermediate GHG emissions:
CO₂ emissions around current levels until 2050, then falling but not reaching net zero by 2100
- The **SSP 8.5** very high GHG emissions:
CO₂ emissions triple by 2075

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely range in °C (2081–2100)
SSP1-1.9	very low GHG emissions: CO ₂ emissions cut to net zero around 2050	1.6 °C	1.4 °C	1.0 – 1.8
SSP1-2.6	low GHG emissions: CO ₂ emissions cut to net zero around 2075	1.7 °C	1.8 °C	1.3 – 2.4
SSP2-4.5	intermediate GHG emissions: CO ₂ emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0 °C	2.7 °C	2.1 – 3.5
SSP3-7.0	high GHG emissions: CO ₂ emissions double by 2100	2.1 °C	3.6 °C	2.8 – 4.6
SSP5-8.5	very high GHG emissions: CO ₂ emissions triple by 2075	2.4 °C	4.4 °C	3.3 – 5.7

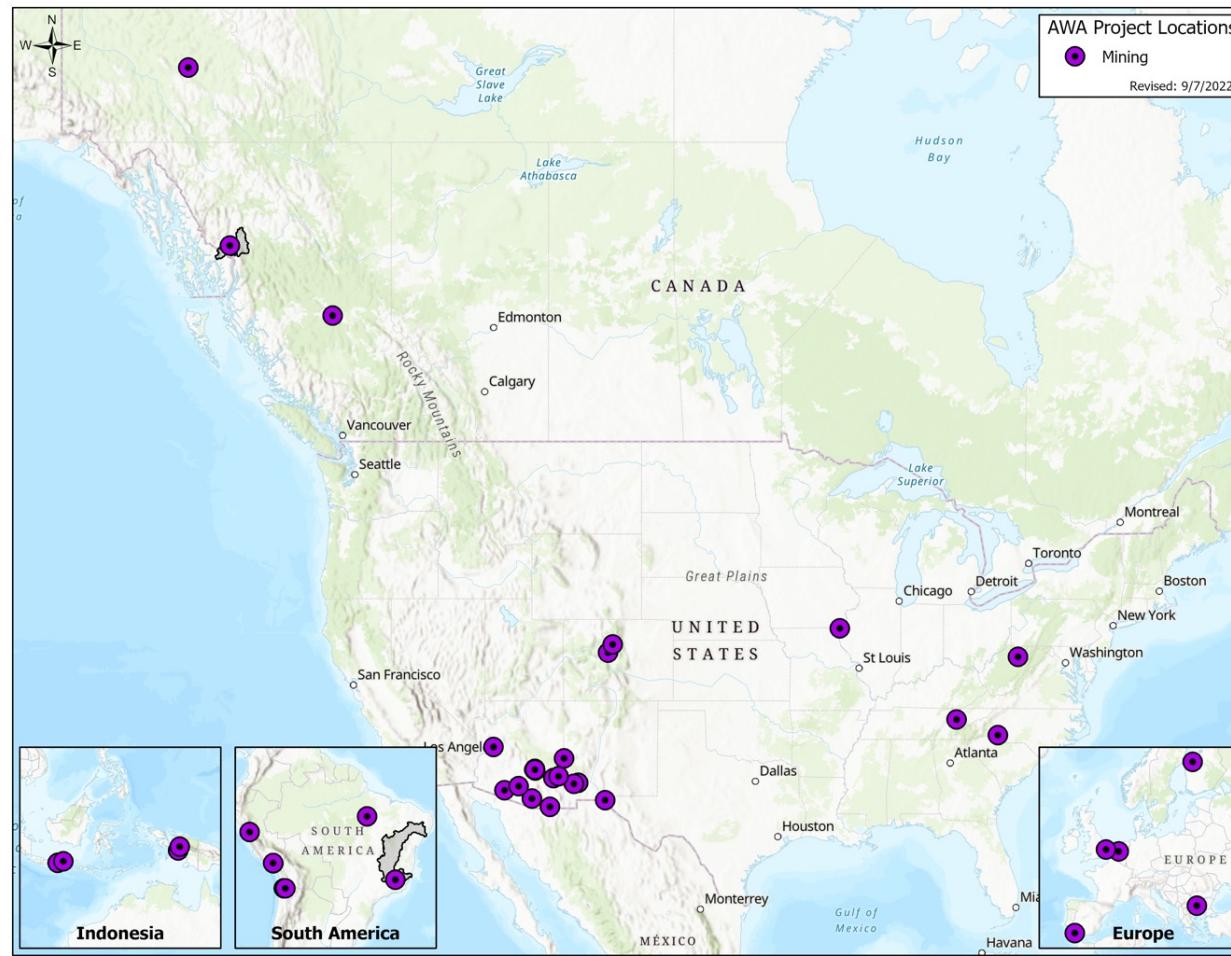


*** SP45 values are “likely” and SP85 “unlikely”

2) “Within Uncertainty” Term

- The meaning of “***within uncertainty***” for this analysis
- Multiple sources of uncertainty and varying ranges of uncertainty
 - Gauge/Observed Precipitation
 - Point measurement 5 to 15% percent for long-term series, and as high as 75% for individual storm events
 - Frequency Analysis
 - Typically, 24-hour 100-year error bounds are approximately +/-18%
 - Climate Projections
 - Regional Models can be quite large 20 to >50%
 - PMP Storm In-place Maximization Factor
 - Range between 5 and 30%, with an average around 20%
- Consider +/- 20% to be within uncertainty of the analysis results.

