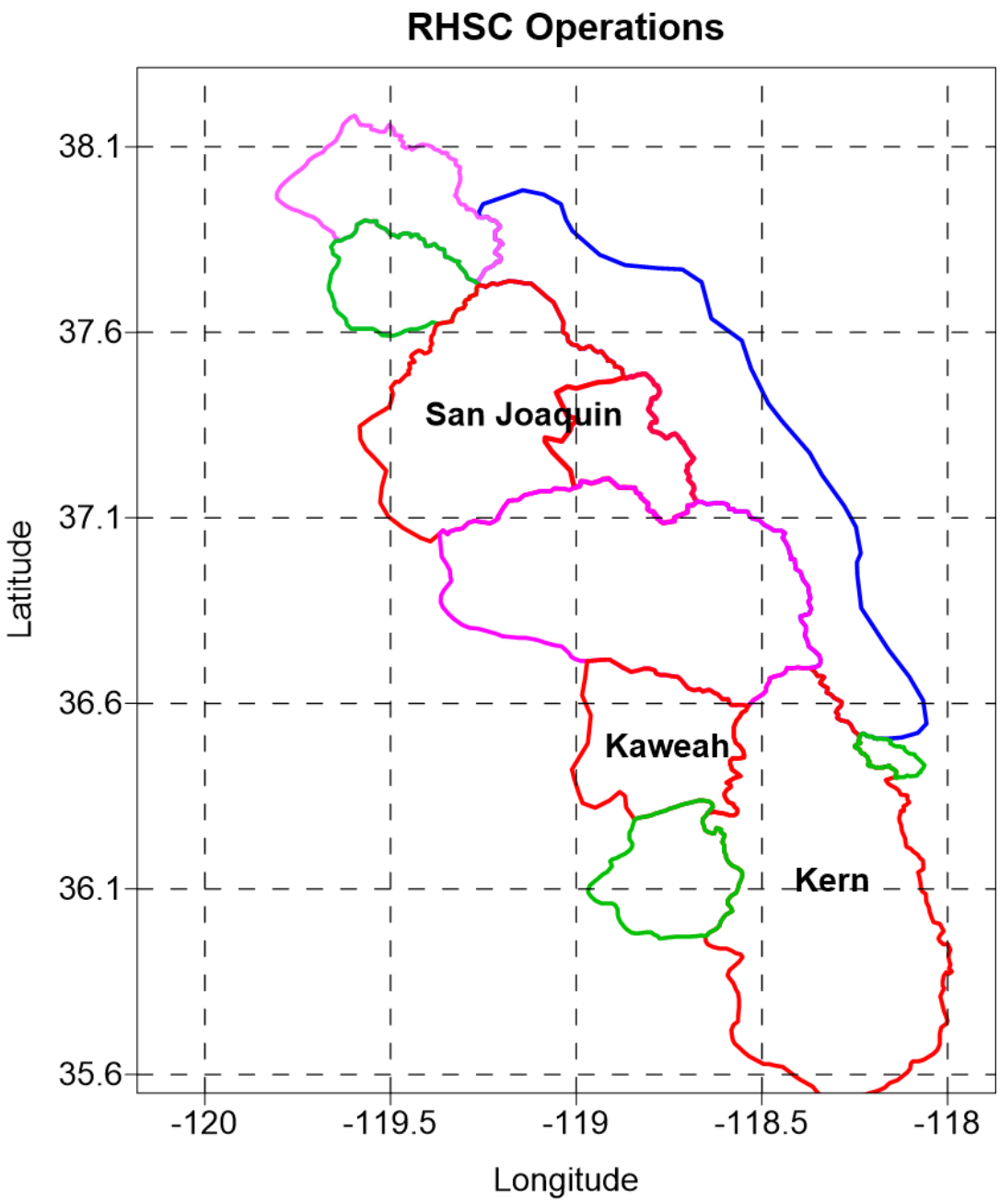
CLOUD SEEDING ACTIVITIES IN THE SOUTHERN SIERRA NEVADA

By
Rick Stone
RHS Consulting, Ltd
Reno, NV

Seeding Program Goals

- Three operational programs: Kaweah, Kern and San Joaquin (Nov-Apr)
- To increase snowpack and streamflow flowing into watershed reservoirs
- These are purely Operational Programs – not a research programs
- Evaluations are limited in scope and expense – statistical vs. physical methods


RHSC Operations
38.1
37.6
37.1
36.6
36.1
35.6
Latitude
-120
-119.5
-119
-118.5
-118
Longitude
San Joaquin
Kaweah
Kern

Seeding Strategies

- Seed aggressively at higher rates (up to 3kg/hr)
- Aircraft seeds at the top of the SLW layer to optimize seeding effect, not tied to the -6 ^{o}C
- Fly faster patterns to fill cloud volume
- Radiometer and Satellite Enhanced Vapor used to identify seed opportunities before radar echoes are detected as vapor builds upwind of the barrier

Strageties (cont'd)

- Ops planned based on explicit SLW forecasts, Cloud Seeding Index (water/ice ratio)
- Aircraft seeding conducted mostly before surface front passage when SLW and Max CSI are forecast
- Seed mixed phase systems with high CSR's and moderate precip rates with SLW.
- Strategic location of Radiometer is key to validating SLW forecasts and optimizing aircraft seeding altitude.

Program Details

- Twin Engine Aircraft equipped with ejectable and end burning flares
- Remote Ground-based Generators
- NEXRAD Radar (Latest version of Titan)
- Radiometer
- HydroWRF
- Statistical Evaluation – Streamflow and SWE
- Physical Evalution - Snow Chemistry
- Fresno Based Operations

Seeding Aircraft

- Piper PA-31P, PA-31T and BE-90
- Seeding equipment, LB's and EJ's
- Known Ice, Pressurized, Oxygen
- Weather Radar
- IFR GPS WAAS

Flares and Equipment

Building a Seeding Aircraft

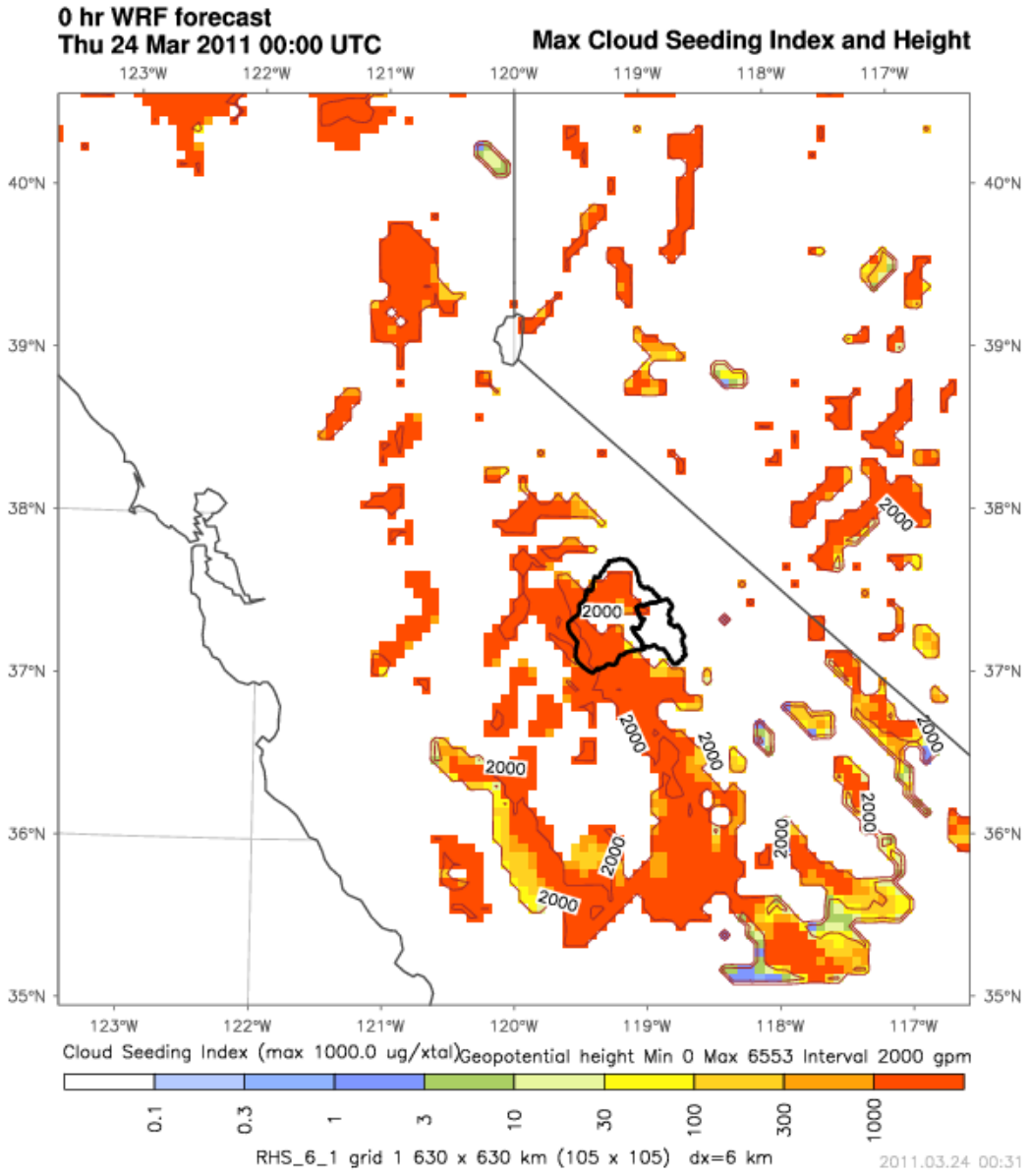
HydroWRF Model

- Automated QPF forecast system to support cloud seeding operations with EXPLICIT SLW AND ICE FORECASTS
- Based on the WRF-ARW – current version 3.4
- 36-hour forecast generated *continuously* every 6 hours
- High-resolution grids (outer spacing 6-km; inner spacing 1-km)
- Precipitation forecast at the sub-basin level; input to hydrologic operations model

