

Monitoring Freezing Levels across California: Quantifying the Impacts of ARs and the Recent El Niño

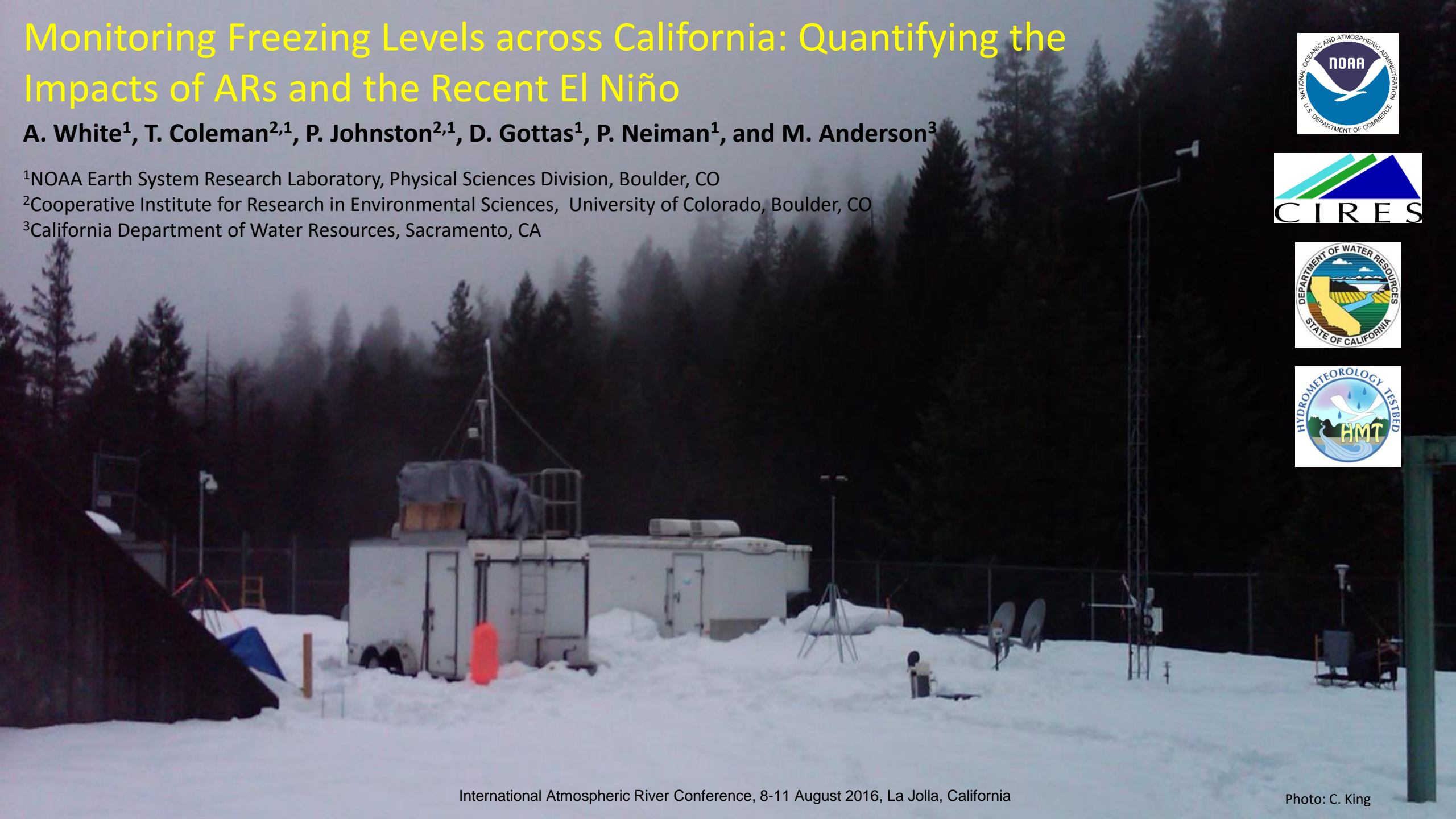


A. White¹, T. Coleman^{2,1}, P. Johnston^{2,1}, D. Gottas¹, P. Neiman¹, and M. Anderson³

¹NOAA Earth System Research Laboratory, Physical Sciences Division, Boulder, CO

²Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO

³California Department of Water Resources, Sacramento, CA



Outline

- Motivation for work
- Definitions: Freezing level vs. Snow level (as defined in this talk)
- Instrumentation and analysis methods
- Results from several Sierra Nevada locations
- Results from two coastal locations
- Results from a long-term coastal site – includes impacts of ARs
- Summary
- Future Work

Motivation

California, Oregon, and the West Coast of North America in general experienced an abysmal winter ski season during the winter of 2014-15. Obviously drought contributed, but for the storms that did occur, were the freezing levels higher than climatology?

If climate change leads to earlier runoff (i.e., during the wet season), reservoir managers may be required to alter their management strategy in order to preserve water for later use during the dry season.