AWA Climate Change Study Locations

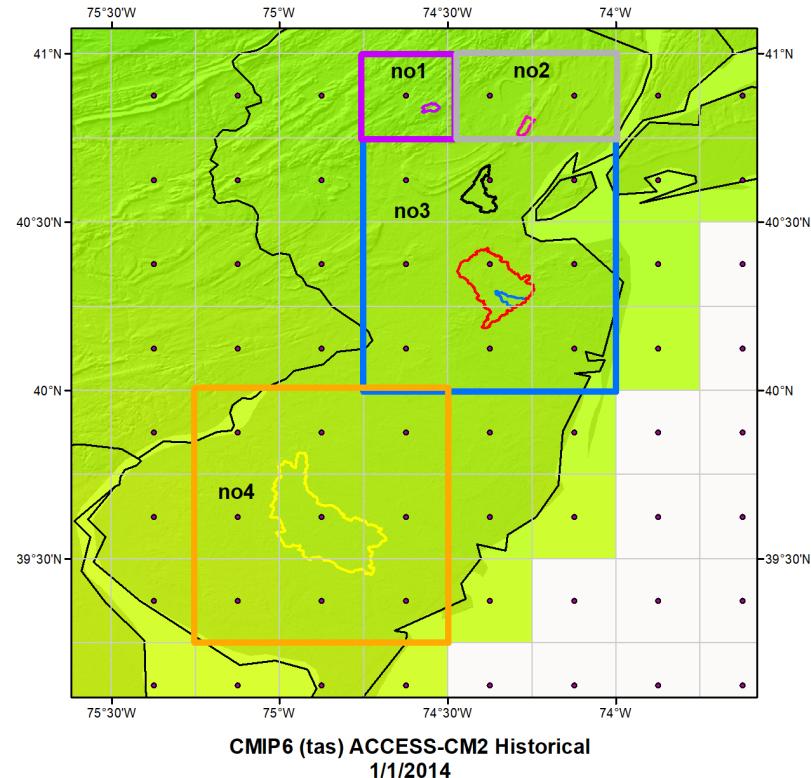


CMIP6 Climate Model Projections-NJ Example

NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)

- Total of 35 climate models
- 9 models did not have all data
 - (6) Missing years and/or variables
 - (3) 30-days per month
- Used 26 models on daily time step
 - Temperature
 - Relative humidity
 - Precipitation

Region#	Basin	Domain
NJ_Region_1	Shongum	41.0, -74.75, 40.75, -74.5
NJ_Region_2	Orange	41.0, -74.5, 40.75, -74.0
NJ_Region_3	New Market, Durernal, Englishtown	40.75, -74.75, 40.0, -74.0
NJ_Region_4	Lenape	40.0, -75.25, 39.25, -74.5



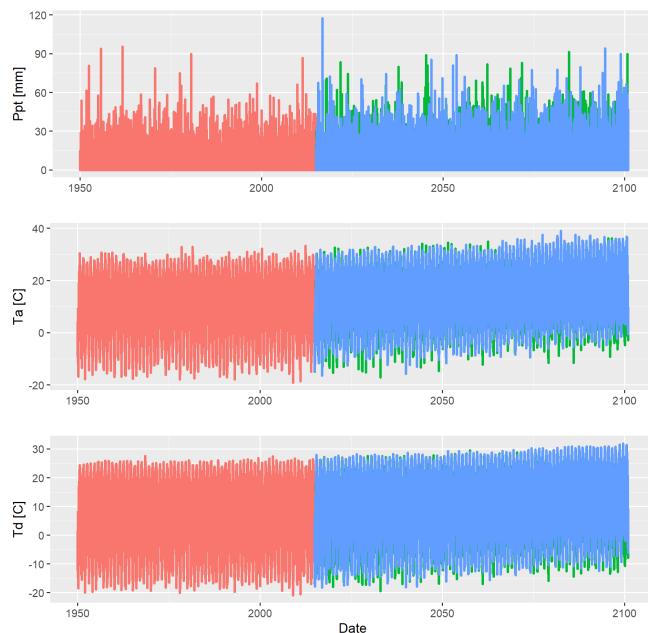
Climate Model Projections Used

- 26 models on daily time step
 - Temperature (tas)
 - Relative humidity (hurs)
 - Precipitation (pr)