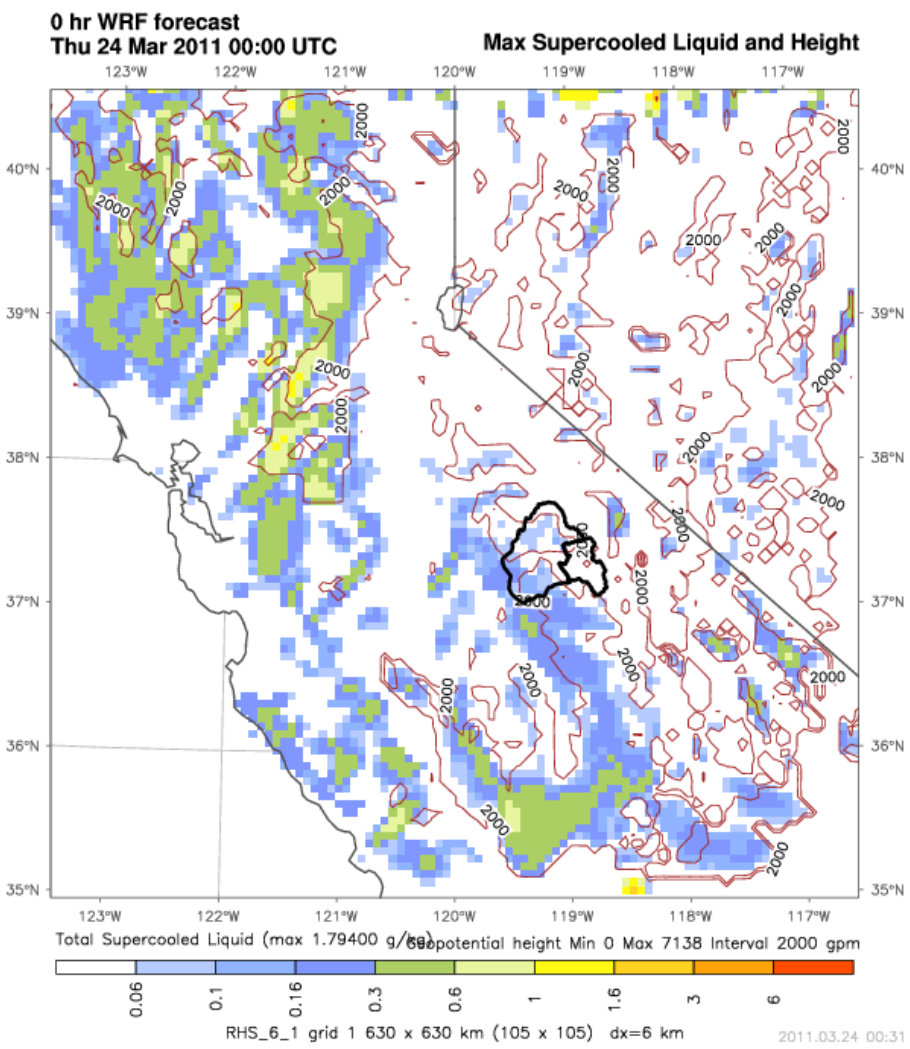
HydroWRF Operational Forecast Products

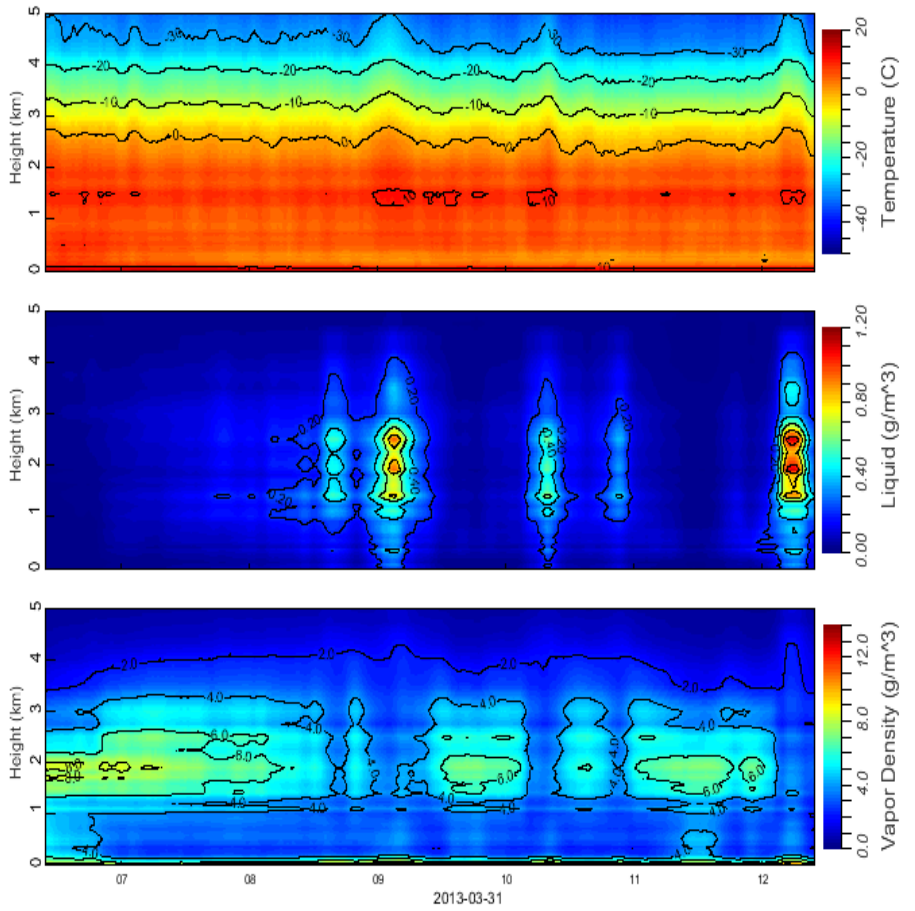
- 500 mb, 700 mb , Surface Winds, Rel. Hum., Pressure, Temps, Precipitation, Accumlation, Cloud Cover, Radar Echo, etc.
- Gridded data for used in RAOB (ops planning) and targeting model
- Turbulence (4,000 - 20,000'), Vertical Cross Sections
- **SLW, ICC and CSI**

Max Cloud Seeding Index

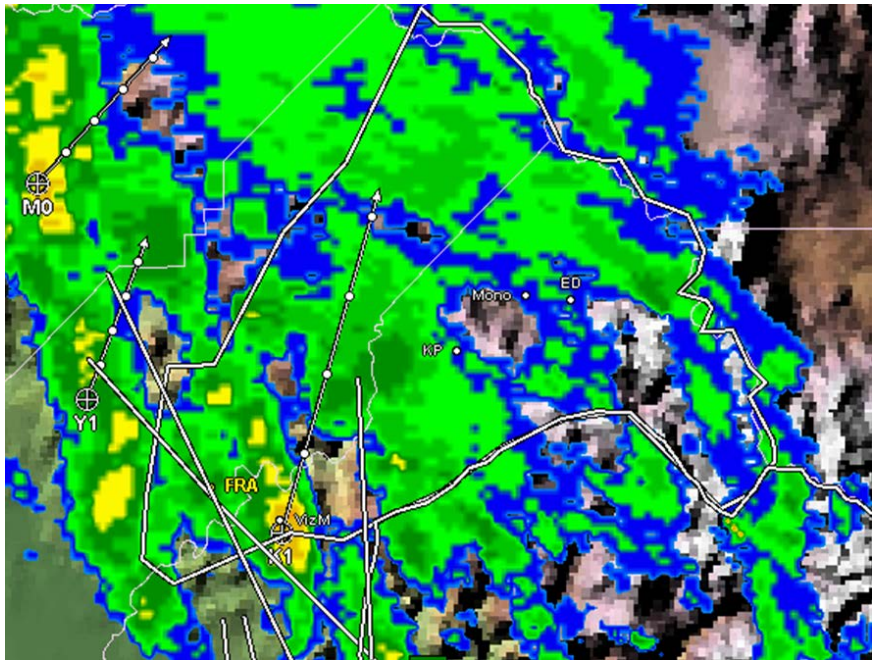


Does it Work? - 110225 @ 0500Z




Height (km)
Temperature (C)
Liquid (g/m^3)
Vapor Density (g/m^3)
07
08
09
10
11
12
2013-03-31

radiometrics
corporation


M0
Y1
FRA
VizM
Mono
ED
KP

Evaluation Methods

- Snow Survey Data – Generalized Kriging
- Streamflow – Ratio Regressions updated with new data to reflect recent trends. Log transformation used improve confidence bounds
- Snow Chemistry

SWE Analysis

- Snow records extend from 1925-present
- Data publicly available from CDWR-CDEC
- Southern Sierra – 118 sites available with varying records, April 1 data most consistent because of water planning needs
- Densities vary by Watershed
- Newer sites excluded with less than three years record prior to the start of seeding
- Data stratified by individual project ops

Project Ops – Data Stratification

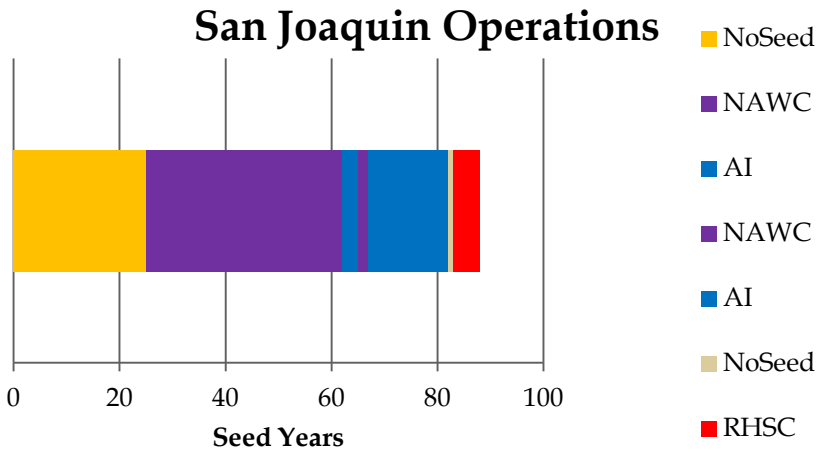
NON-SEEDED PERIODS

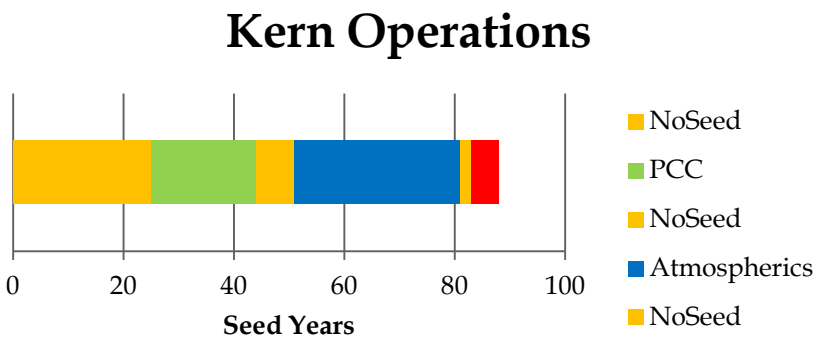
- Kaweah: 1925-1955, *1956-1976*
- Kern: 1925-1950, 1970-1976
- Kings: 1925-1955, 1982-1987
- San Joaquin: 1925-1950, 2008

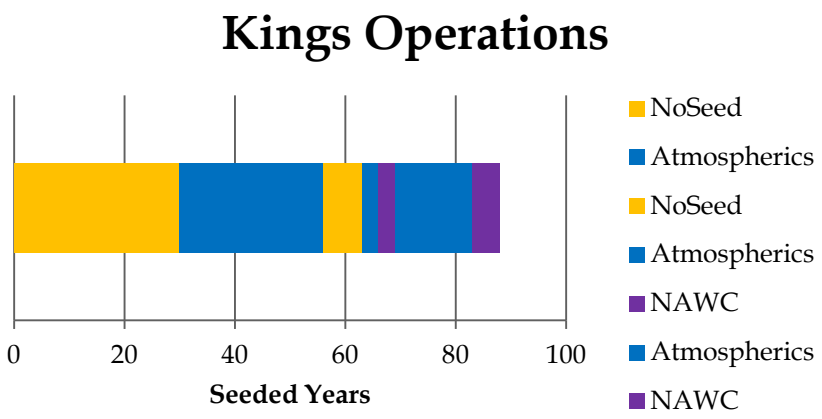
SEEDED PERIODS

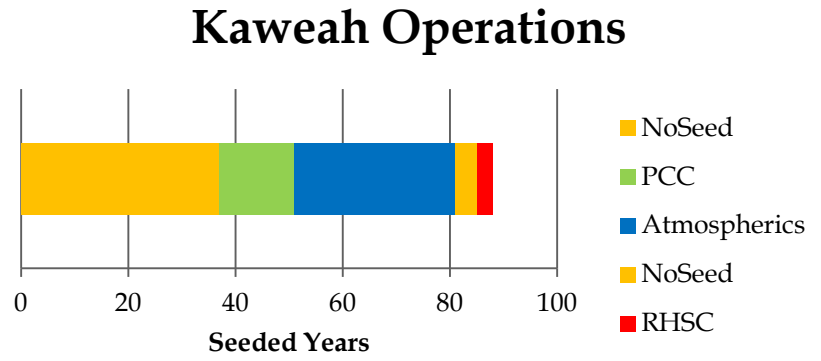
- Kaweah: *1962-1976*, 1977-2007, 2010-present
- Kern: *1951-1970*, 1977-today
- Kings: 1955-1981, 1988-today
- San Joaquin: 1951-2007, 2009-today