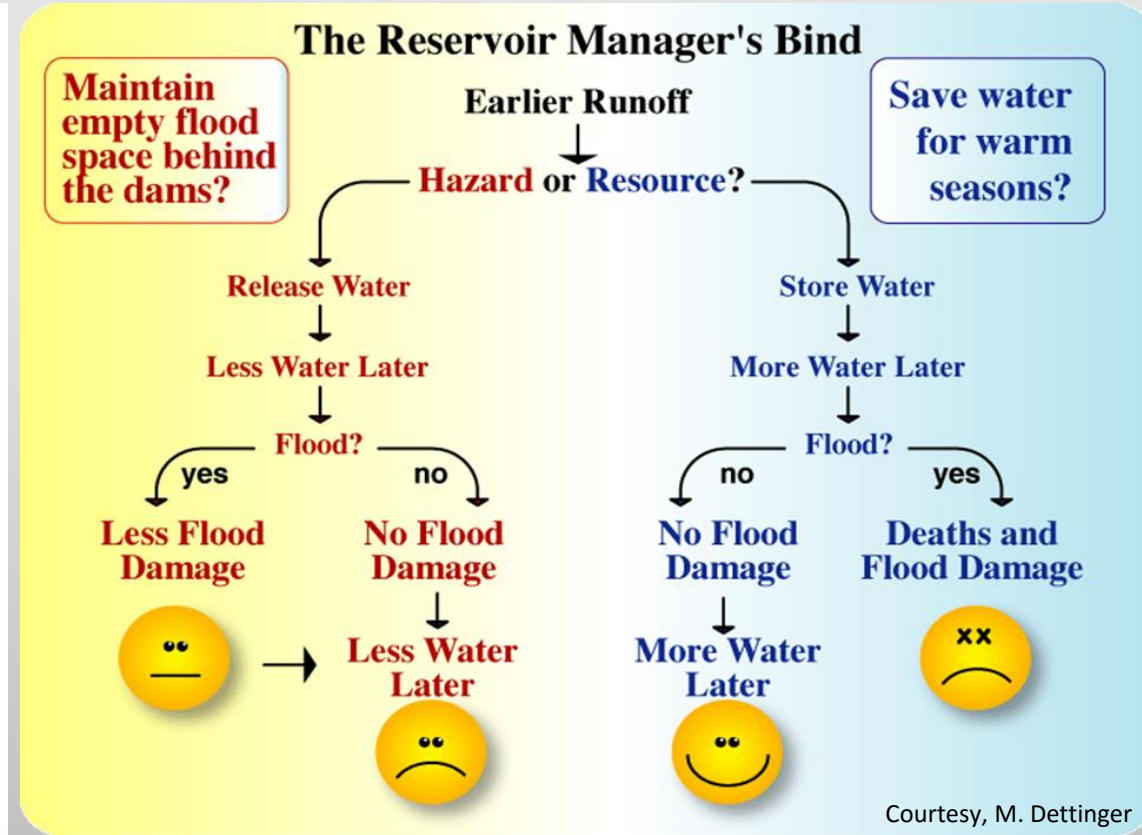
Mt. Bachelor's season, a history

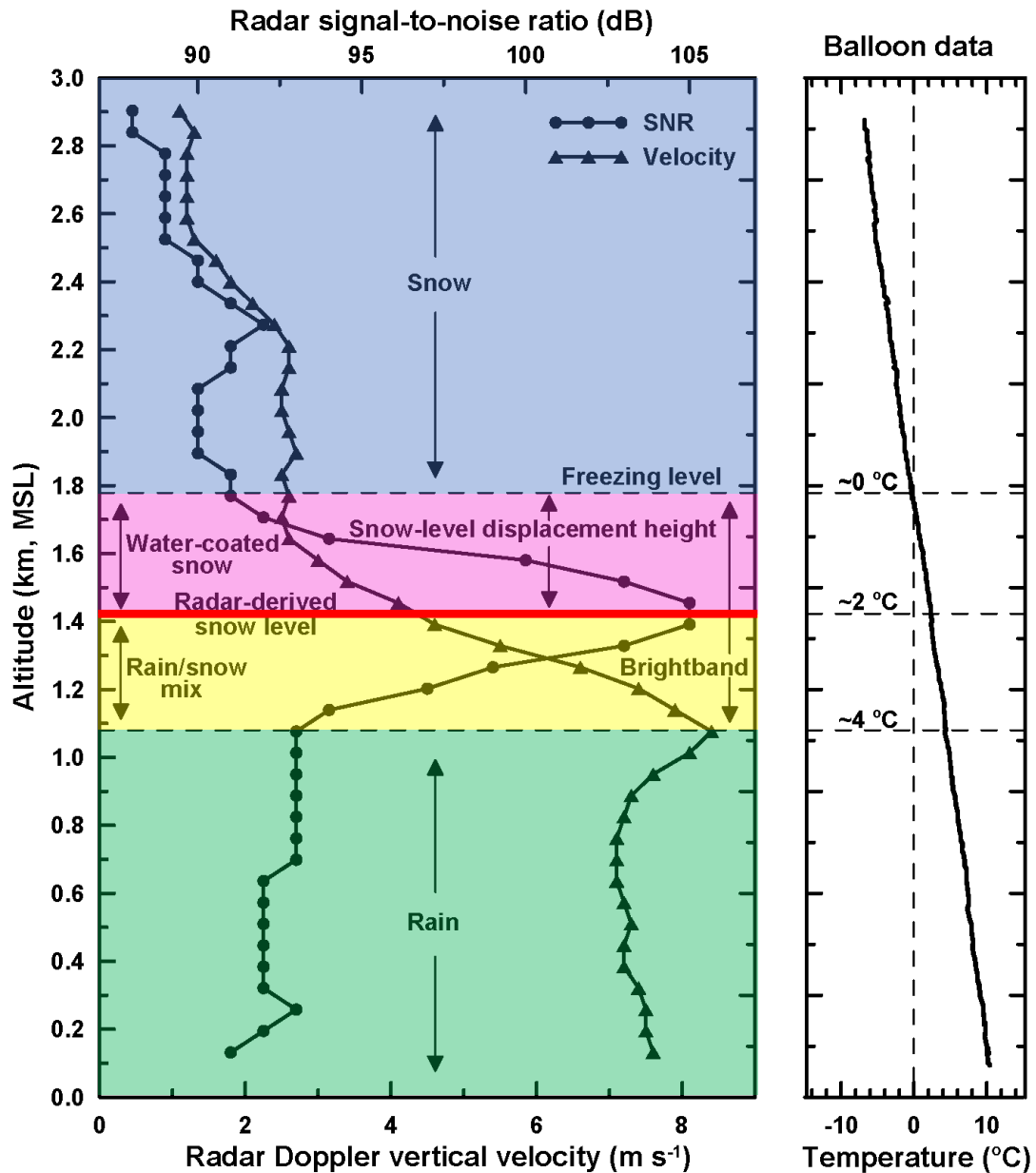
Mt. Bachelor is closing Sunday because of a low snowpack. The total seasonal snowfall at the resort was 212 inches, the lowest on record in the last 10 years. It's the resort's shortest ski season since 2008-09. The shortest on record was 1976-77, when the mountain was open from Jan. 2 through April 30, a 108-day operating season.



Source: Mt. Bachelor Ski Resort

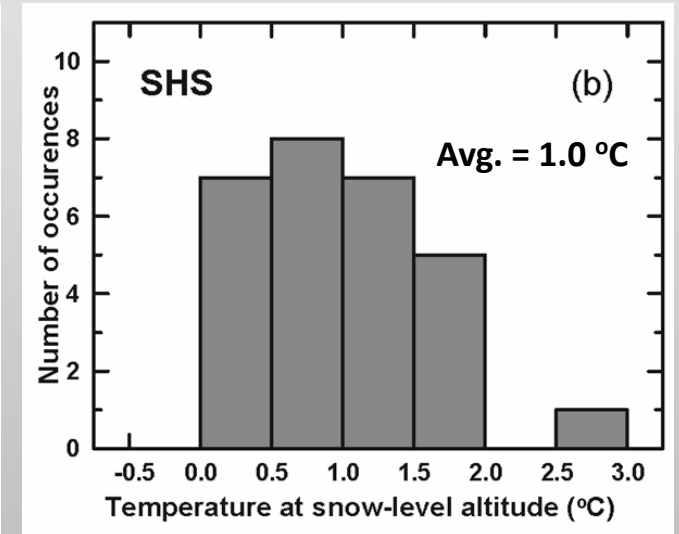
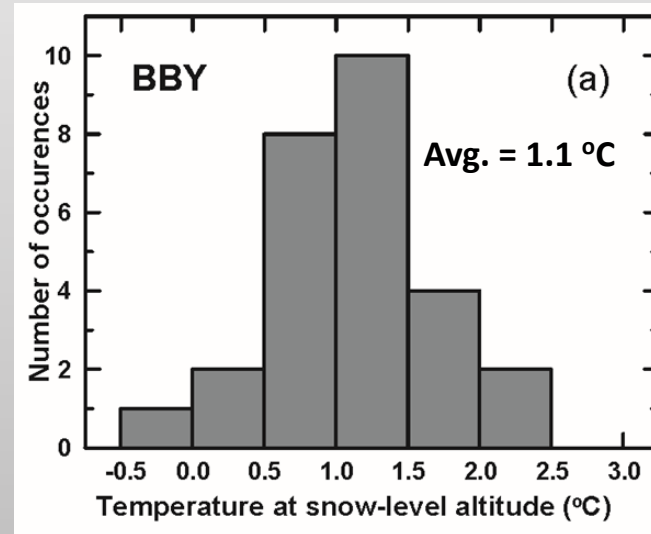
Greg Cross / The Bulletin





Definitions

- We used vertically pointing radar data to detect the radar bright band during precipitation.
- We detected the altitude of the maximum reflectivity in the bright band and defined this as the “snow-level altitude.”
- This altitude is generally warmer than the 0 °C level because it indicates that the melting process has already begun.
- The temperature at the snow-level altitude can vary, but it is generally taken to be at about +1 °C.



Instrumentation



S-band Pulsed Precipitation Profiling Radar (S-PROF; White et al., 2001 *Jtech*)