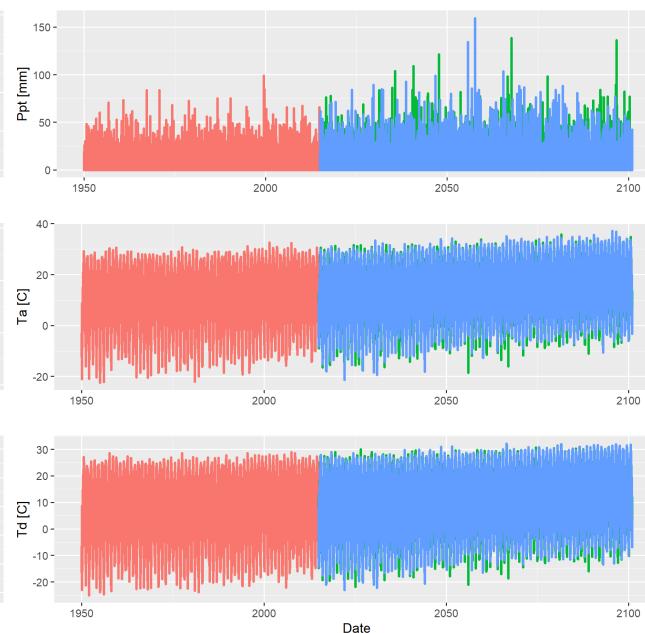
Model #	Model Name	Relative Humidity (hurs)			Precipitation (pr)			Temperature (tas)		
		HISTORICAL	SSP45	SSP85	HISTORICAL	SSP45	SSP85	HISTORICAL	SSP45	SSP85
1	ACCESS-CM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
2	ACCESS-ESM1-5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
4	CanESM5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
5	CESM2-WACCM	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
6	CESM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
7	CMCC-CM2-SR5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
8	CMCC-ESM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
9	CNRM-CM6-1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
10	CNRM-ESM2-1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
11	EC-Earth3-Veg-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
12	EC-Earth3	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
13	FGOALS-g3	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
14	GFDL-CM4_gr1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
15	GFDL-CM4_gr2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
16	GFDL-ESM4	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
17	GISS-E2-1-G	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
21	INM-CM4-8	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
22	INM-CM5-0	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
23	IPSL-CM6A-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
26	MIROC-ES2L	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
27	MIROC6	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
28	MPI-ESM1-2-HR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
29	MPI-ESM1-2-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
30	MRI-ESM2-0	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
33	NorESM2-MM	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
34	TaiESM1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100

Climate Model Analysis Input (Model 1, 8, 33)

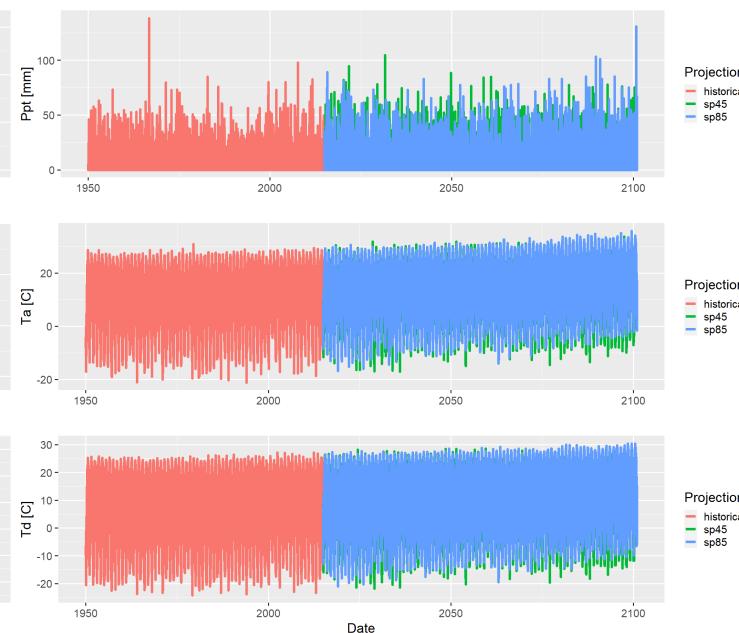
Model #1



Model #8



Model #33

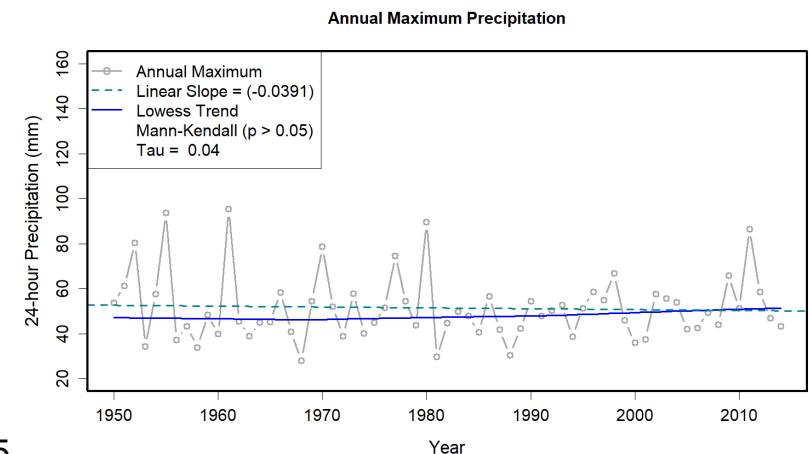


Climate Change Analysis Methods

- **1) Trend Analysis** for 1-day, 3-day, and Annual
 - Model projections (Historic, SSP45, SSP85)
 - All Season, Summer, Winter
- **2) Monthly Analysis**
 - Model projections (Historic, SSP45, SSP85)
 - Precipitation and temperature
- **3) Precipitation Frequency Analysis** for 1-day, 3-day, and Annual
 - All Season, Summer, and Winter
 - Model projections (Historic, SSP45, SSP85)
 - Estimate PF for 1-year through 1000-year
 - Quantify changes

Model Trend Analysis (1-day Example)