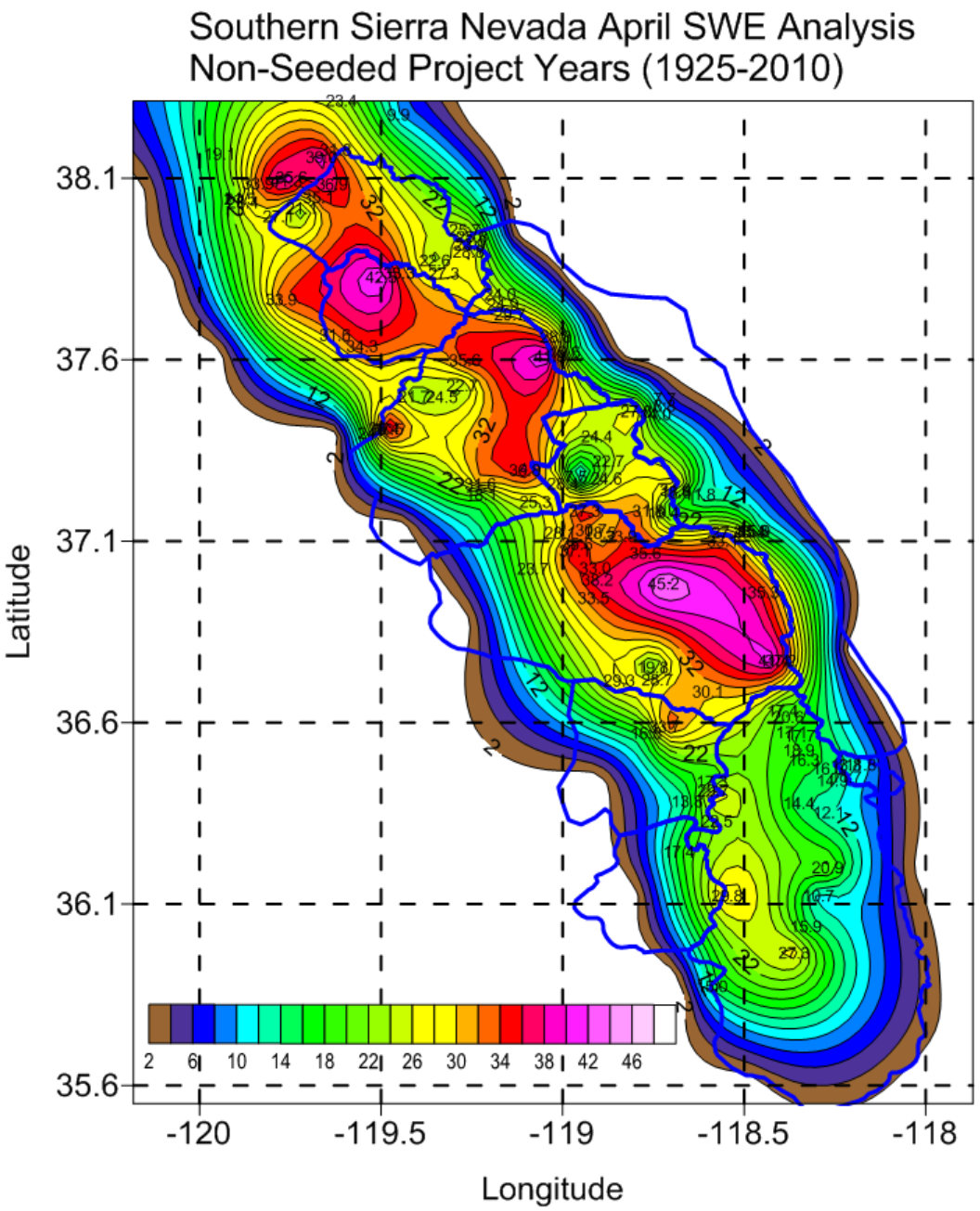
Southern Sierra Project Timelines

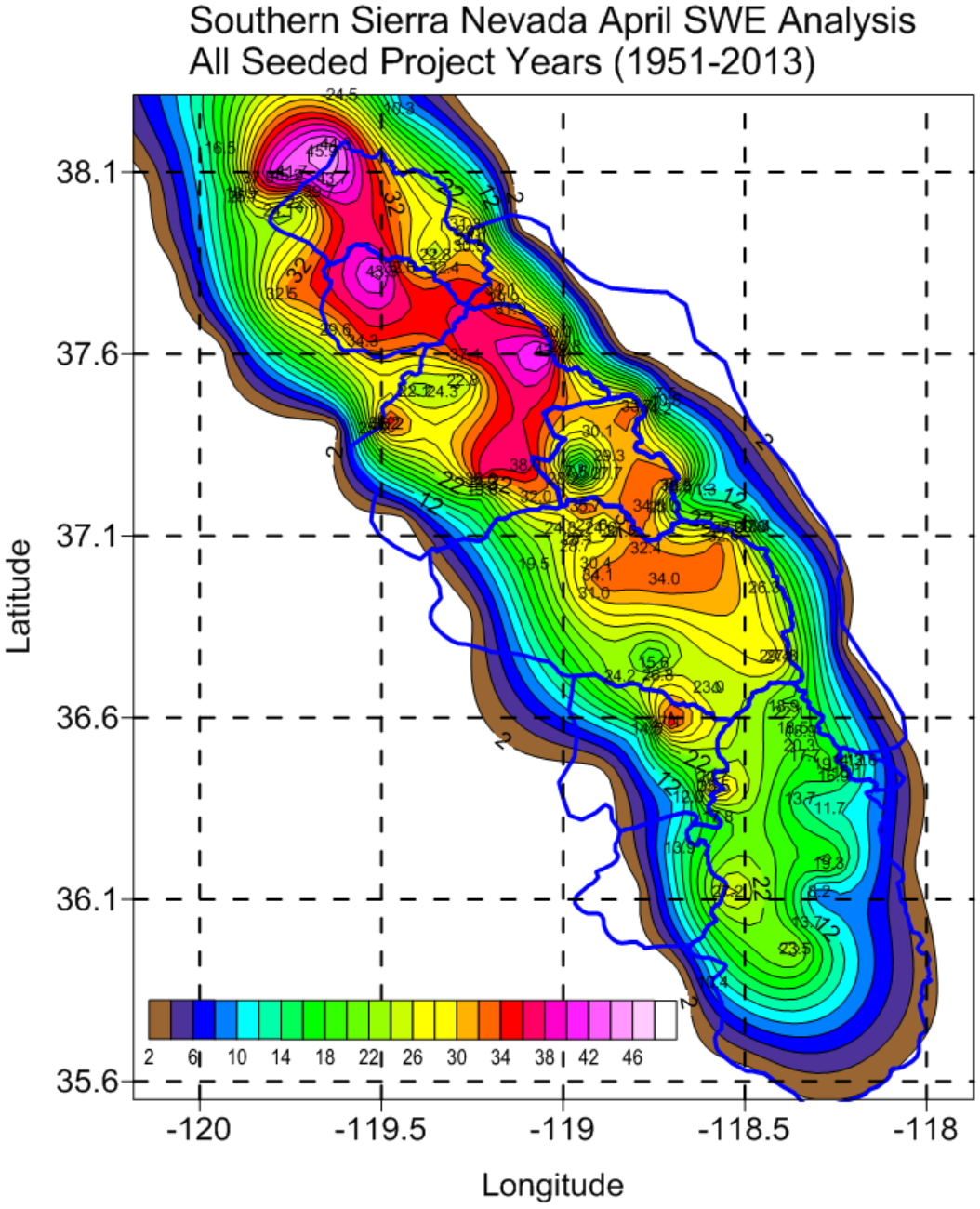


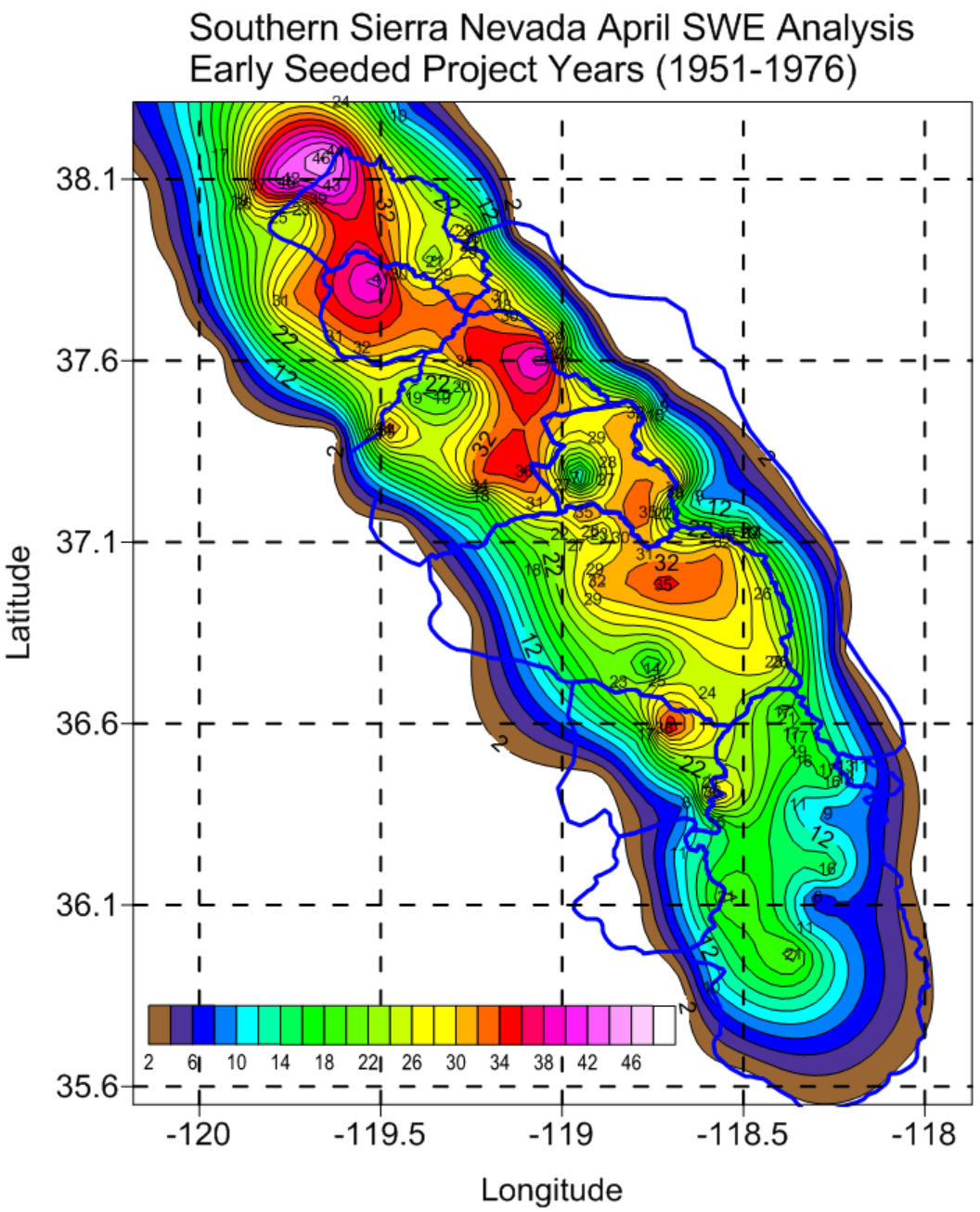







Southern Sierra Nevada April SWE Analysis
Non-Seeded Project Years (1925-2010)
Latitude
38.1
37.6
37.1
36.6
36.1
35.6
-120
-119.5
-119
-118.5
-118
Longitude
2 6 10 14 18 22 26 30 34 38 42 46


Southern Sierra Nevada April SWE Analysis
All Seeded Project Years (1951-2013)
Latitude
38.1
37.6
37.1
36.6
36.1
35.6
-120
-119.5
-119
-118.5
-118
Longitude
2 6 10 14 18 22 26 30 34 38 42 46


Southern Sierra Nevada April SWE Analysis
Early Seeded Project Years (1951-1976)
Latitude
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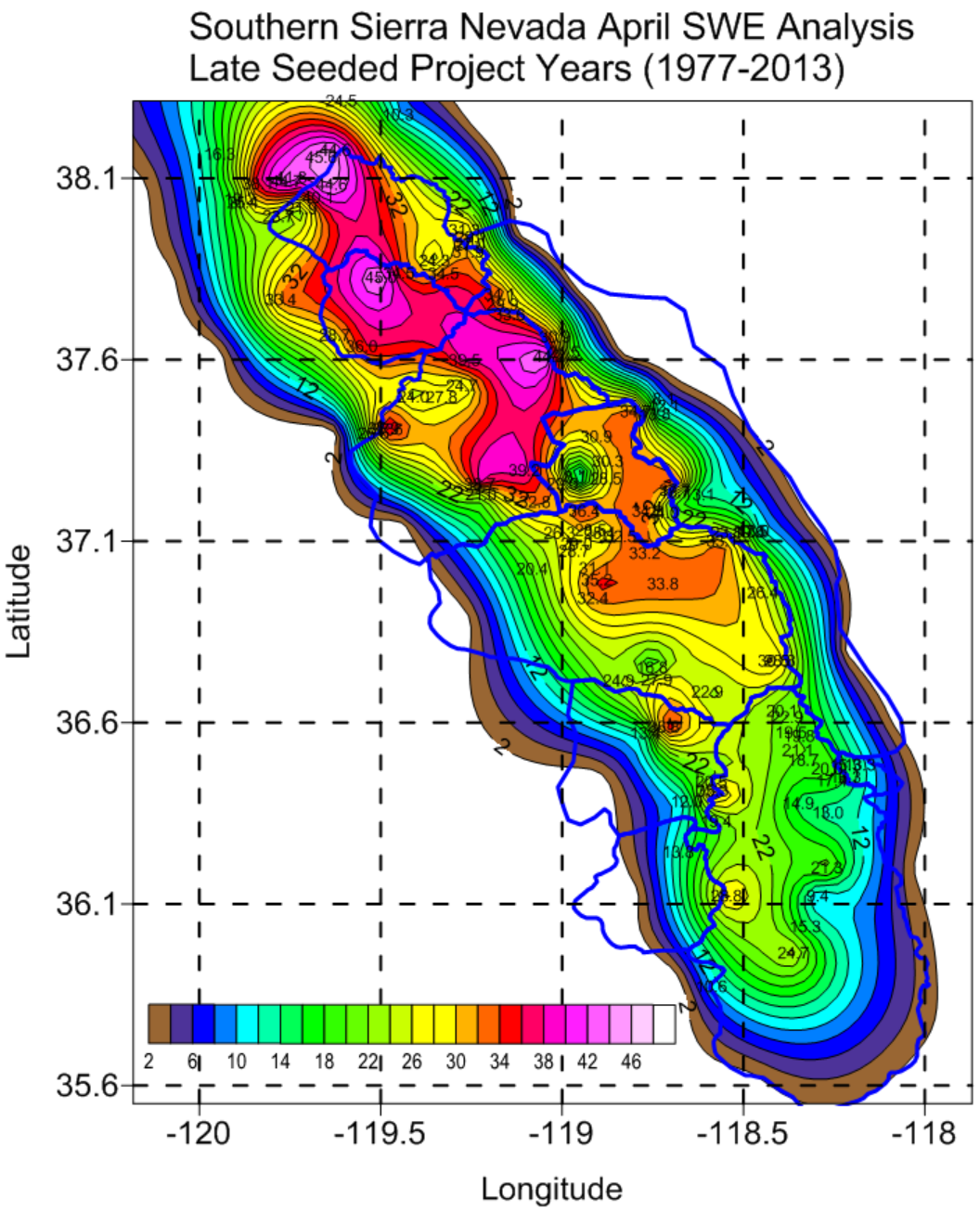
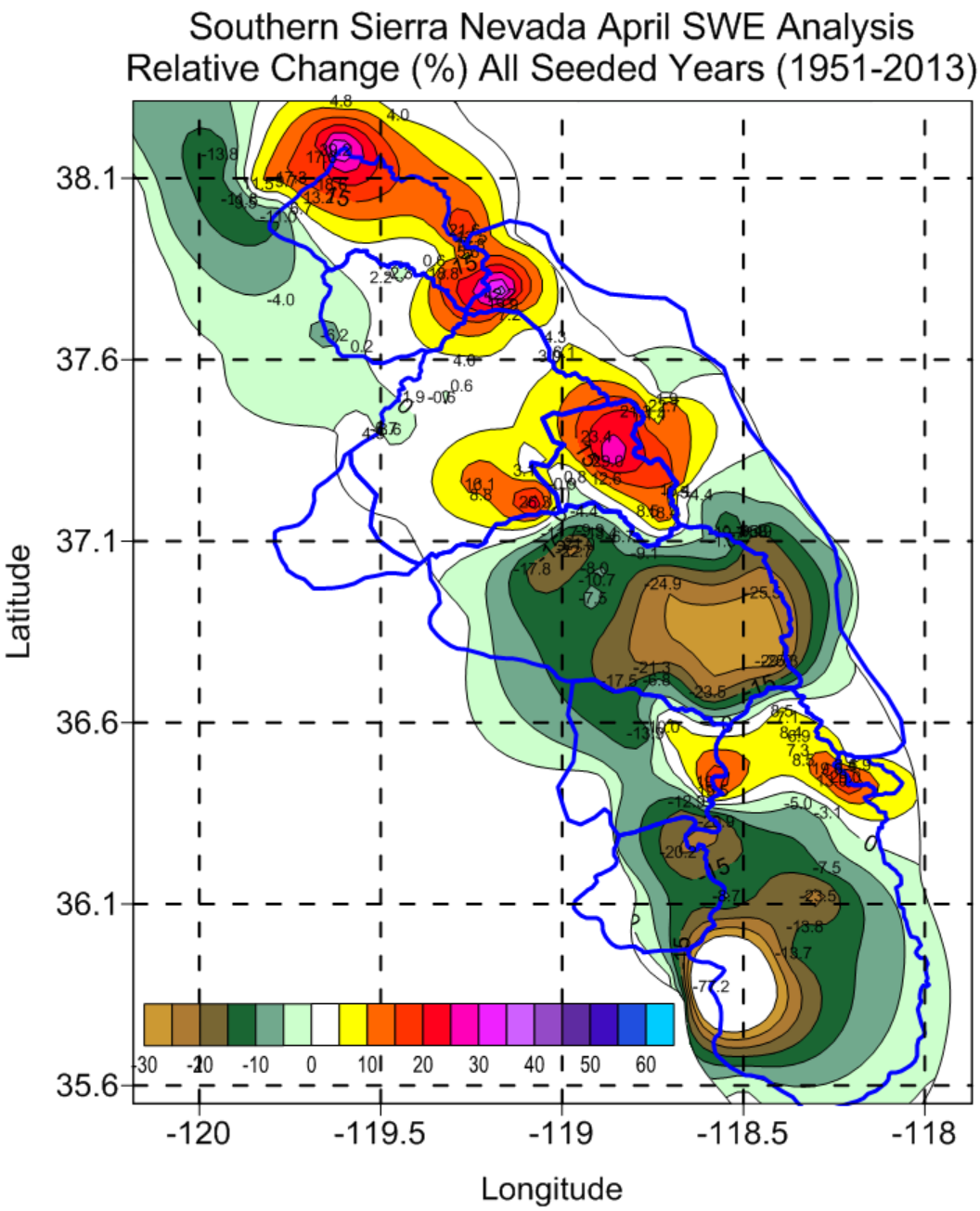
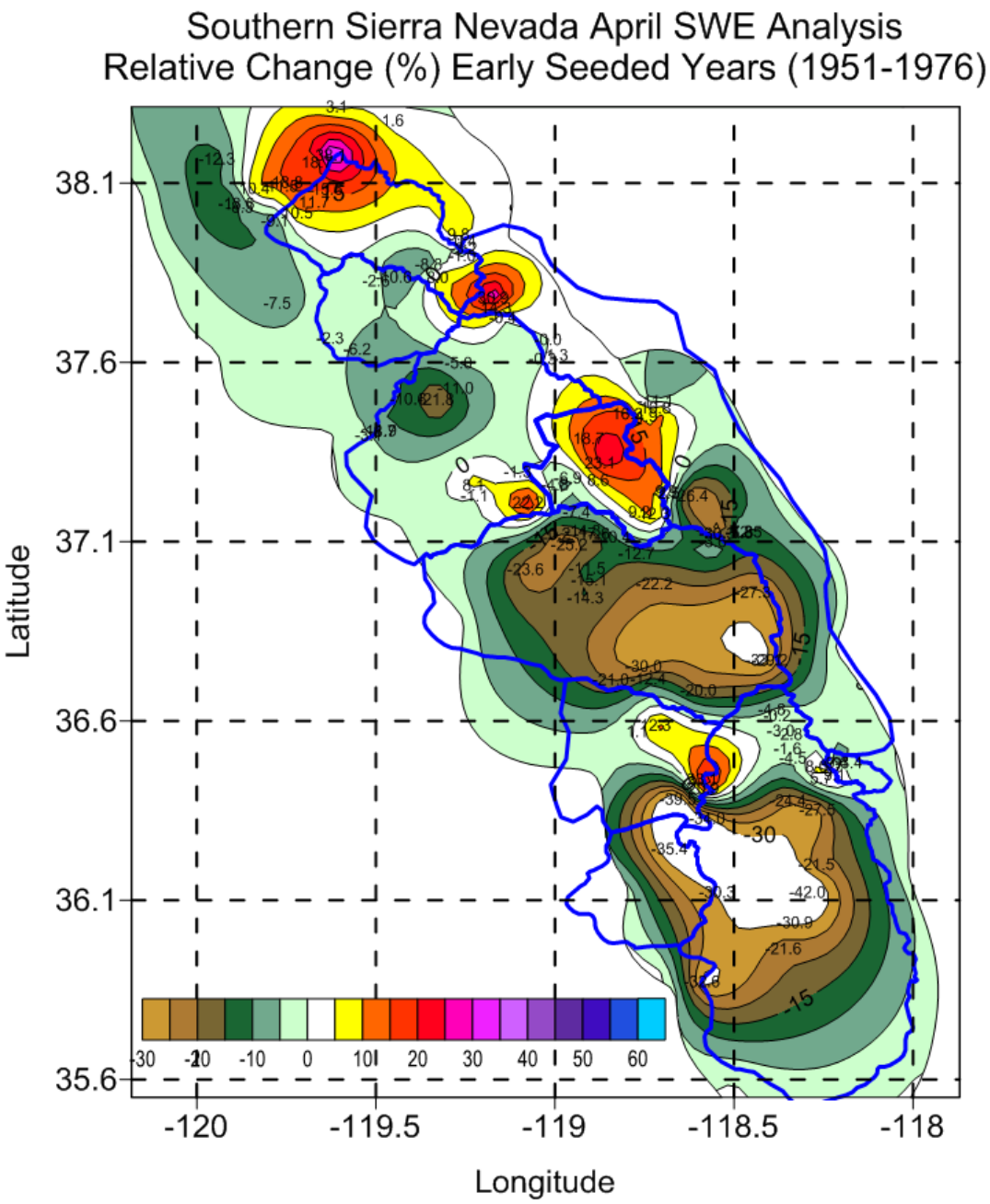
37.6
37.1
36.6
36.1
35.6
-120
-119.5
-119
-118.5
-118
Longitude
2 6 10 14 18 22 26 30 34 38 42 46