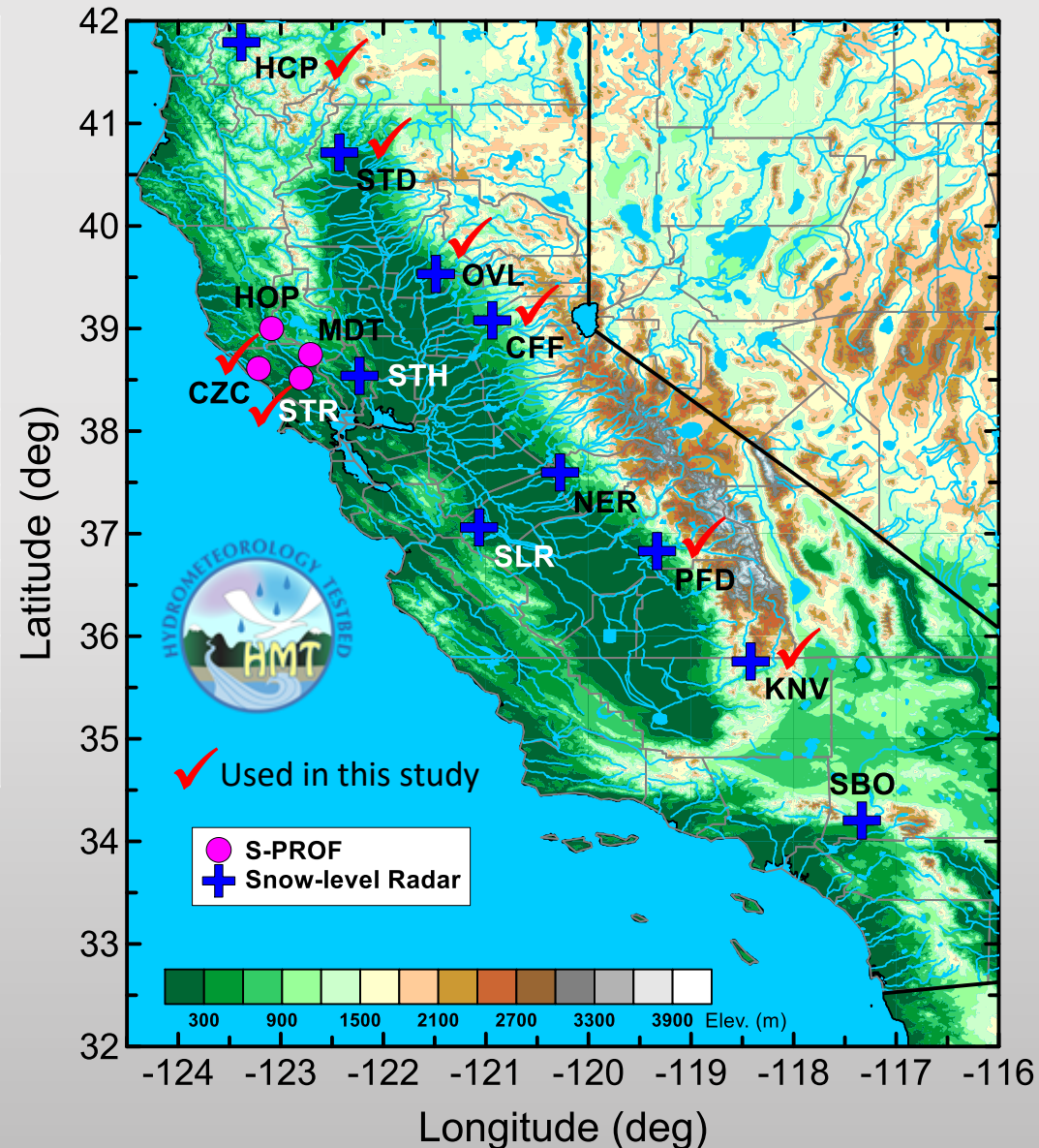


FM-CW Precipitation Profiling Radar (Snow-level Radar; Johnston et al, 2016 *JTech*, submitted)

Instrumentation

Parameter	Typical configuration for the S-PROF	Typical configuration for the Snow-level Radar
Operating frequency	2.875 GHz	2.835 GHz
Antenna diameter	2.4 m	1.2 m
Average transmit power	20 W	0.7 W
Beamwidth	2.5 degrees	5.7 degrees
Range gate spacing	60 m	40 m
Lowest range gate	159 m	40 m
Highest range gate	10,176 m	10,080 m

- S-PROF deployments are supported by the Sonoma County Water Agency and NOAA's Hydrometeorology Testbed (HMT; hmt.noaa.gov).
- Snow-level Radar deployments are supported by the California Department of Water Resources and NOAA HMT.



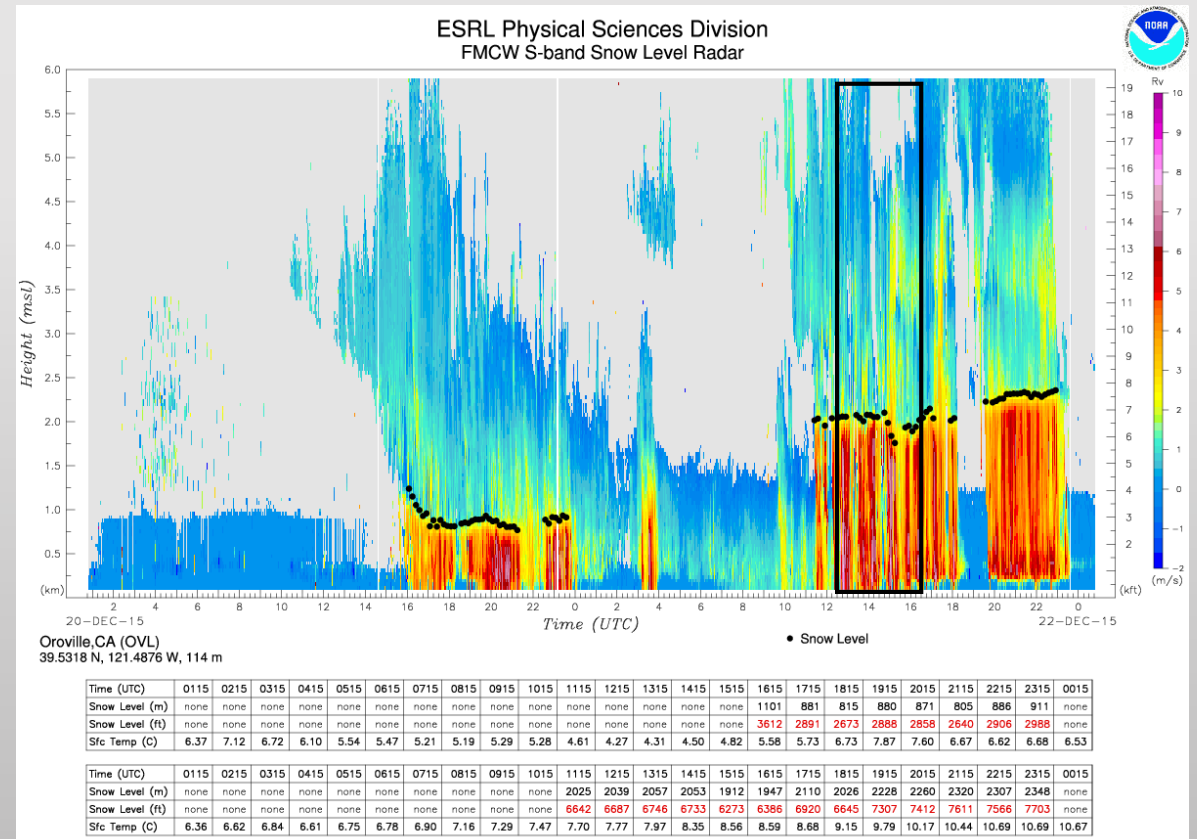
Analysis Methods

- We used the rainfall process partitioning scheme, developed by White et al., 2003 (*J. Hydrometeor.*) to separate out periods when a bright band (BB) was present.

JD	Start	End	Rain	#pr	#rn	#BB	#NBB	BB alt	Cd top	R type
355	1230	1300	1.270	51	40	36	4	2.034	5.094	hybrid
355	1300	1330	1.016	52	47	12	35	1.994	3.314	warm
355	1330	1400	1.016	52	52	49	3	1.994	5.954	hybrid
355	1400	1430	1.016	51	51	39	12	2.074	3.034	hybrid
355	1430	1500	0.254	(not analyzed)						
355	1500	1530	0.762	51	51	27	24	1.754	3.914	hybrid
355	1530	1600	0.762	52	52	44	8	1.914	5.034	hybrid
355	1600	1630	0.762	51	51	50	1	1.914	5.314	hybrid

- For all periods that were labeled BB, we further required there to be \geq five profiles in each period that exhibited a BB signature (to help eliminate noise).