- 1-day AMS Trend Analysis (Mann-Kendall)
- 1) Model 1
 - trend depends on period investigated
 - Historical: **no trend**
 - SP45: **no trend**
 - SP85: **increasing trend**
- 2) Model 2
 - trend depends on period investigated
 - Historical: **no trend**
 - SP45: **no trend**
 - SP85: **no trend**
- 3) Model 4
 - trend depends on period investigated
 - Historical: **no trend**
 - SP45: **no trend**
 - SP85: **increasing trend**



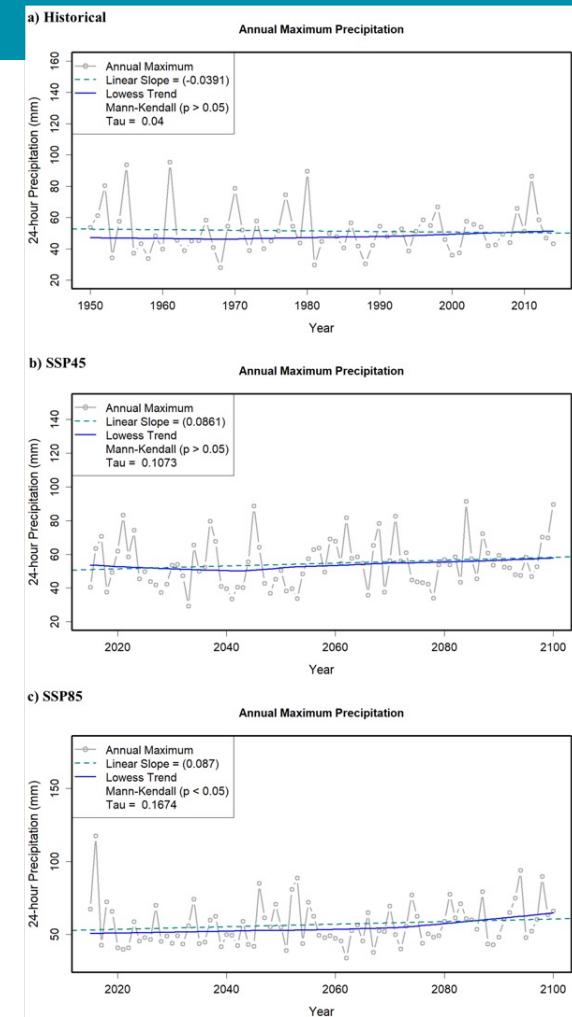
- 4) Model 5
 - trend depends on period investigated
 - Historical: **no trend**
 - SP45: **increasing trend**
 - SP85: **no trend**
- 5) Model 6
 - trend depends on period investigated
 - Historical: **no trend**
 - SP45: **no trend**
 - SP85: **no trend**

Completed for 1-day, 3-day, annual, and by season



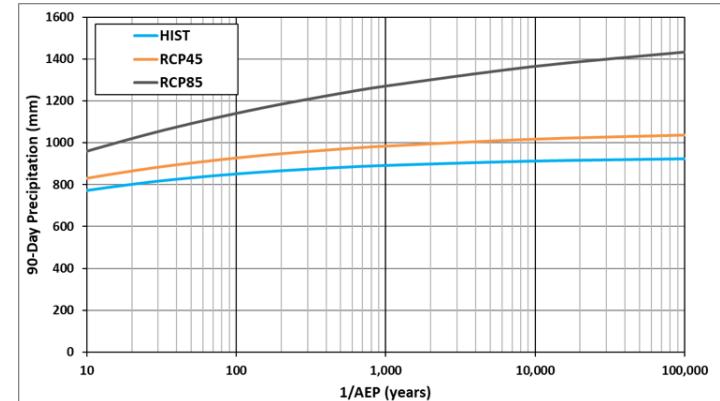
Climate Model Trend Results

	Precipitation			Temperature
	1-day	3-day	Annual	1-day
Historic	24 – no trend 1 – increase 1 – decrease	26 – no trend 0 – increase 0 – decrease	26 – no trend 0 – increase 0 – decrease	7 – no trend 19 – increase 0 – decrease
	20 – no trend 6 – increase 0 – decrease	18 – no trend 4 – increase 0 – decrease	17 – no trend 9 – increase 0 – decrease	1 – no trend 25 – increase 0 – decrease
	11 – no trend 15 – increase 0 – decrease	14 – no trend 12 – increase 0 – decrease	4 – no trend 22 – increase 0 – decrease	0 – no trend 26 – increase 0 – decrease