Southern Sierra Nevada April SWE Analysis
Late Seeded Project Years (1977-2013)
Latitude
38.1
37.6
37.1
36.6
36.1
35.6
-120
-119.5
-119
-118.5
-118
Longitude
2 6 10 14 18 22 26 30 34 38 42 46


Southern Sierra Nevada April SWE Analysis
Relative Change (%) All Seeded Years (1951-2013)
Latitude
38.1
37.6
37.1
36.6
36.1
35.6
-120
-119.5
-119
-118.5
-118
Longitude
-30
-20
-10
0
10
20
30
40
50
60


Southern Sierra Nevada April SWE Analysis
Relative Change (%) Early Seeded Years (1951-1976)
Latitude
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37.6
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36.6
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Longitude
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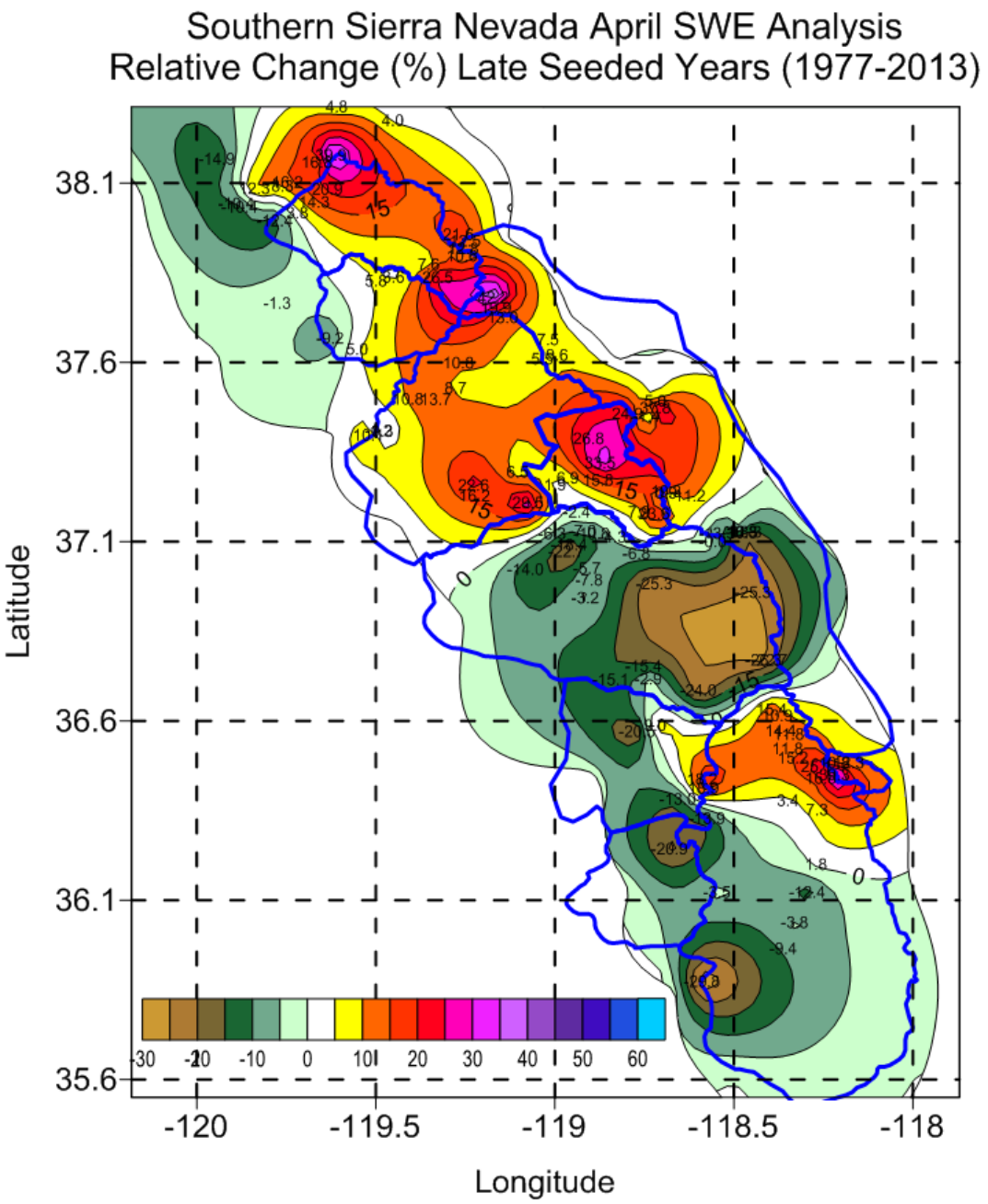
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Longitude
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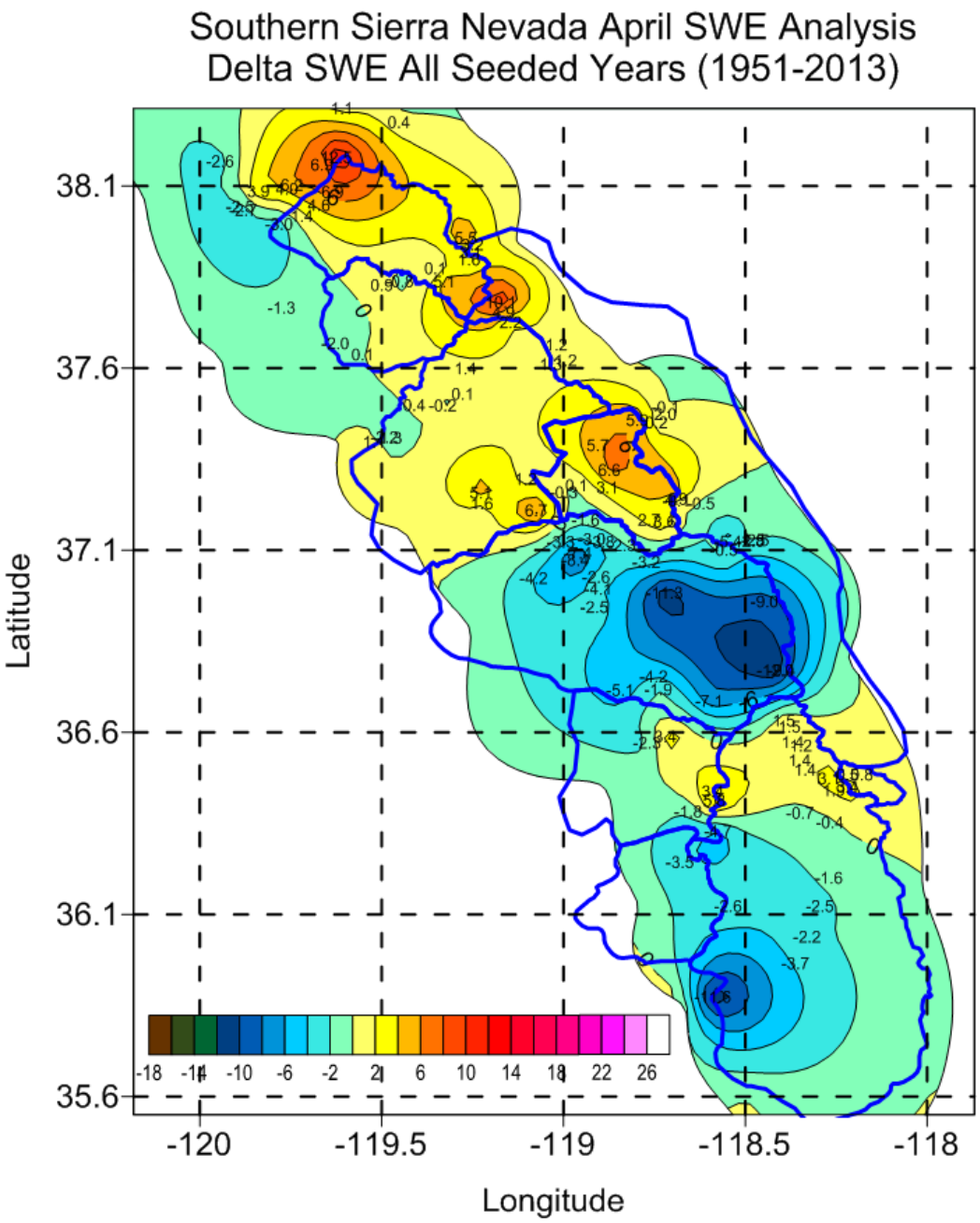
Southern Sierra Nevada April SWE Analysis
Delta SWE All Seeded Years (1951-2013)
Latitude
38.1
37.6
37.1
36.6
36.1
35.6
-120
-119.5
-119
-118.5
-118
Longitude
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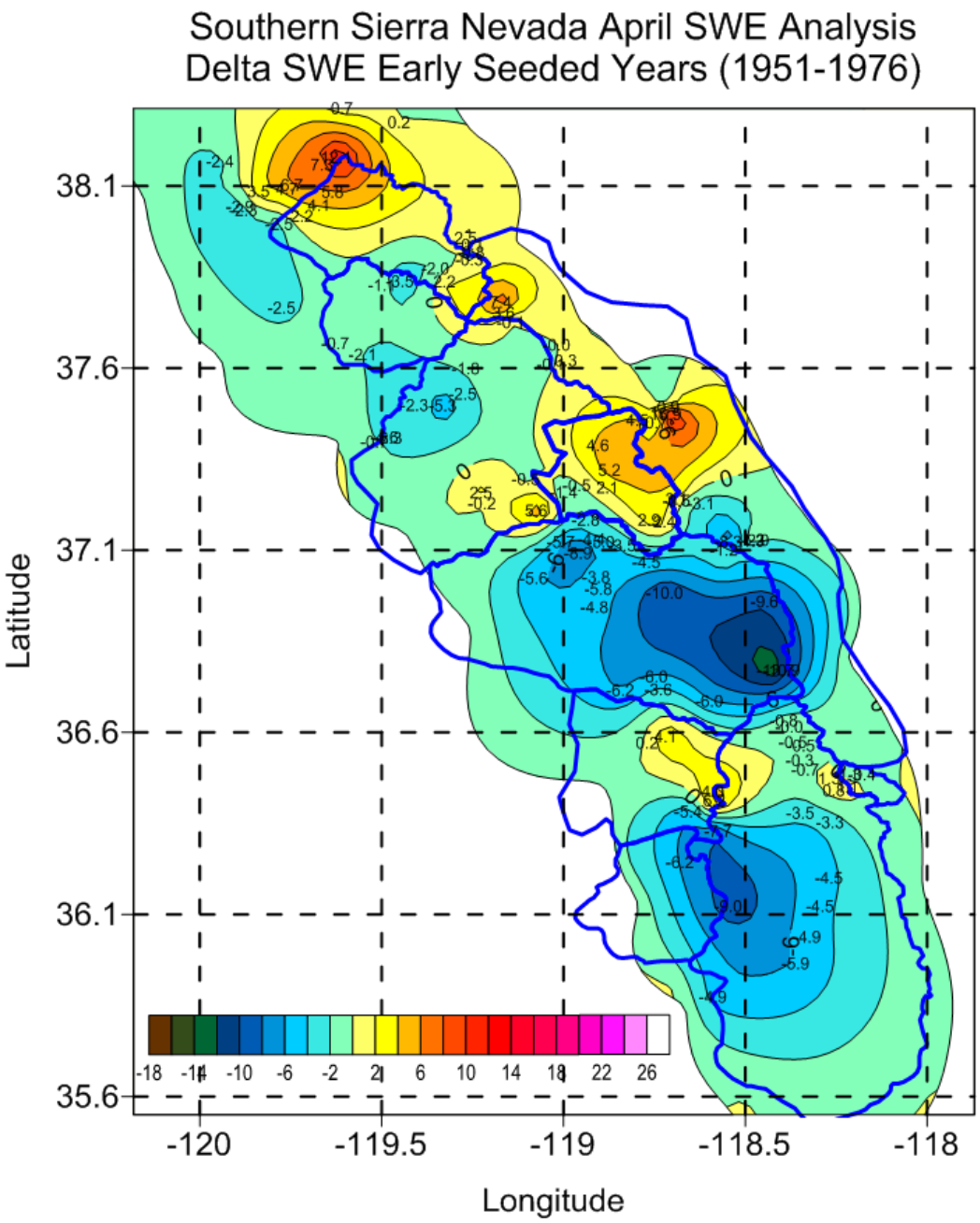
-2
2
6
10
14
18
22
26