- Analyze all ½-hour with > 0.5 mm of precipitation
- Simple majority: $>50\%$ profiles have a BB \rightarrow BB rain (cold or hybrid). Otherwise NBB rain assigned.
- Hybrid is defined as having a positive slope of reflectivity below the BB.
- Exclude all NBB rain periods (except snow; next slide)



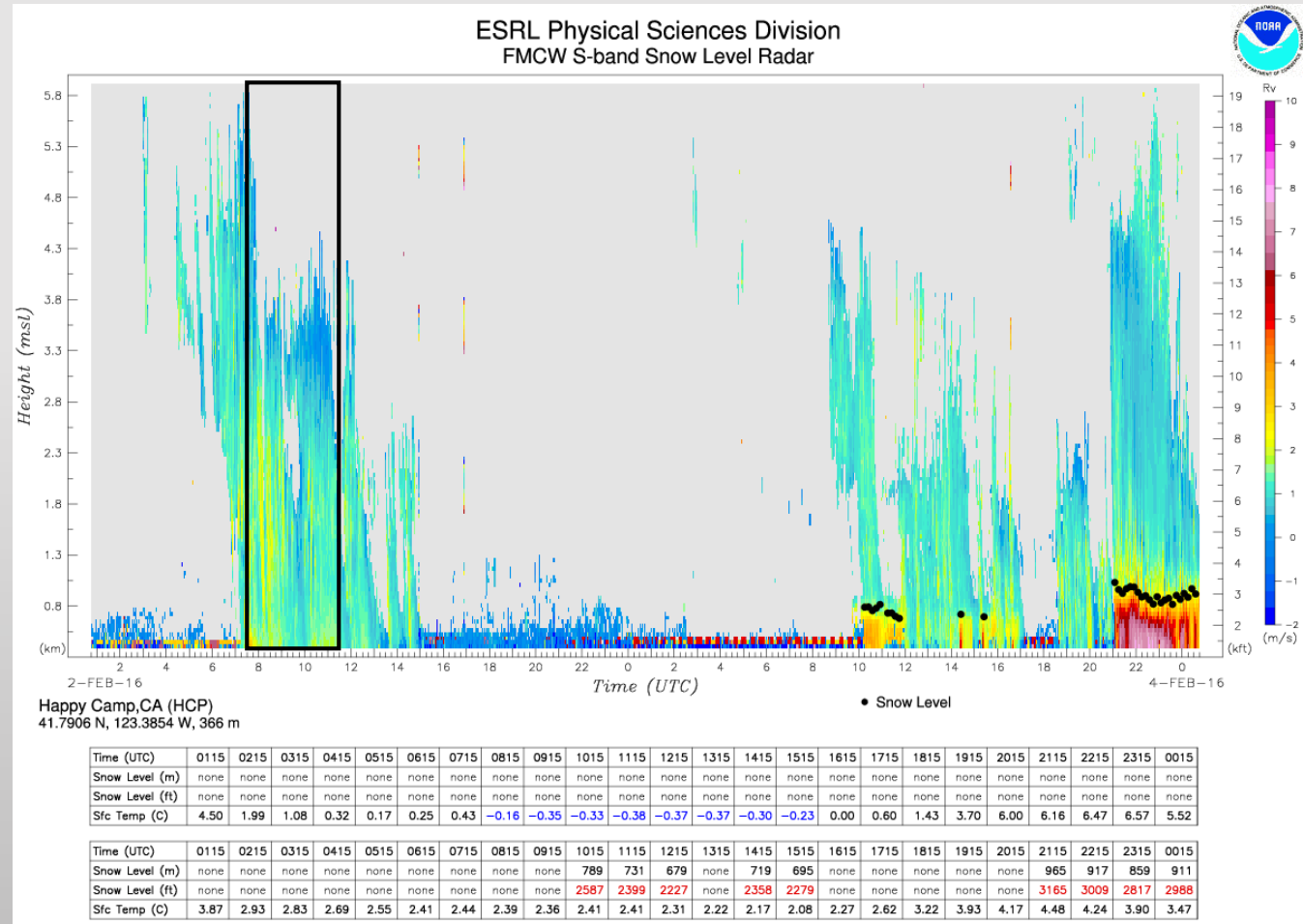
Analysis Methods

- Periods that indicated NBB (or “warm”) rain were further analyzed subjectively to determine if snow was falling at the surface. For these cases the elevation of the site was assigned to be the snow level.