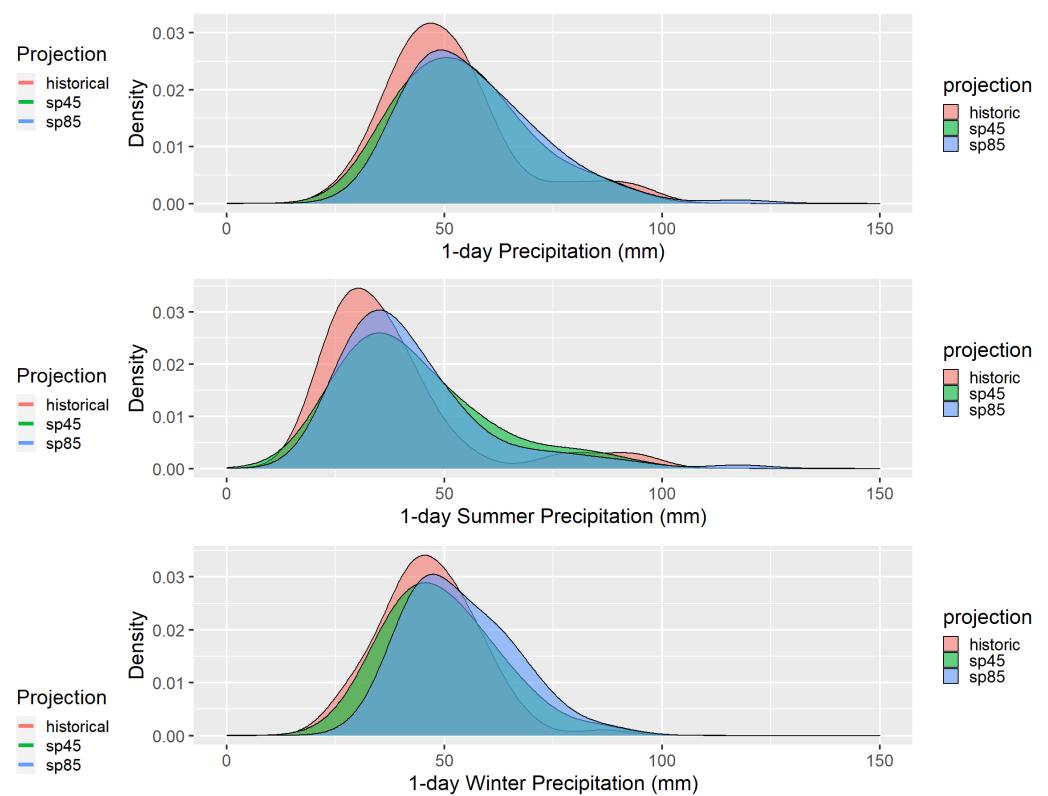
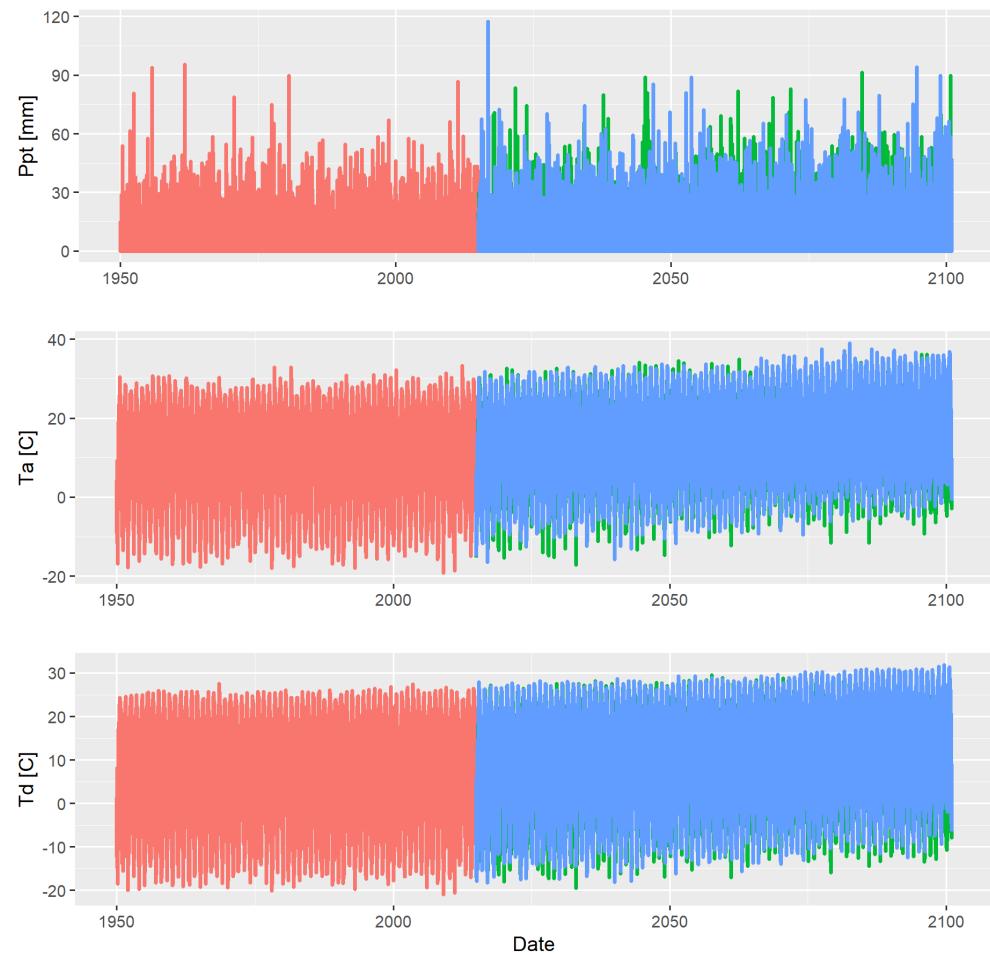


Frequency Analysis (L-moments)