Southern Sierra Nevada April SWE Analysis
Delta SWE Early Seeded Years (1951-1976)
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37.6
37.1
36.6
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35.6
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Longitude
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22
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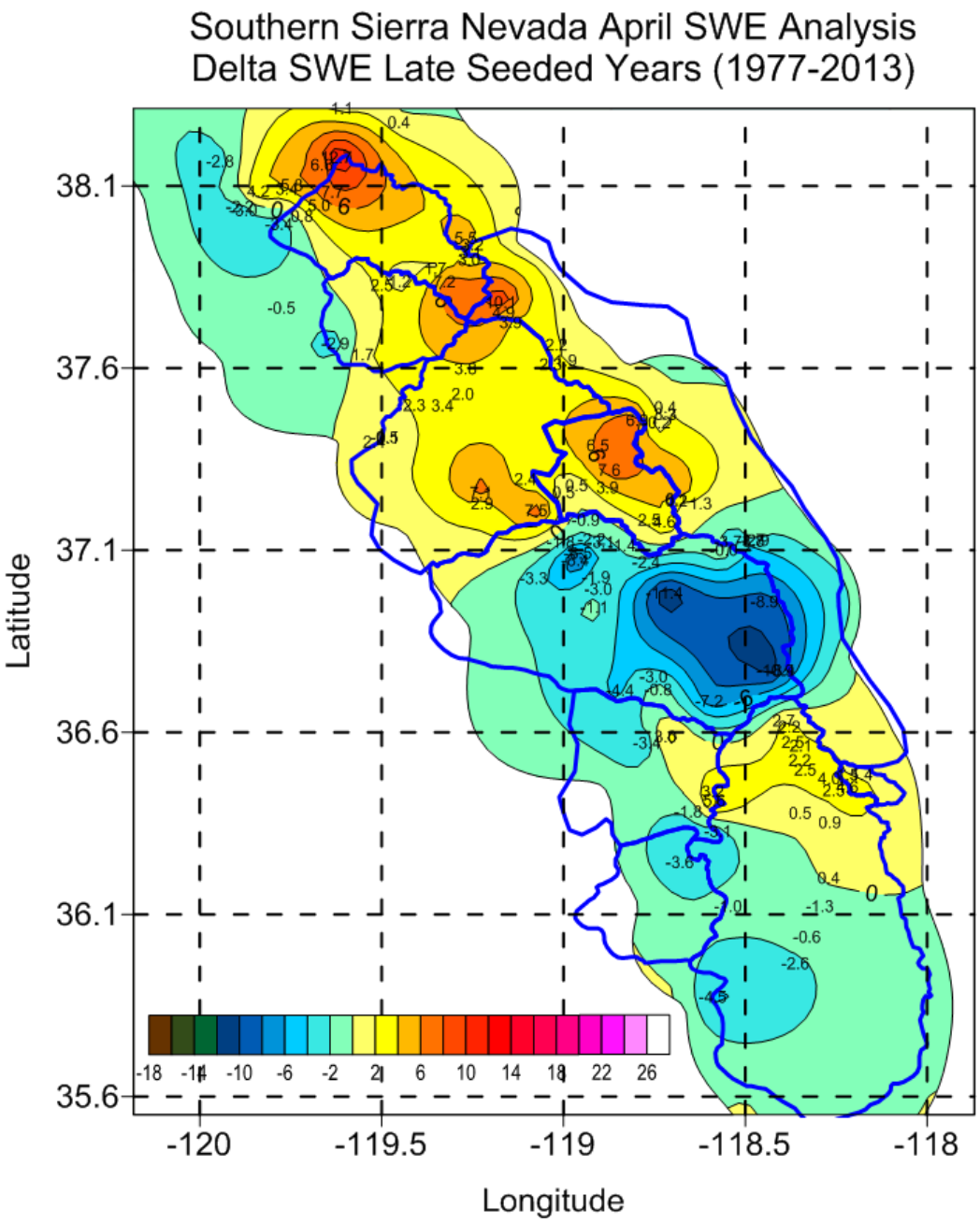
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Longitude
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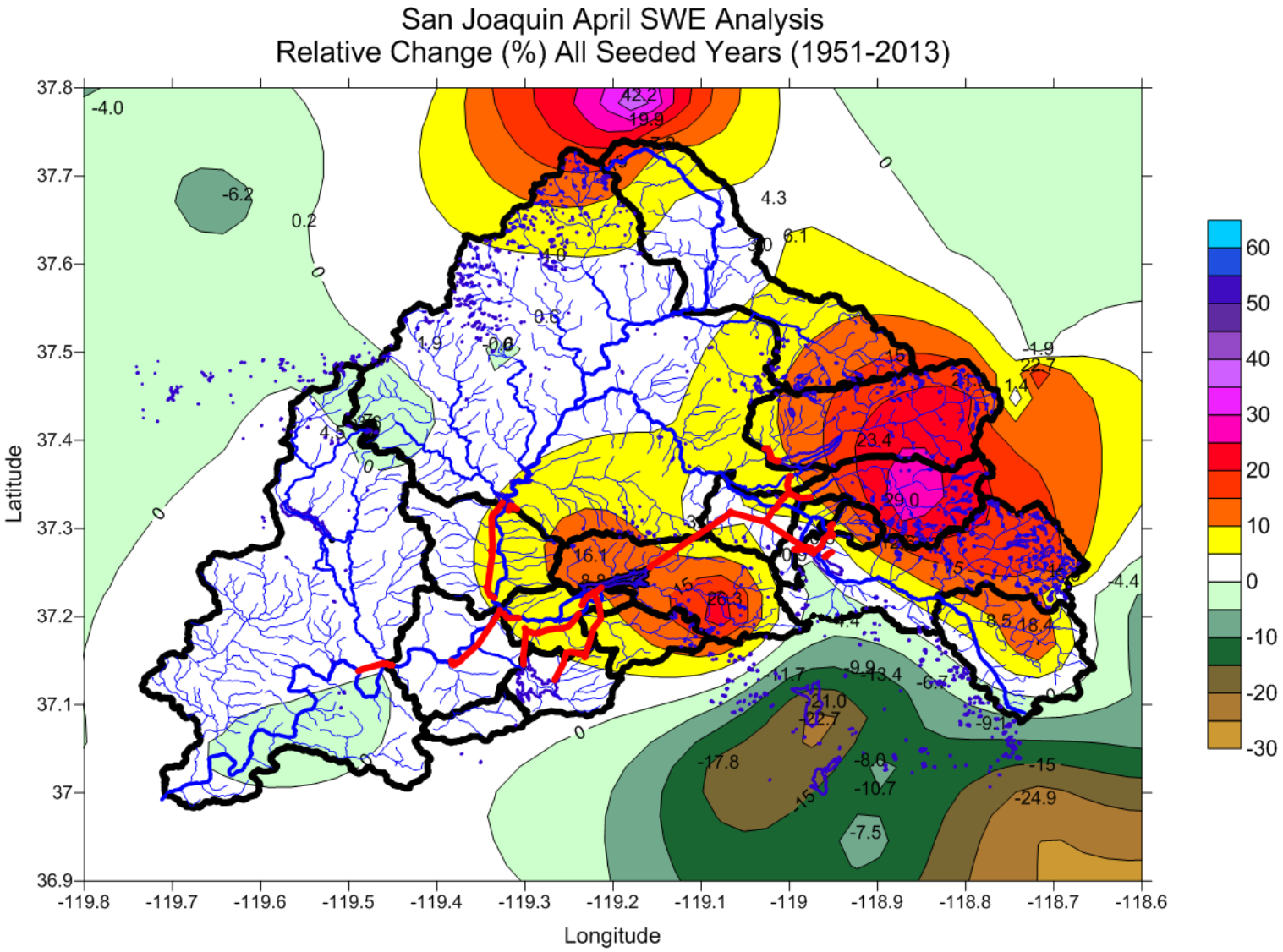
San Joaquin April SWE Analysis
Relative Change (%) All Seeded Years (1951-2013)
Latitude
Longitude
37.8
37.7
37.6
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37.4
37.3
37.2
37.1
37
36.9
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-119.7
-119.6
-119.5
-119.4
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-119.1
-119
-118.9
-118.8
-118.7
-118.6
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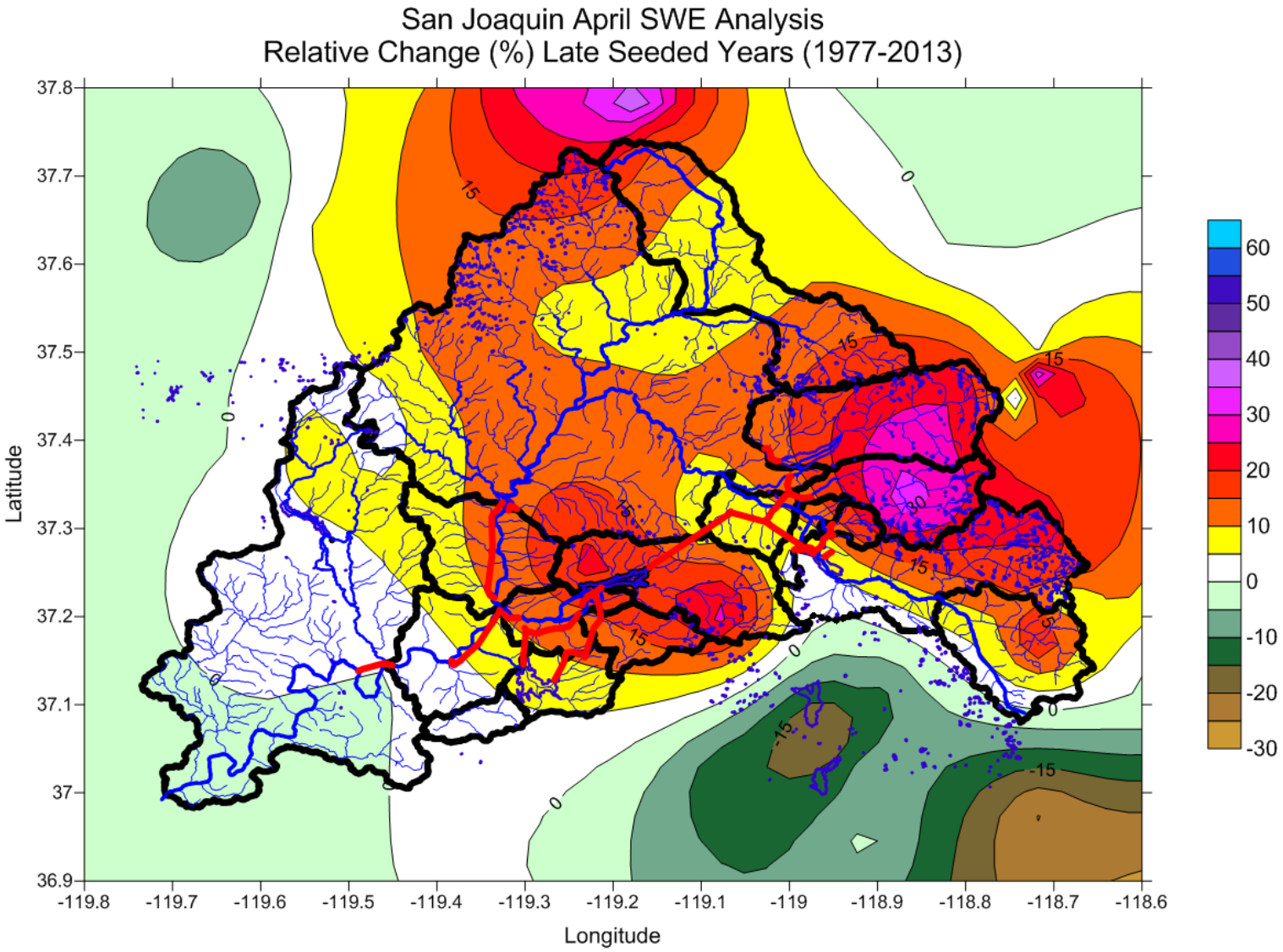
-20
-30