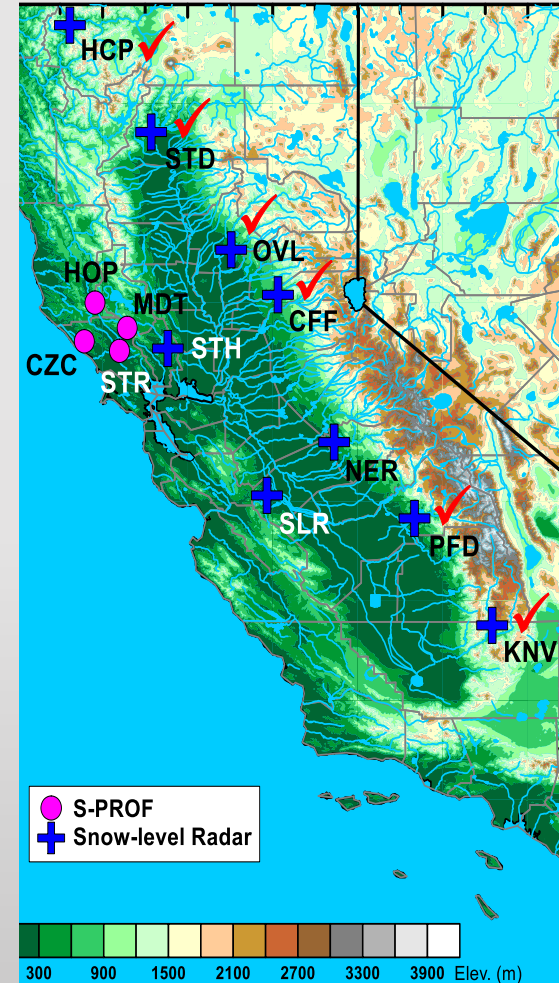
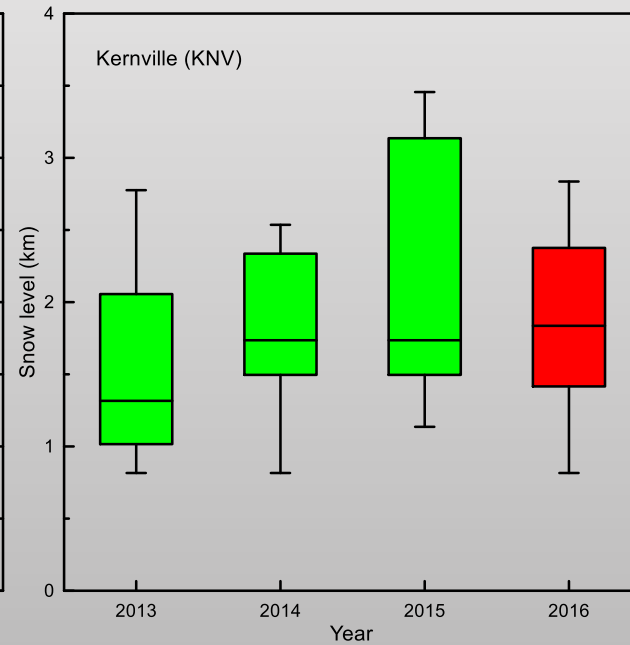
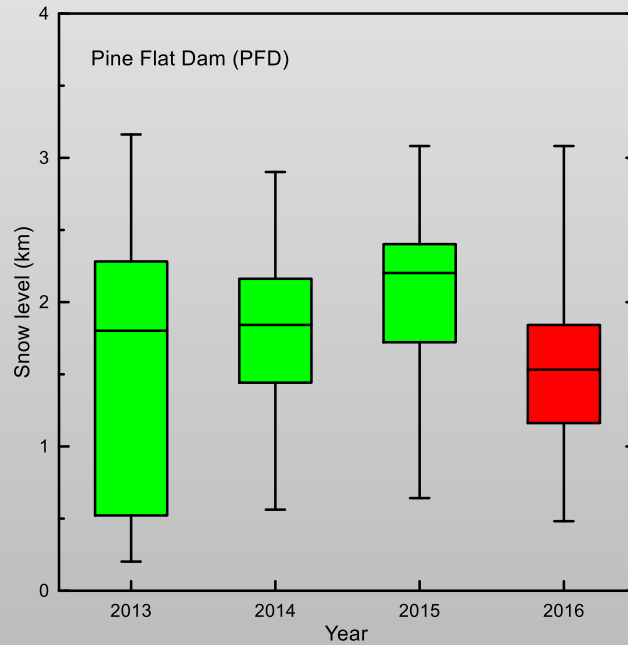
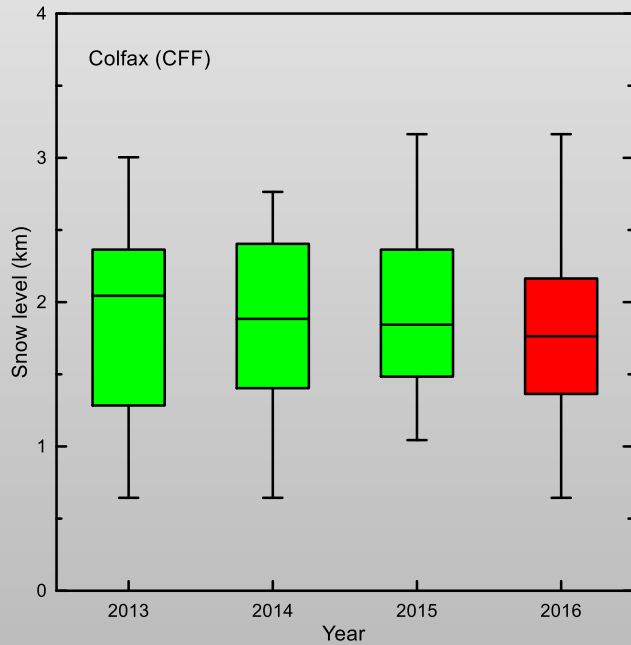
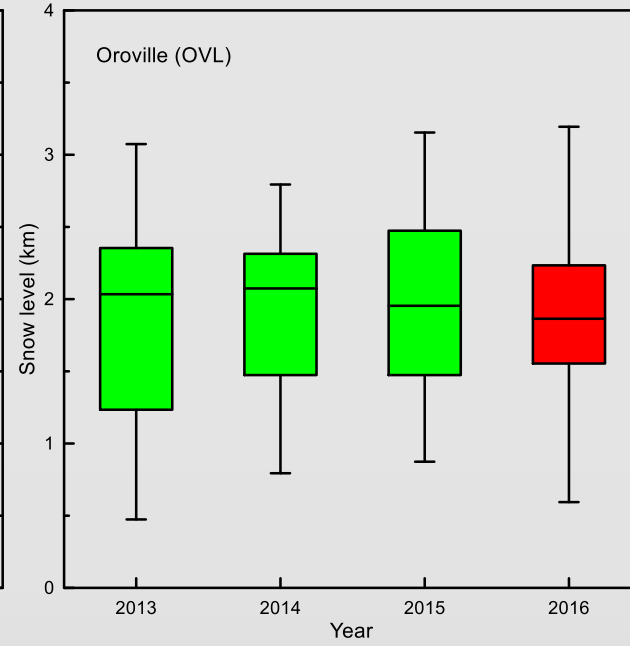
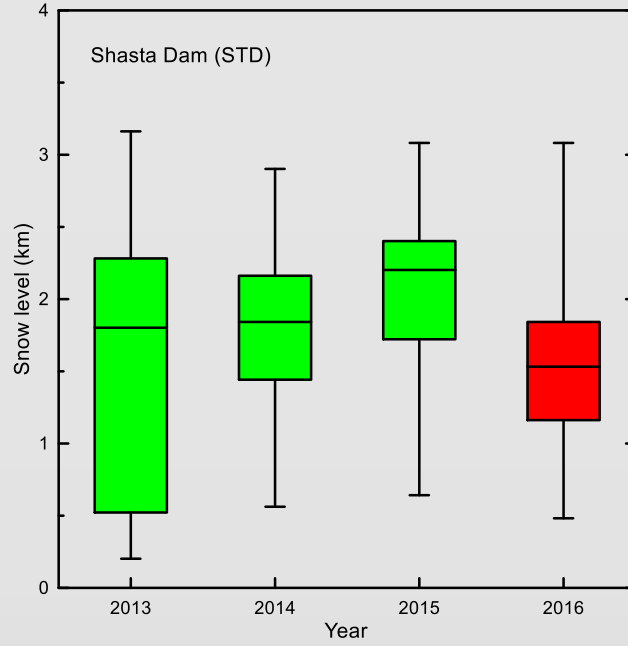
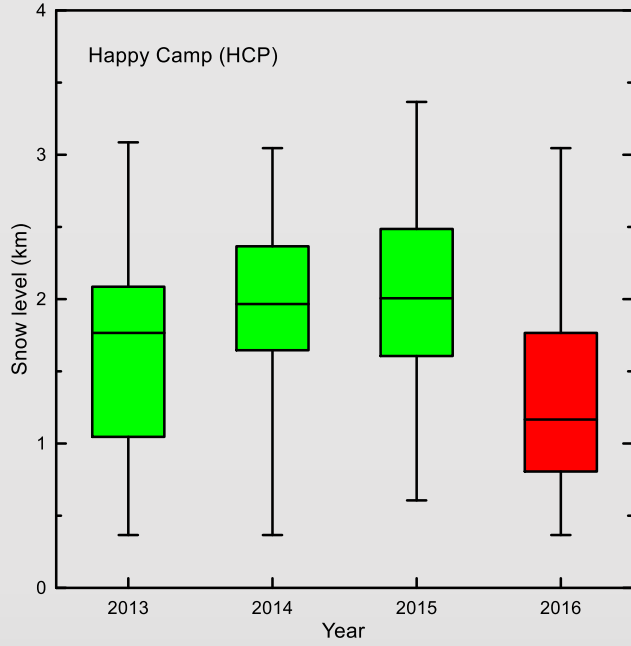
JD	Start	End	Rain	#pr	#rn	#BB	#NBB	BB alt	Cd top	R type	
033	0730	8000	1.016	49	49	6	43	0.466	4.606	warm	
033	8000	0830	0.254	(not analyzed)							
033	0830	0900	0.762	49	49	0	49	-9.999	3.606	warm	
033	0900	0930	0.254	(not analyzed)							
033	0930	1000	0.000	(not analyzed)							
033	1000	1030	0.508	49	49	0	49	-9.999	7.140	warm	
033	1030	1100	0.762	49	49	0	49	-9.999	3.675	warm	
033	1100	1130	0.762	49	49	0	49	-9.999	3.203	warm	