- 1-day, 3-day, 365-day L-moment Frequency Analysis (Historic, SSP45, SSP85)
- All Precipitation, Summer, Winter
 - Identification of Probability Distribution
 - Goodness-of-fit measures
 - L-moment Ratio Diagram
 - The regional weighted average L-Skewness and L-Kurtosis tend to be near the GEV distribution
 - Derivation of Uncertainty bounds
 - Monte-carlo simulation
 - Point Value Annual Exceedance Estimates
 - Compare 10-, 50-, 100-, 500-, and 1000-year AEPs



Climate Model (Model 1)



Frequency Analysis (Model 1 Example)

*** 1-Day Precipitation										
	10yr	50yr	100yr	500yr	1000yr	Pct Change			Average	
Historical	70.1	92.8	103.5	131.1	144.3	-	-	-	-	93%
SP45	73.7	90.7	97.5	112.5	118.5	105%	98%	94%	86%	82%
SP85	76.1	99.1	109.9	137.6	150.9	108%	107%	106%	105%	105% 106%

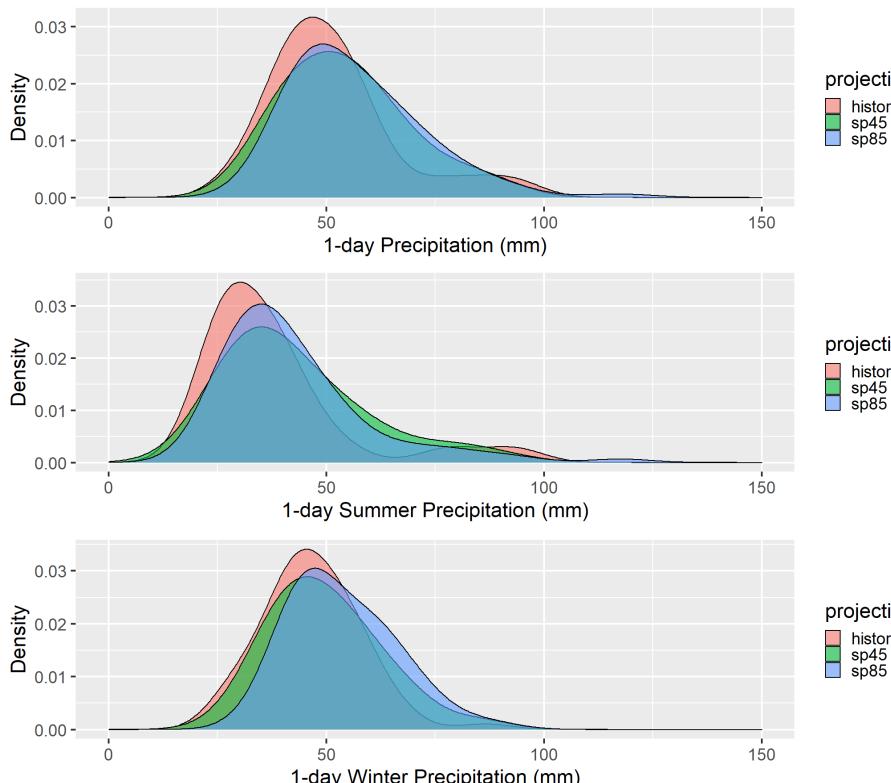
*** 1-Day Summer										
	10yr	50yr	100yr	500yr	1000yr	Pct Change			Average	
Historical	56.4	92.4	114.3	188.1	233.4	-	-	-	-	-
SP45	63.8	91.3	104.8	141.4	159.7	113%	99%	92%	75%	68% 89%
SP85	62.2	93.9	111.3	163.5	192.4	110%	102%	97%	87%	82% 96%

*** 1-Day Winter										
	10yr	50yr	100yr	500yr	1000yr	Pct Change			Average	
Historical	61.0	70.6	73.9	80.1	82.3	-	-	-	-	-
SP45	66.9	81.6	87.4	99.8	104.8	110%	116%	118%	125%	127% 119%
SP85	69.6	84.5	90.6	104.3	109.9	114%	120%	123%	130%	134% 124%

*** 3-Day Precipitation										
	10yr	50yr	100yr	500yr	1000yr	Pct Change			Average	
Historical	103.1	135.3	149.9	186.1	202.7	-	-	-	-	-
SP45	110.2	137.5	148.7	173.7	184.2	107%	102%	99%	93%	91% 98%
SP85	120.1	157.5	174.1	214.8	233.2	116%	116%	116%	115%	115% 116%

* 3-Day Summer										
	10yr	50yr	100yr	500yr	1000yr	Pct Change			Average	
Historical	86.9	133.2	160.3	247.7	299.3	-	-	-	-	-
SP45	96.2	128.8	143.5	180.0	196.8	111%	97%	90%	73%	66% 87%
SP85	99.2	142.1	163.9	224.5	255.7	114%	107%	102%	91%	85% 100%