San Joaquin April SWE Analysis
Relative Change (%) Late Seeded Years (1977-2013)
Latitude
Longitude
37.8
37.7
37.6
37.5
37.4
37.3
37.2
37.1
37
36.9
-119.8
-119.7
-119.6
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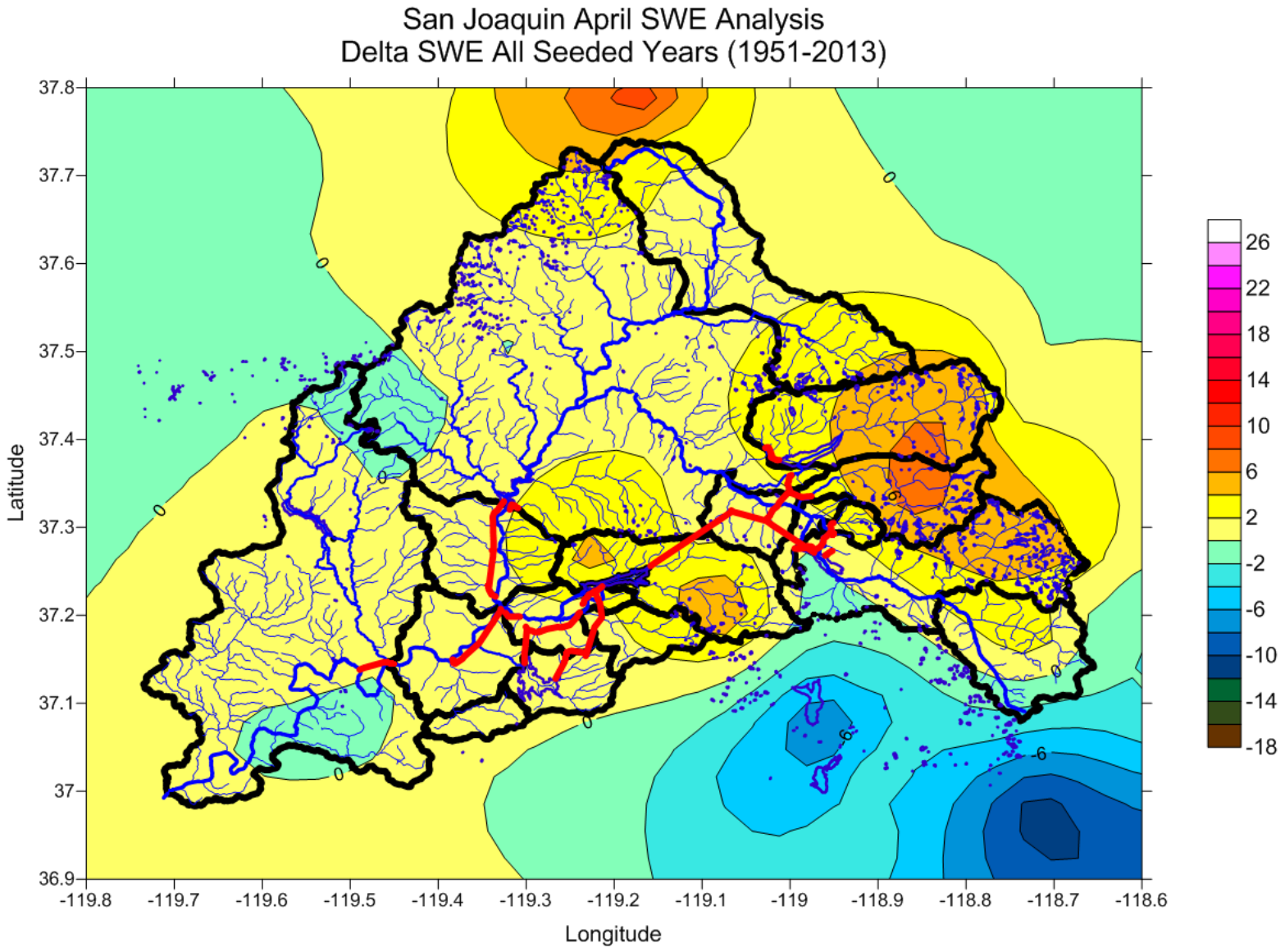
San Joaquin April SWE Analysis
Delta SWE All Seeded Years (1951-2013)
Latitude
Longitude
37.8
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37.2
37.1
37
36.9
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-119.7
-119.6
-119.5
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-119.3
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-119
-118.9
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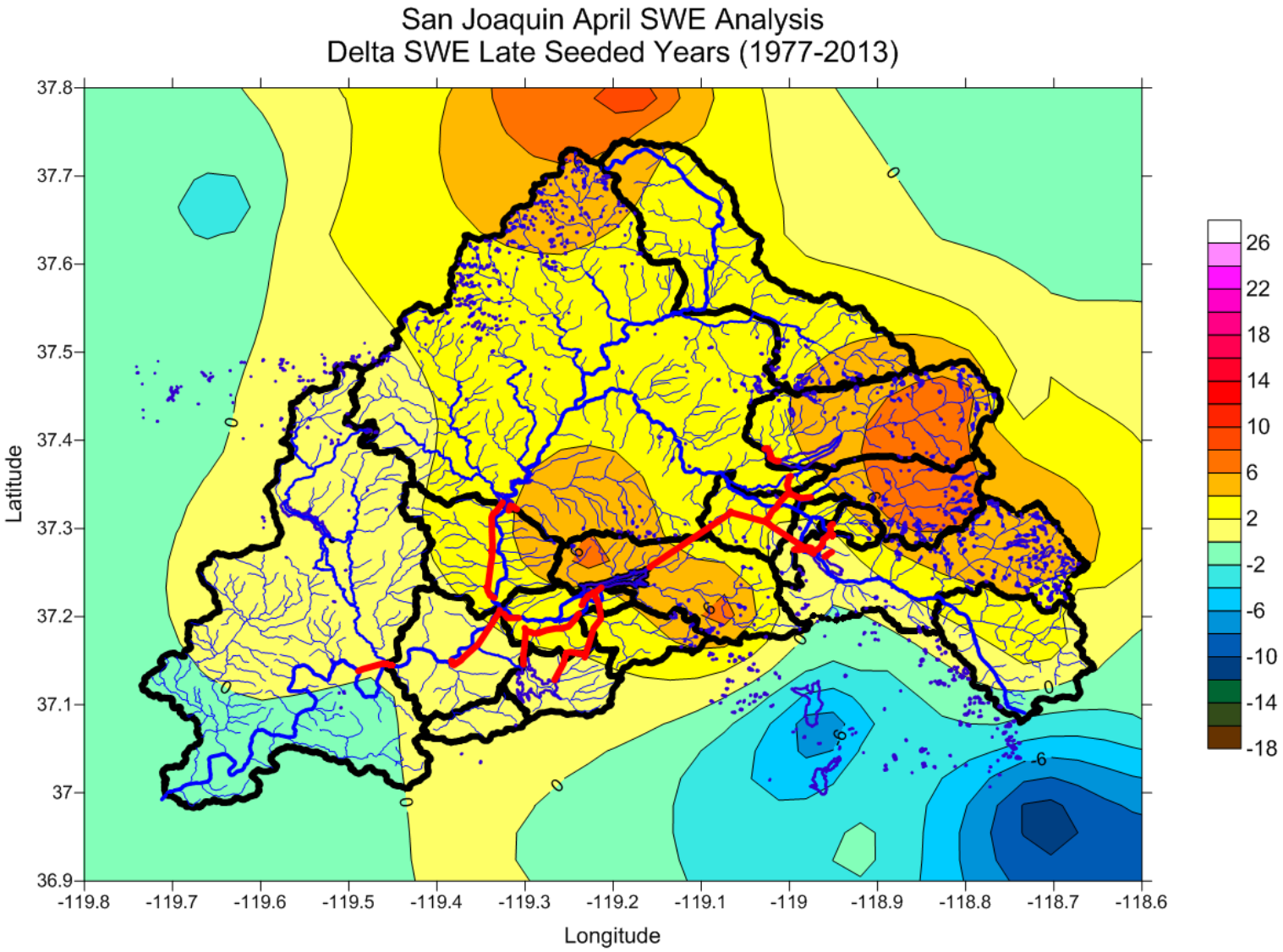
San Joaquin April SWE Analysis
Delta SWE Late Seeded Years (1977-2013)
Latitude
Longitude
37.8
37.7
37.6
37.5
37.4
37.3
37.2
37.1
37
36.9
-119.8
-119.7
-119.6
-119.5
-119.4
-119.3
-119.2
-119.1
-119
-118.9
-118.8
-118.7
-118.6
26
22
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14
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-2
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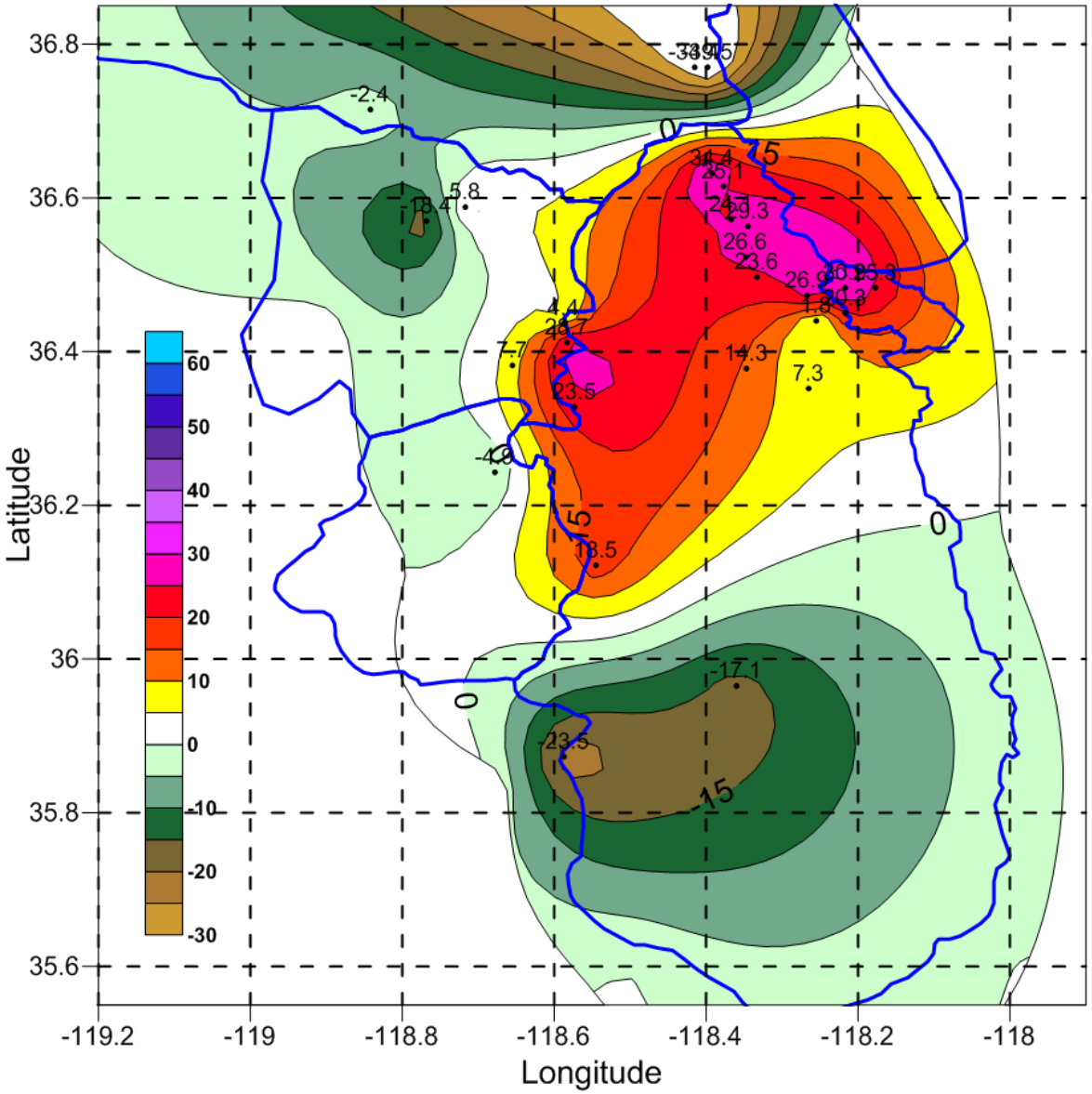
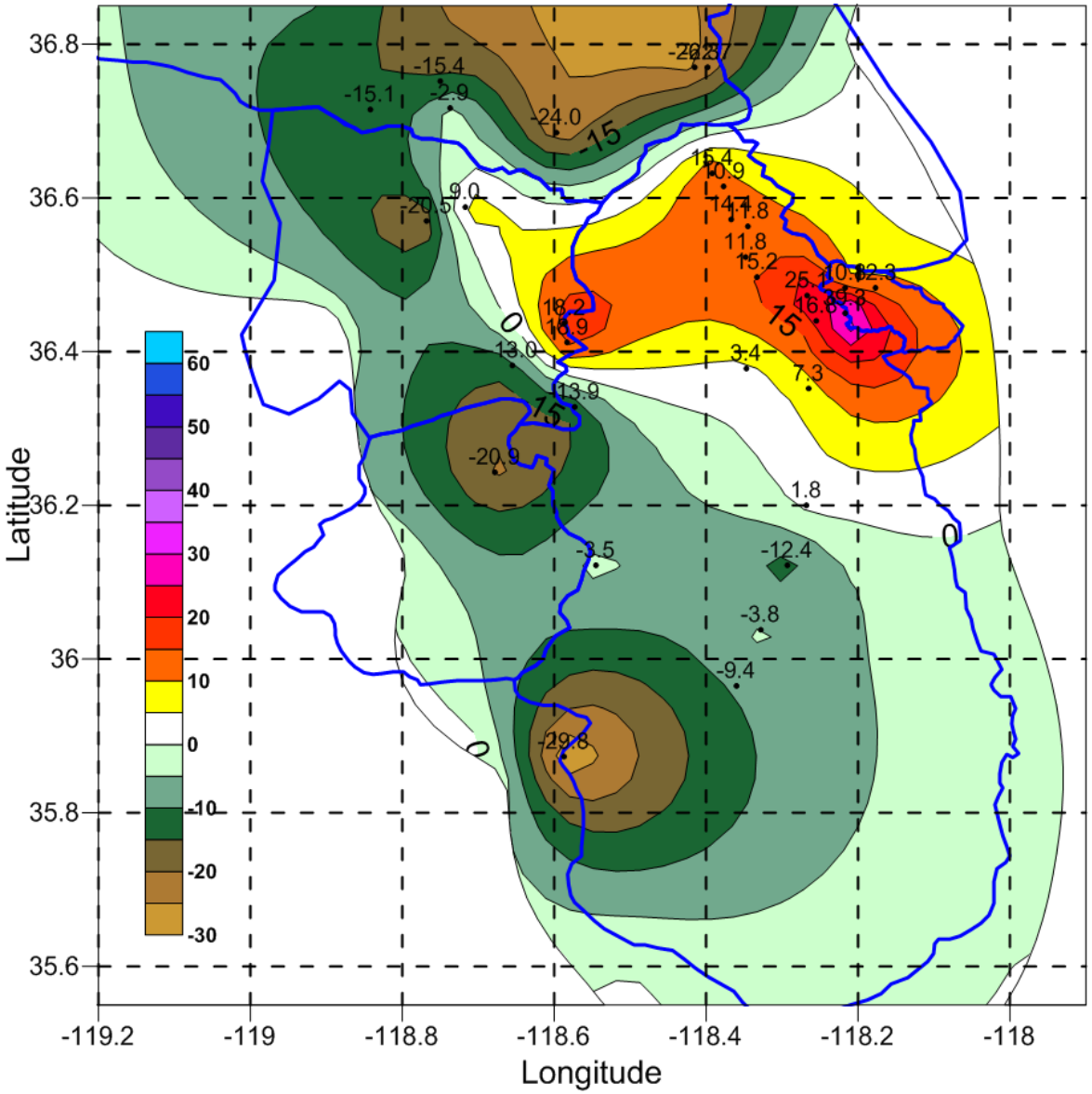
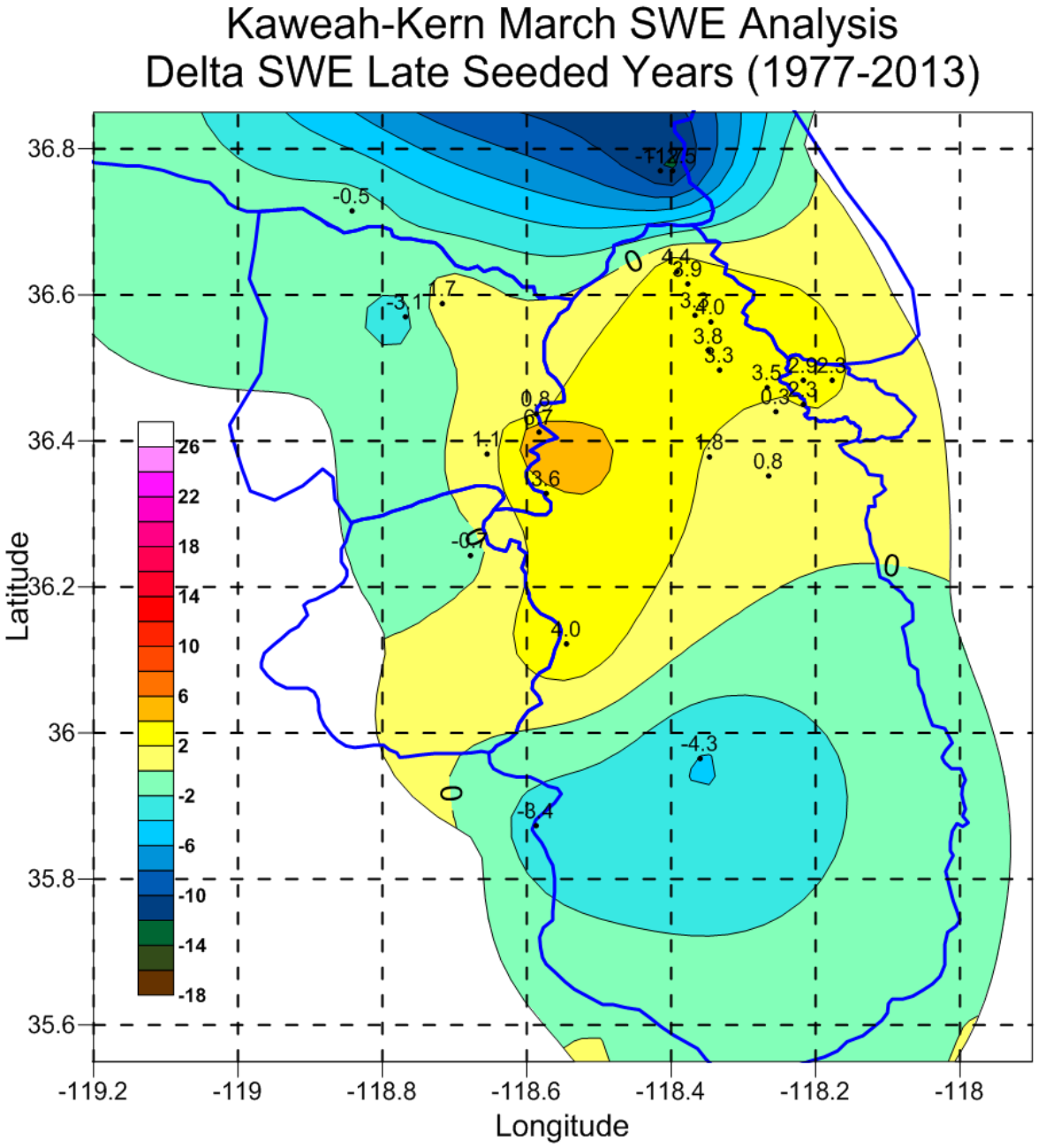
-6