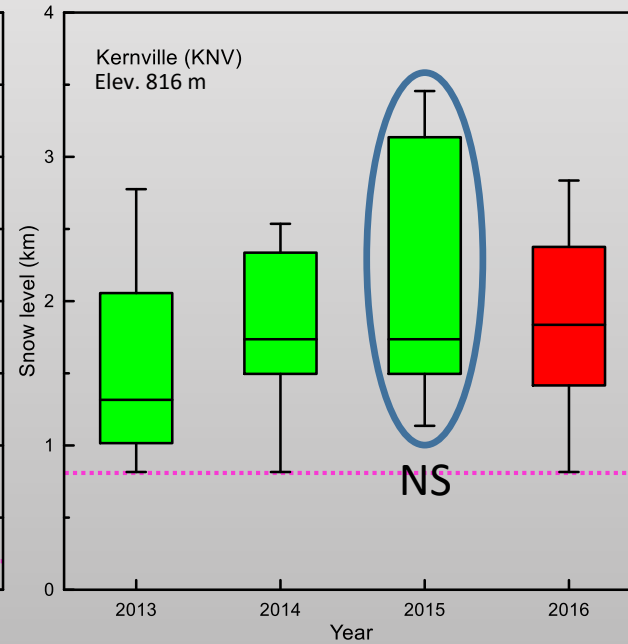
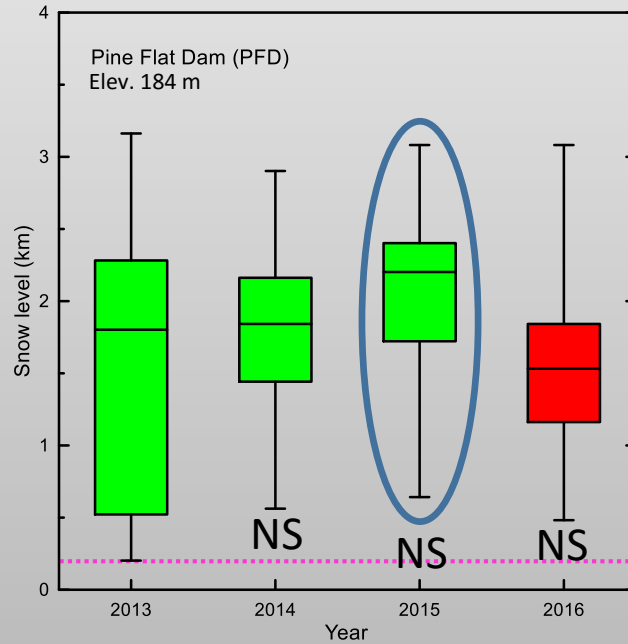
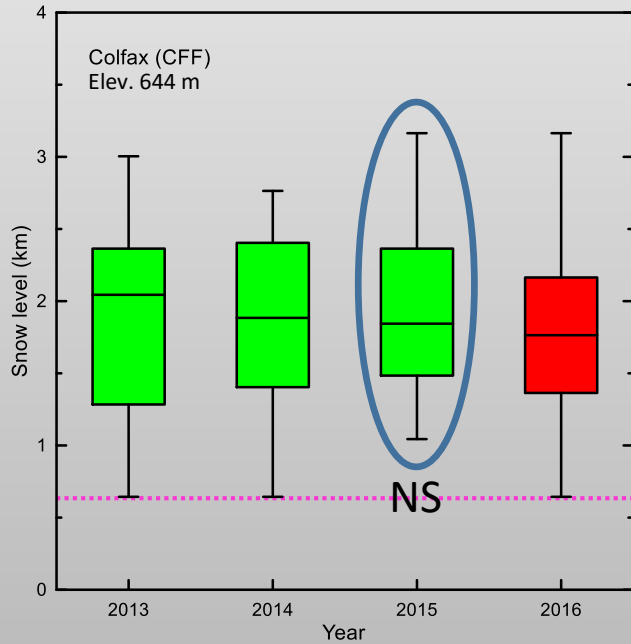
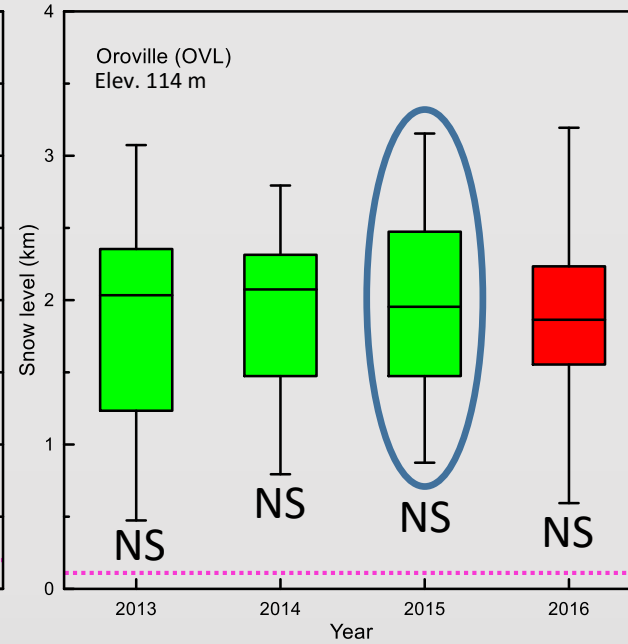
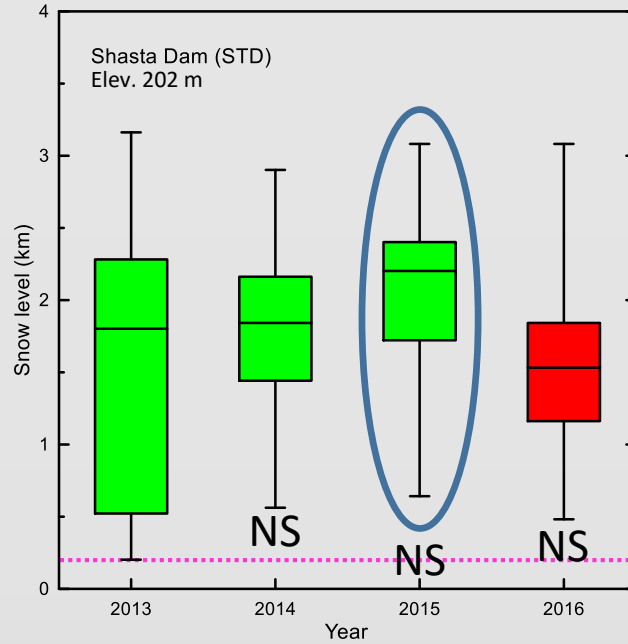
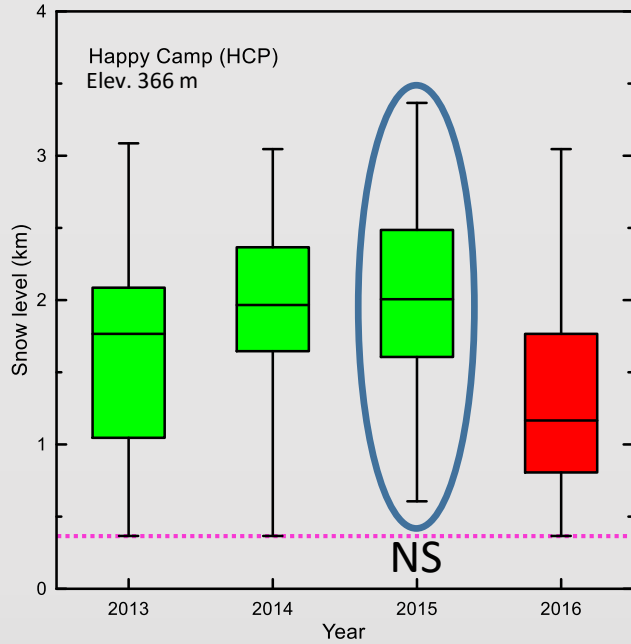
JD	Start	End	Rain	#pr	#rn	#BB	#NBB	BB alt	Cd top	R type	
033	0730	8000	1.016	49	49	6	43	0.366	4.606	snow	
033	8000	0830	0.254	(not analyzed)							
033	0830	0900	0.762	49	49	0	49	0.366	3.606	snow	
033	0900	0930	0.254	(not analyzed)							
033	0930	1000	0.000	(not analyzed)							
033	1000	1030	0.508	49	49	0	49	0.366	7.140	snow	
033	1030	1100	0.762	49	49	0	49	0.366	3.675	snow	
033	1100	1130	0.762	49	49	0	49	0.366	3.203	snow	