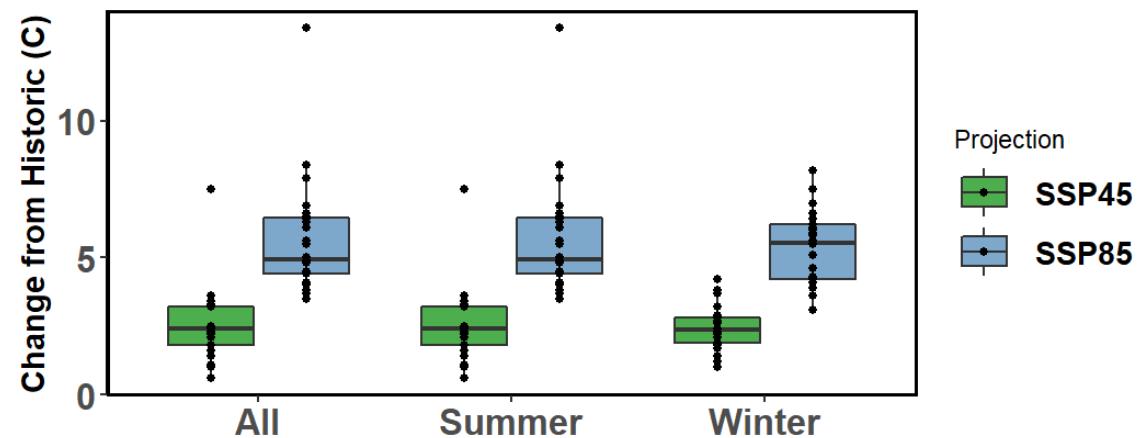
* 3-Day Winter										
	10yr	50yr	100yr	500yr	1000yr	Pct Change			Average	
Historical	91.9	123.6	138.9	179.6	199.7	-	-	-	-	-
SP45	101.0	130.2	142.8	172.3	185.2	110%	105%	103%	96%	93% 101%
SP85	110.0	146.3	163.3	206.8	227.5	120%	118%	118%	115%	114% 117%



*** 365-Day										
	10yr	50yr	100yr	500yr	1000yr	Pct Change			Average	
Historical	1379	1462	1486	1526	1538	-	-	-	-	-
SP45	1517	1626	1658	1708	1722	110%	111%	112%	112%	112% 111%
SP85	1571	1691	1728	1792	1812	114%	116%	117%	118%	116% 116%

Summary Temperature Annual Maximum

- 1-day (ssp45; ssp85)
 - All = 2.4 C; 4.9 C
 - Summer = 2.4 C; 4.9 C
 - Winter = 2.4 C; 5.5 C

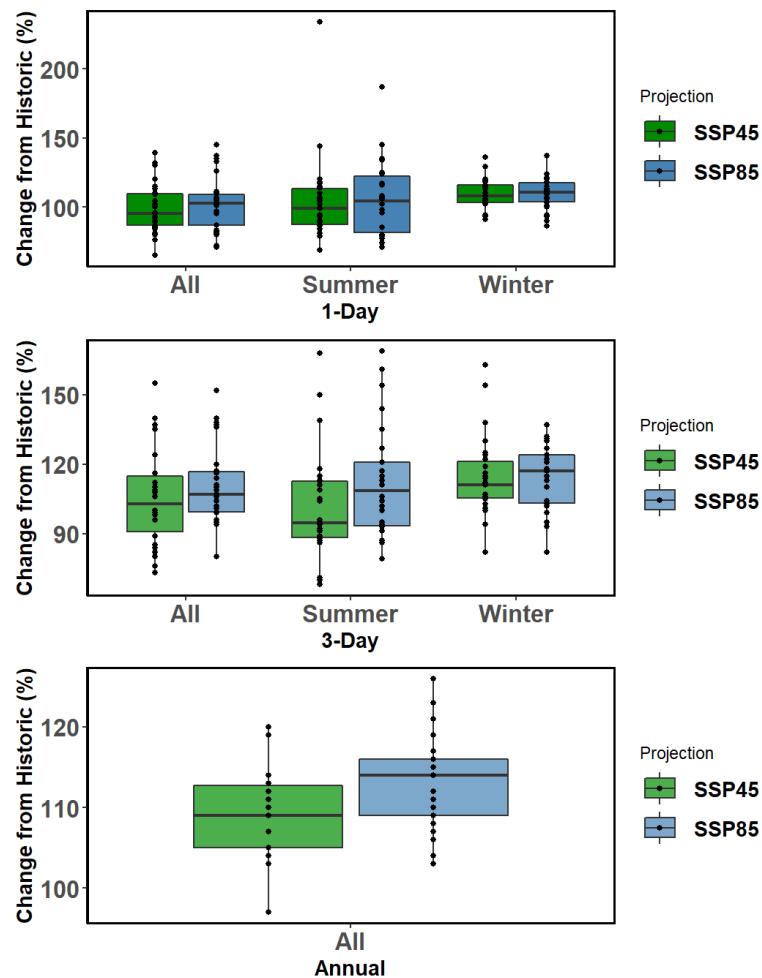


*** Frequency based results, 26 RCM

+++ Boxplots based on these data

Summary Precipitation Frequency

- **1-day (sp45; sp85)**
 - All = -4%; 3%
 - Summer = -1%; 4%
 - Winter = 8%; 11%
- **3-day**
 - All = 3%; 7%
 - Summer = -5%; 9%
 - Winter = 11%; 17%
- **Annual**
 - All = 9%; 14%