Kaweah-Kern March SWE Analysis
Relative Change (%) Late Seeded Years (1977-2013)

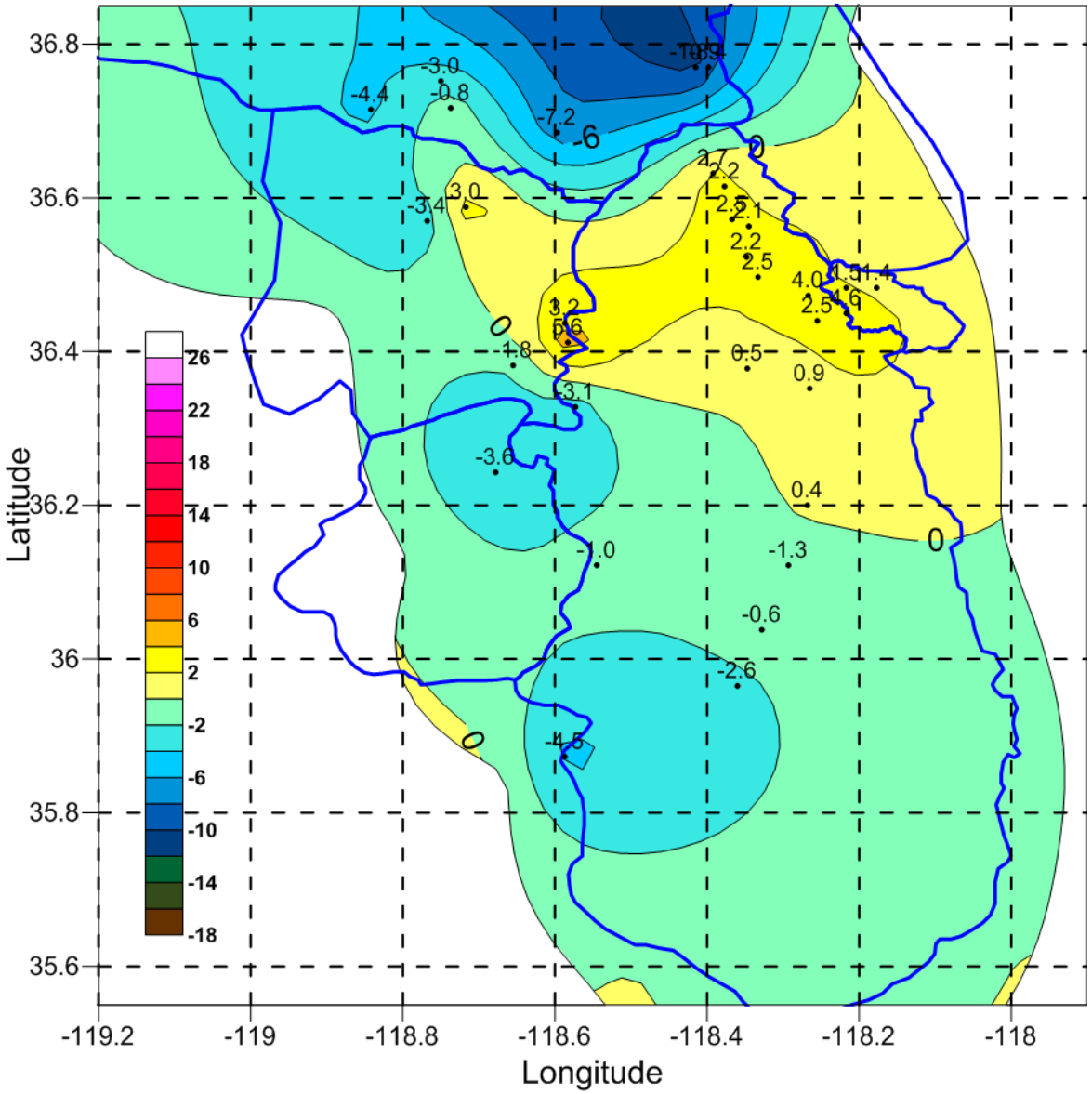


Kaweah-Kern April SWE Analysis
Relative Change (%) Late Seeded Years (1977-2013)




Kaweah-Kern March SWE Analysis
Delta SWE Late Seeded Years (1977-2013)
Latitude
Longitude
36.8
36.6
36.4
36.2
36
35.8
35.6
-119.2
-119
-118.8
-118.6
-118.4
-118.2
-118
26
22
18
14
10
6
2
-2
-6
-10
-14
-18
-12.5
-0.5
-3.1
1.7
4.4
3.9
3.7
4.0
3.8
3.3
3.5
2.9
2.8
2.3
2.1
0.3
0.8
0.7
1.1
3.6
1.8
0.8
-0.7
4.0
-4.3
-8.4
0

Kaweah-Kern April SWE Analysis
Delta SWE Late Seeded Years (1977-2013)