Results: Sierra Nevada sites



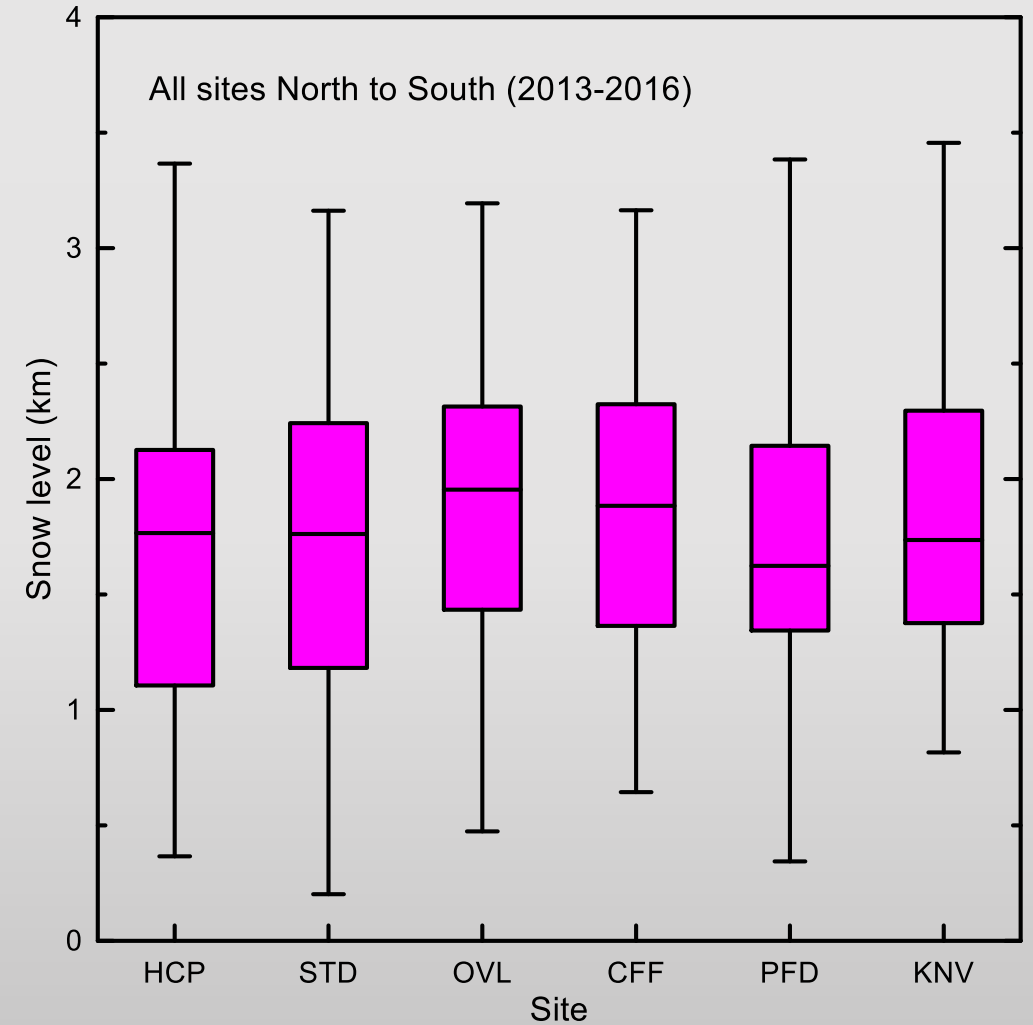
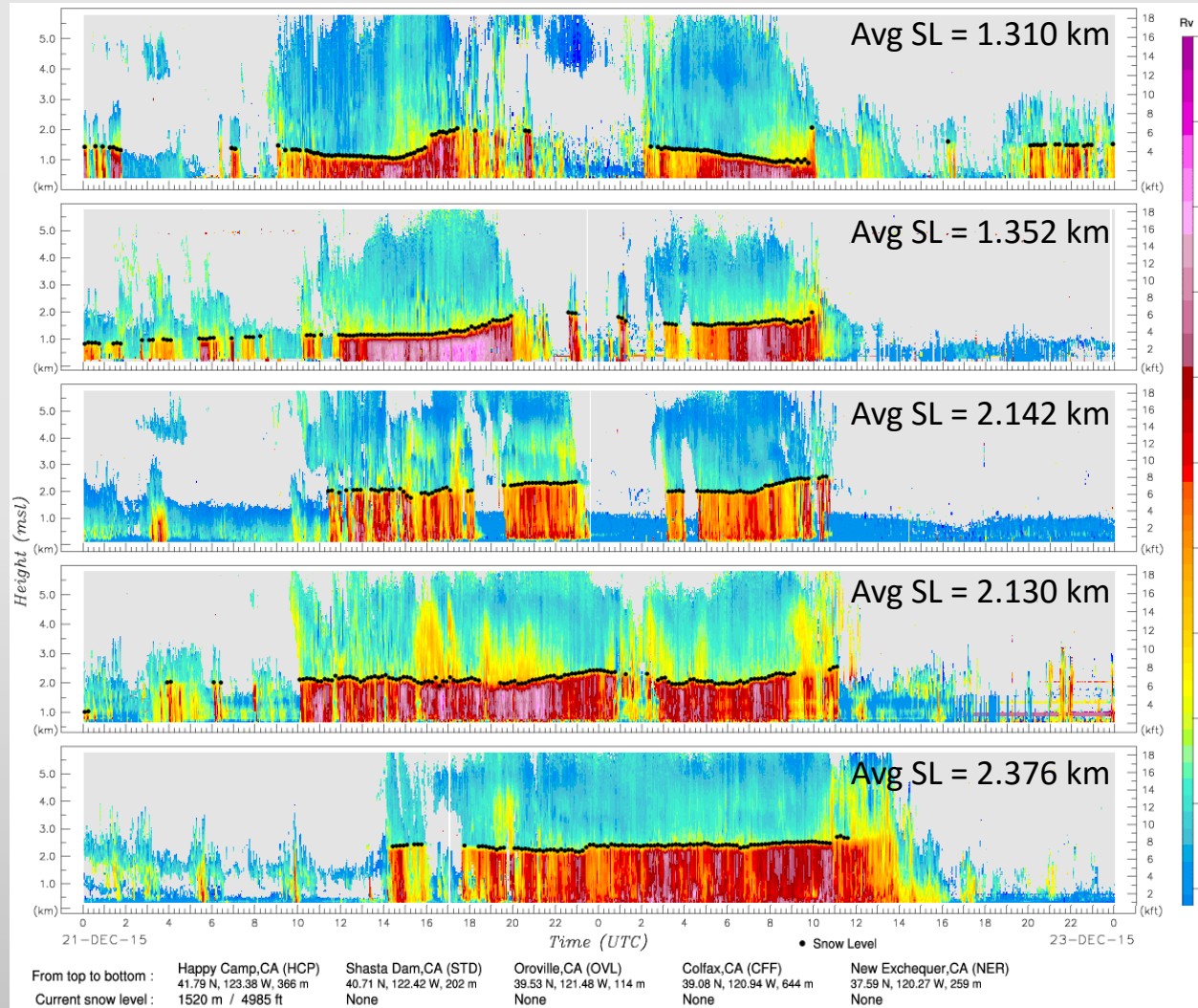
Results: Sierra Nevada sites



- Results from last four winters:
 - Green = drought
 - Red = El Niño
- El Niño did not produce higher snow levels than drought years.
- Higher snow levels in general and higher minimum snow level were observed during the 2015 drought winter.
- None of the sites observed snow during the 2015 drought winter.