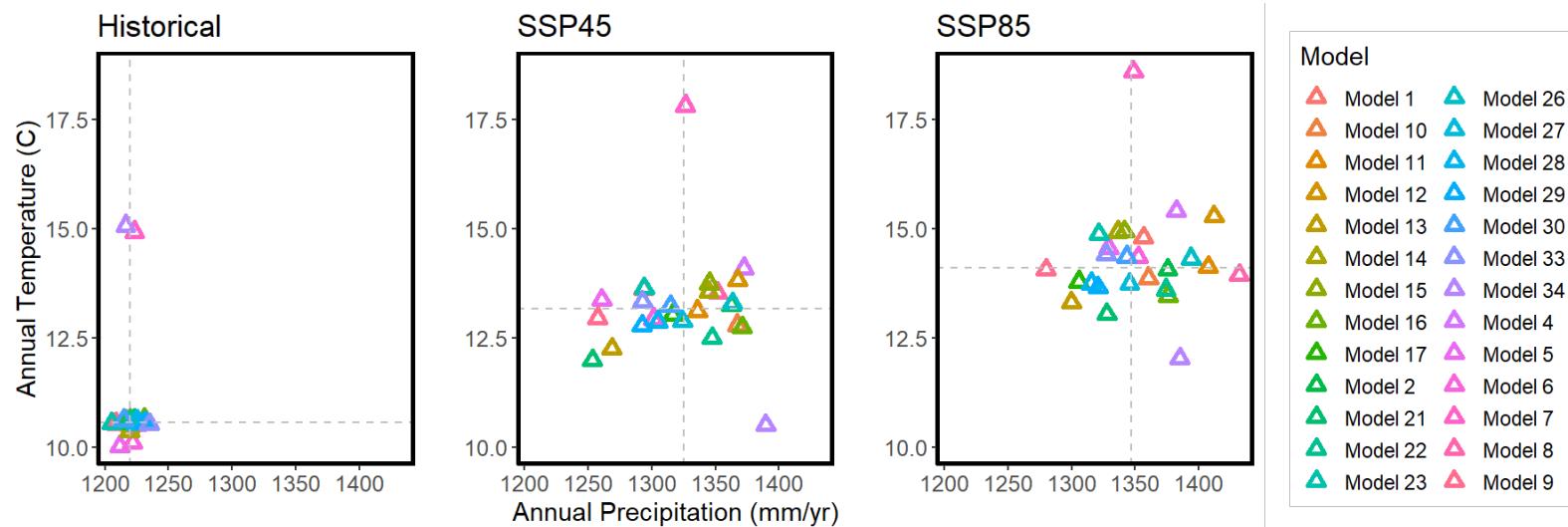


*** Frequency based results, 26 RCM

+++ Boxplots based on these data

Summary Annual Temperature and Precipitation

- **Annual Climatology (temp, ppt)**
 - Historical = 10.6 C; 1220 mm
 - SSP45 = 13.2 C; 1325 mm (**2.6 C; 109%**)
 - SSP85 = 14.1 C; 1347 mm (**3.5 C; 110%**)



*** Climatology, based on 26 RCM



Application of Climate Change Results

Annual Maximum/Frequency Analysis

	SSP45				SSP85			
	Mean	Median	Min	Max	Mean	Median	Min	Max
Temperature 1-Day; C	2.5	2.4	0.6	7.5	5.6	4.9	3.5	13.4
Temperature 1-Day Summer; C	2.5	2.4	0.6	7.5	5.6	4.9	3.5	13.4
Temperature 1-Day Winter PF; C	2.4	2.4	1.0	4.2	5.4	5.5	3.1	8.2
Precipitation 1-Day PF; %	-1	-4	-35	39	2	3	-29	45
Precipitation 1-Day Summer PF; %	4	-1	-31	134	6	4	-29	87
Precipitation 1-Day Winter PF; %	9	8	-9	36	10	11	-14	37
Precipitation 3-Day PF; %	5	3	-27	55	11	7	-20	52
Precipitation 3-Day Summer PF; %	3	-5	-32	68	13	9	-21	69
Precipitation 3-Day Winter PF; %	14	11	-18	63	15	17	-18	37
Precipitation Annual PF; %	9	9	-3	20	14	14	3	26

Climate Change Projections from 2015 through 2100



Application of Climate Change Results

- Results are presented as median values based on model ensemble
- Design Storm and Routing Applications
 - Recommend SSP45 climate scenario as “likely”, SSP85 as “unlikely”
- Results are through 2100 and can be scaled to other periods
 - Example, for 2050 adjustment scale 2100 results by 0.59.

	2050	2100
1-Day Summer PF; %	-1	-1
1-Day Winter PF; %	5	8
3-Day Summer PF; %	-3	-5
3-Day Winter PF; %	7	11

Climate Change Projections from 2015 through 2100

Conclusion

TREND

- **Increase** in Ta and Td
- SSP45 Ppt – most show No Trend/Change
- SSP85 Ppt - most show increase trend

FREQUENCY

- 1-day – SSP45 and SSP85 confidence for **no change** in summer or winter season Ppt magnitude by 2100
 - greatest change most likely in winter seasons
- 3-day – SSP45 and SSP85 confidence for **no change** in summer or winter season in Ppt magnitude by 2100
 - greatest change most likely in winter season
- Annual – SSP45 and SSP85 confidence for **no change** of Ppt magnitude by 2100 and **increase** Temp by 2100

CLIMATOLOGY

- Monthly Climatology – slight **increase** (<20%) in Ppt and **increase** Temp by 2100
- Annual Climatology – slight **increase** (<20%) in annual Ppt and **increase** in annual Temp by 2100



Questions

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