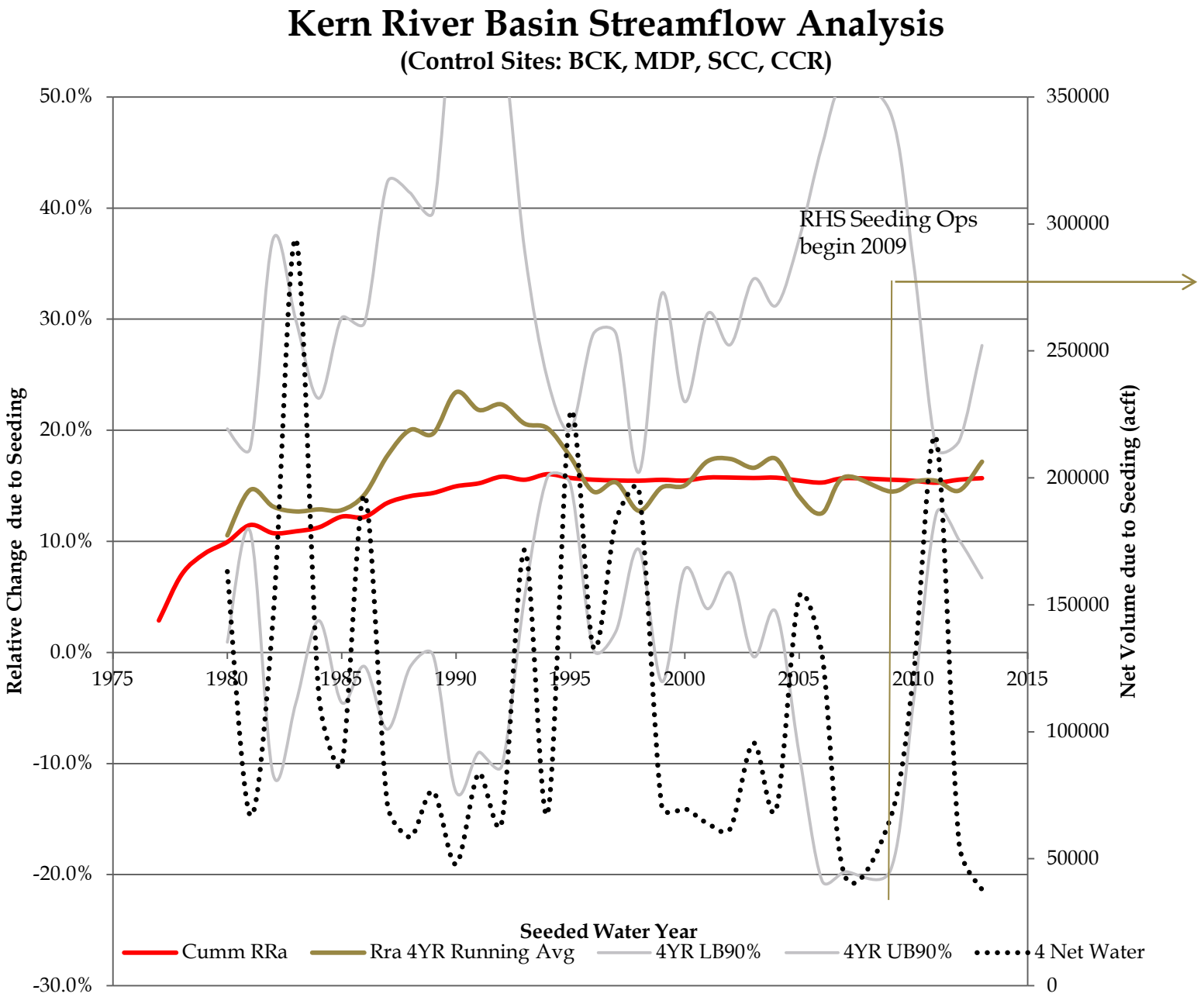


Streamflow Analyses

- Techniques used to assess the San Joaquin include:
- Double ratio and Regression Ratio methods
- Regression ratio analyses extended to include more recent data not provide in previous studies including bootstrapping techniques of Tukey et al. (1978)

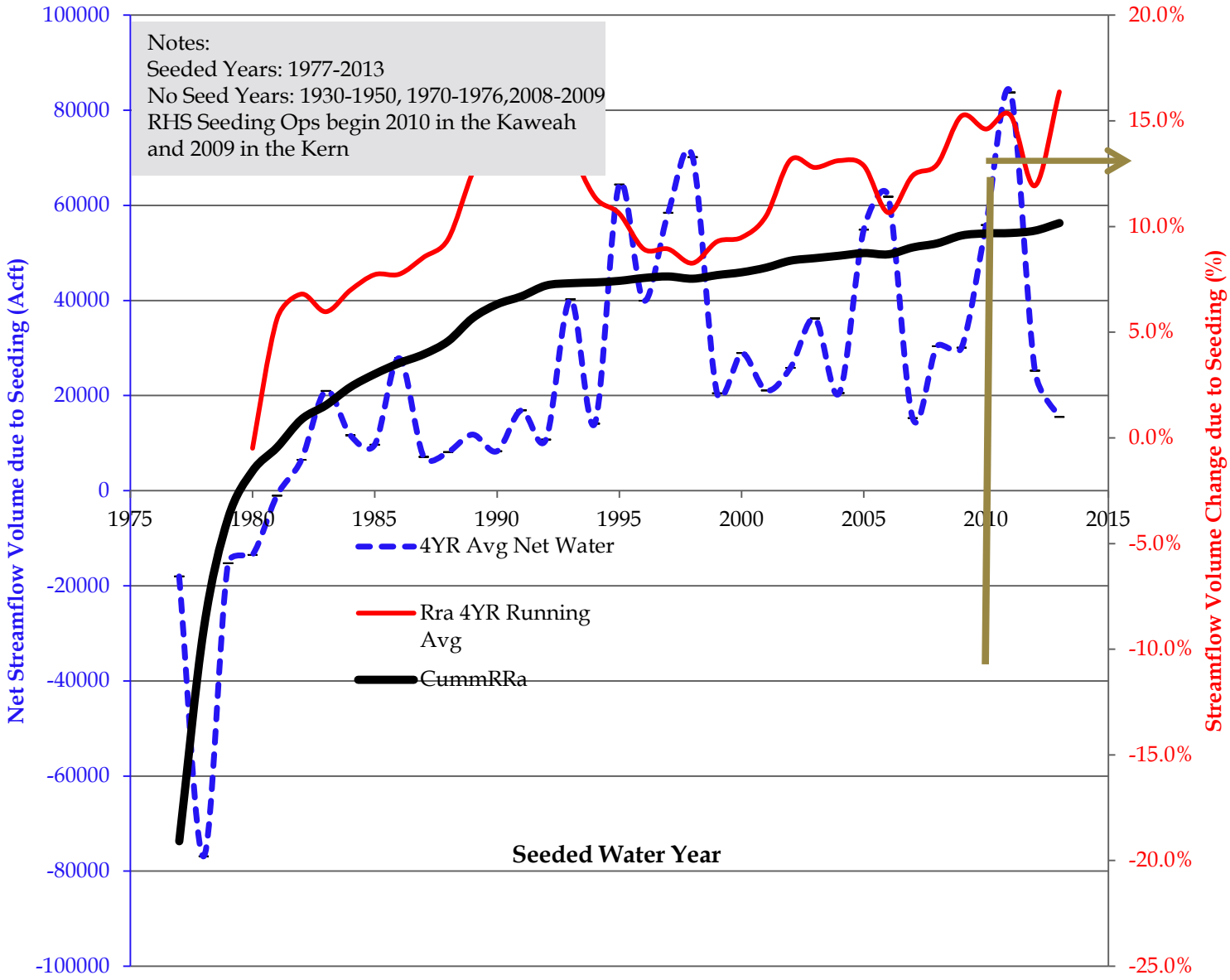
Streamflow Statistical Approach

- RR = SR/SR_{pred}; Regression Ratio
- $SR = TS_O/TS_H$; TS_O is the mean target flow during the operational seeding period and TS_H is the mean target flow during the historical Period
- SR_{pred} = is the ratio of TS_O and TS_H predicted by the target/control ratio over the <u>entire period</u> of analysis.


Kern River Basin Streamflow Analysis
(Control Sites: BCK, MDP, SCC, CCR)
RHS Seeding Ops begin 2009
Relative Change due to Seeding
Net Volume due to Seeding (acft)
Seeded Water Year
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
-10.0%
-20.0%
-30.0%
350000
300000
250000
200000
150000
100000
50000
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
Cumm RRa
Rra 4YR Running Avg
4YR LB90%
4YR UB90%
4 Net Water

Kaweah River Basin Streamflow Analysis

(Control Sites: BCK, MDP, SCC, CCR)

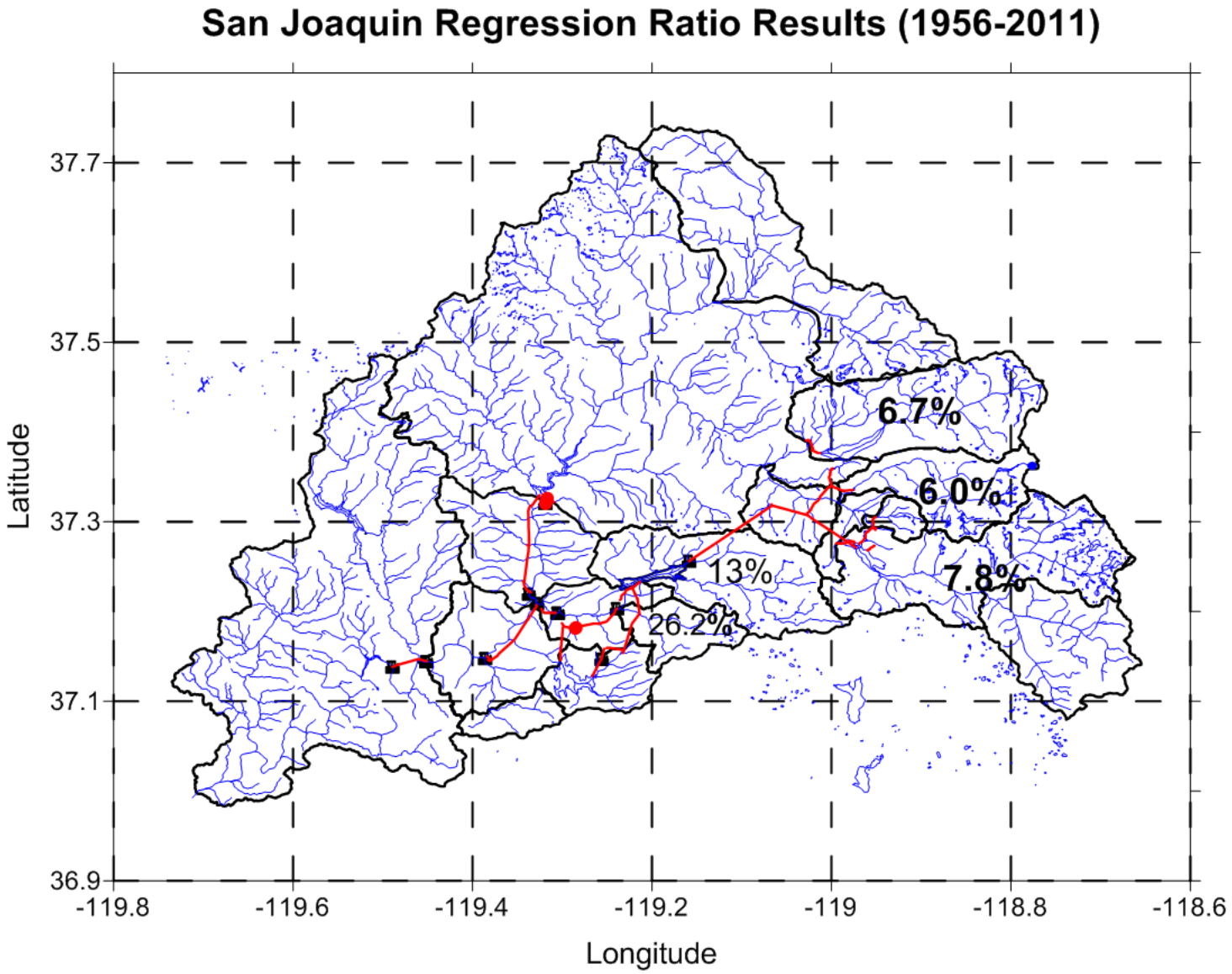


San Joaquin Regression Ratio Analyses

- Independent third party analyses conducted by Jeff Gornbein, UCLA Biomedical Statistics Dept.
- Log transformed data used in regressions
- The 95% confidence bounds are for the true RR and based on non parametric resampling ("bootstrap) with 500 re-samplings
- Robust linear regression using 486 months to compute predicted values in target
- Robust regression used to limit artifacts due to outliers

San Joaquin RR Results
(Gornbien–MDP+SCC controls, Annual Data)

Target				95% Conf bounds			90% Conf bounds	
MNO		DR	**RR**	lower	upper		lower	upper
		1.066	**1.067**	1.017	1.131		1.020	1.115
area				95% Conf bounds			90% Conf bounds	
FLO		DR	**RR**	lower	upper		lower	upper
		1.077	**1.078**	1.019	1.141		1.027	1.129
area				95% Conf bounds			90% Conf bounds	
HNT		DR	**RR**	lower	upper		lower	upper
		1.119	**1.130**	0.992	1.287		1.006	1.254
area				95% Conf bounds			90% Conf bounds	
PIT		DR	**RR**	lower	upper		lower	upper
		1.346	**1.262**	**1.053**	**1.512**		1.070	1.455
area				95% Conf bounds			90% Conf bounds	
BCK		DR	**RR**	lower	upper		lower	upper
		1.059	**1.060**	1.005	1.120		1.012	1.109


San Joaquin Regression Ratio Results (1956-2011)
Latitude
Longitude
37.7
37.5
37.3
37.1
36.9
-119.8
-119.6
-119.4
-119.2
-119
-118.8
-118.6
6.7%
6.0%
7.8%
13%
26.2%

Conclusions

- We're getting better, most aircraft seeding conducted before frontal passage
- SWE data shows promise for providing spatial assessment of seeding effects and aid in the selection of controls – correlates highly with streamflow analyses
- Log transformation and RR analysis by subbasin helps isolate the seeding signal
- Aggressive seeding, better flares, better forecasts, radiometer validation, radiometer vapor and satellite enhanced vapor channel provides early identification of seeding opportunity
- Better models capable of EXPLICIT SLW Forecasts - HydroWRF Model soundings input into ROAB for ops planning helps fine tune seeding strategy (winds, seeding strategies, timing, etc.)

Questions

RTB March 31, 2013