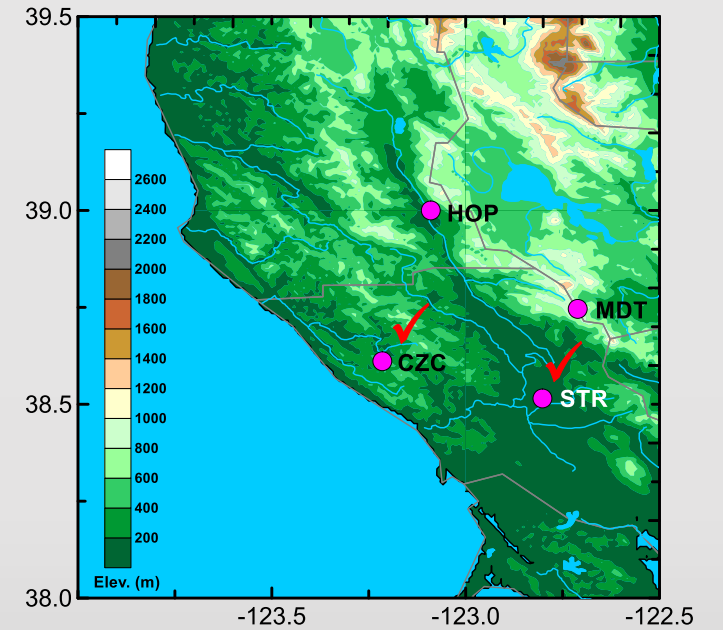
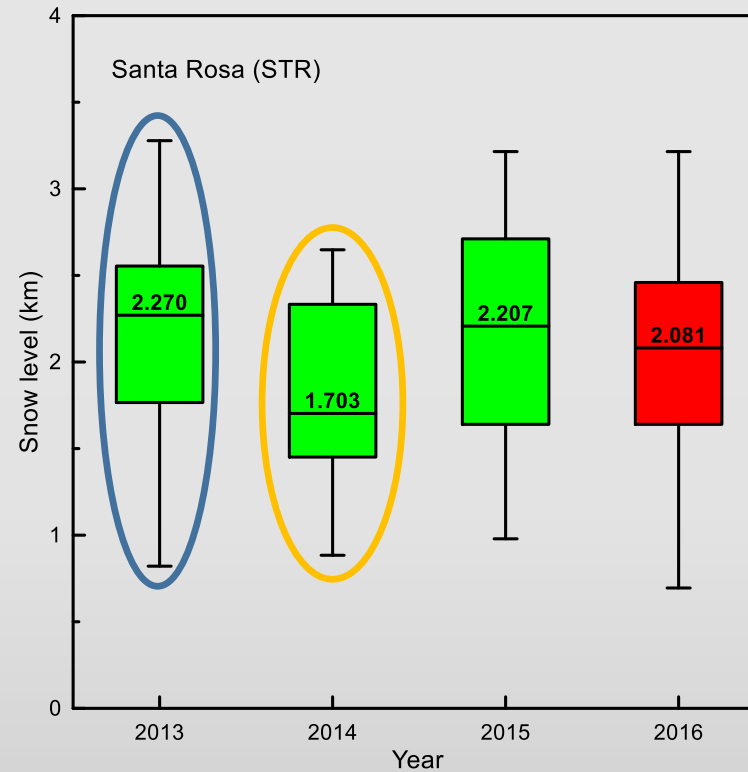
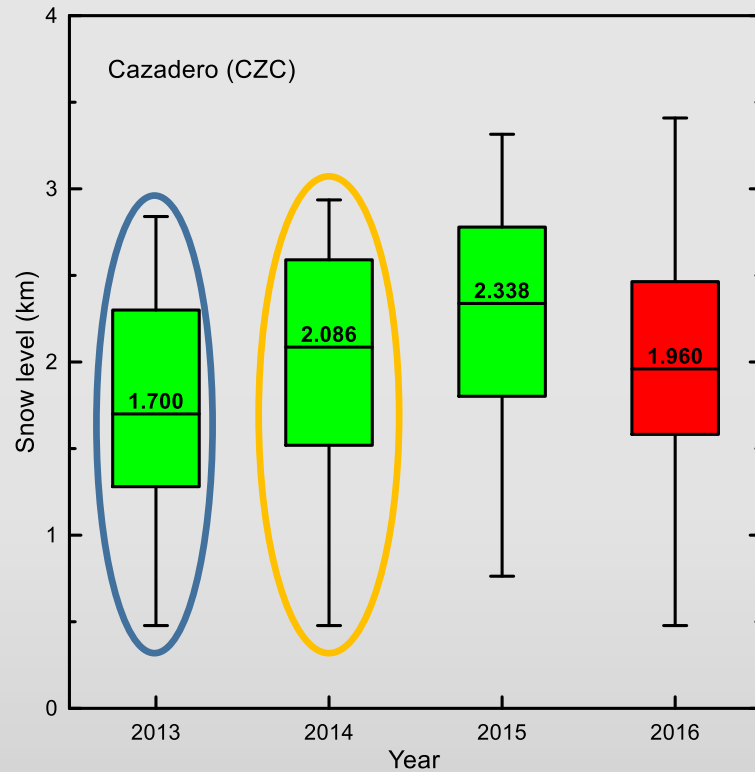
Results: Sierra Nevada sites

00Z 21-Dec-2015 to 00Z 23-Dec-2015



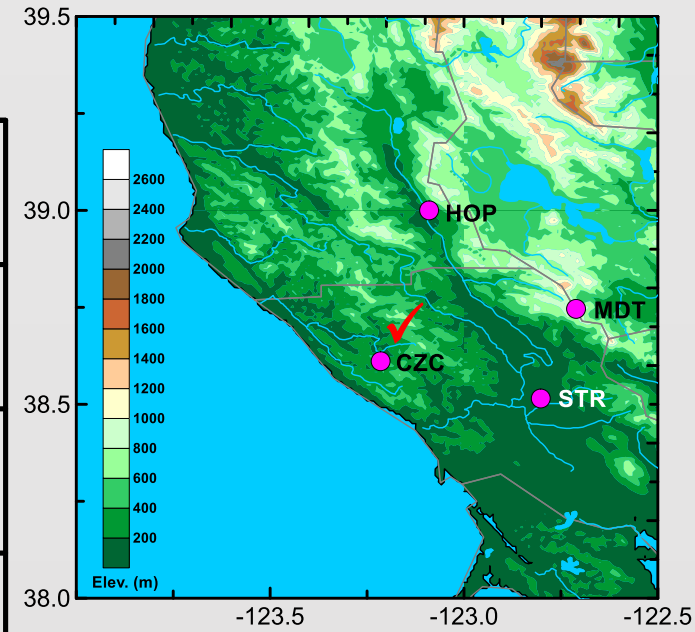
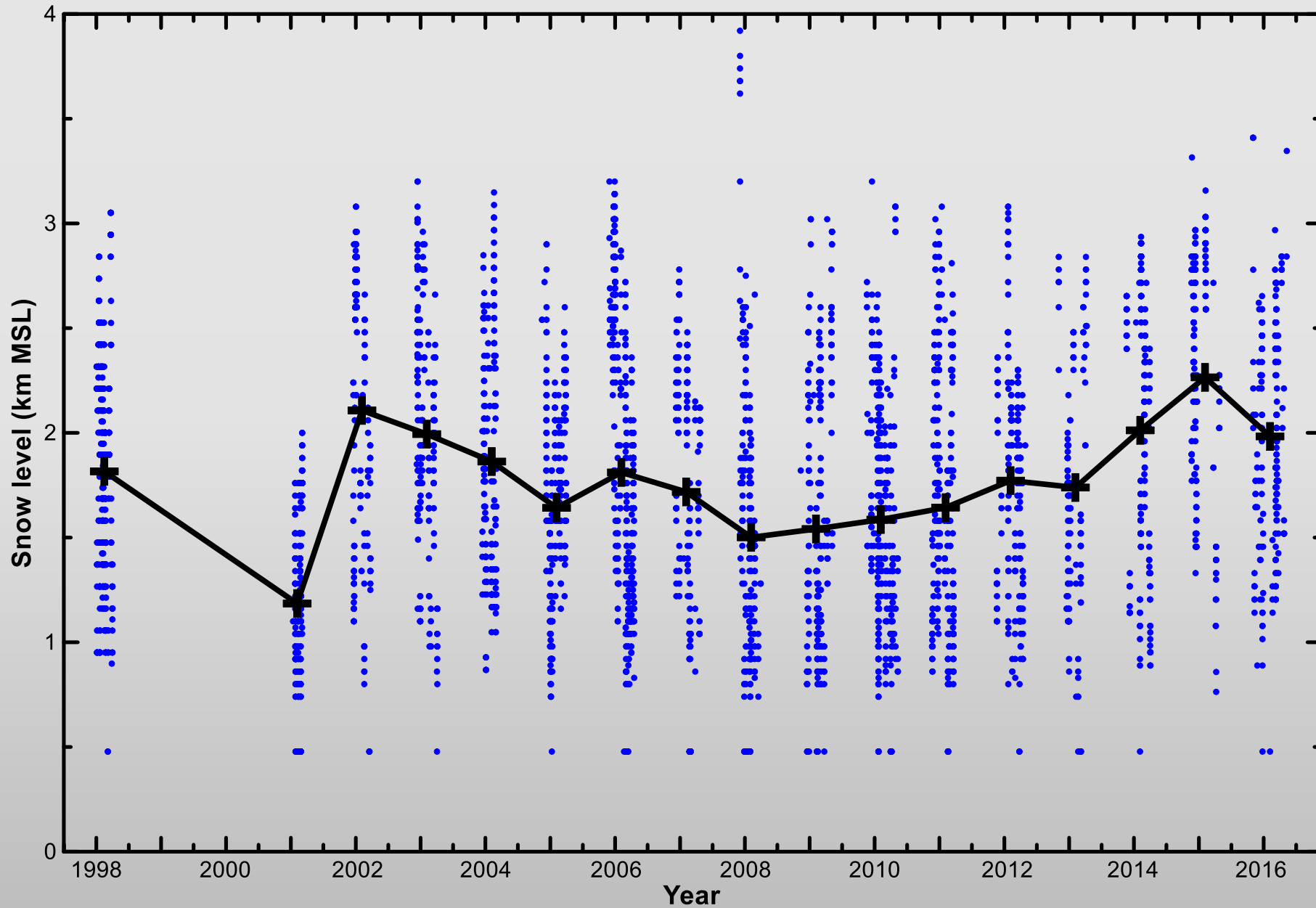
- The latitudinal dependence on snow level that is sometimes observed in individual storms is only weakly reflected in composite statistics from four winter seasons.

Results: Coastal Sites



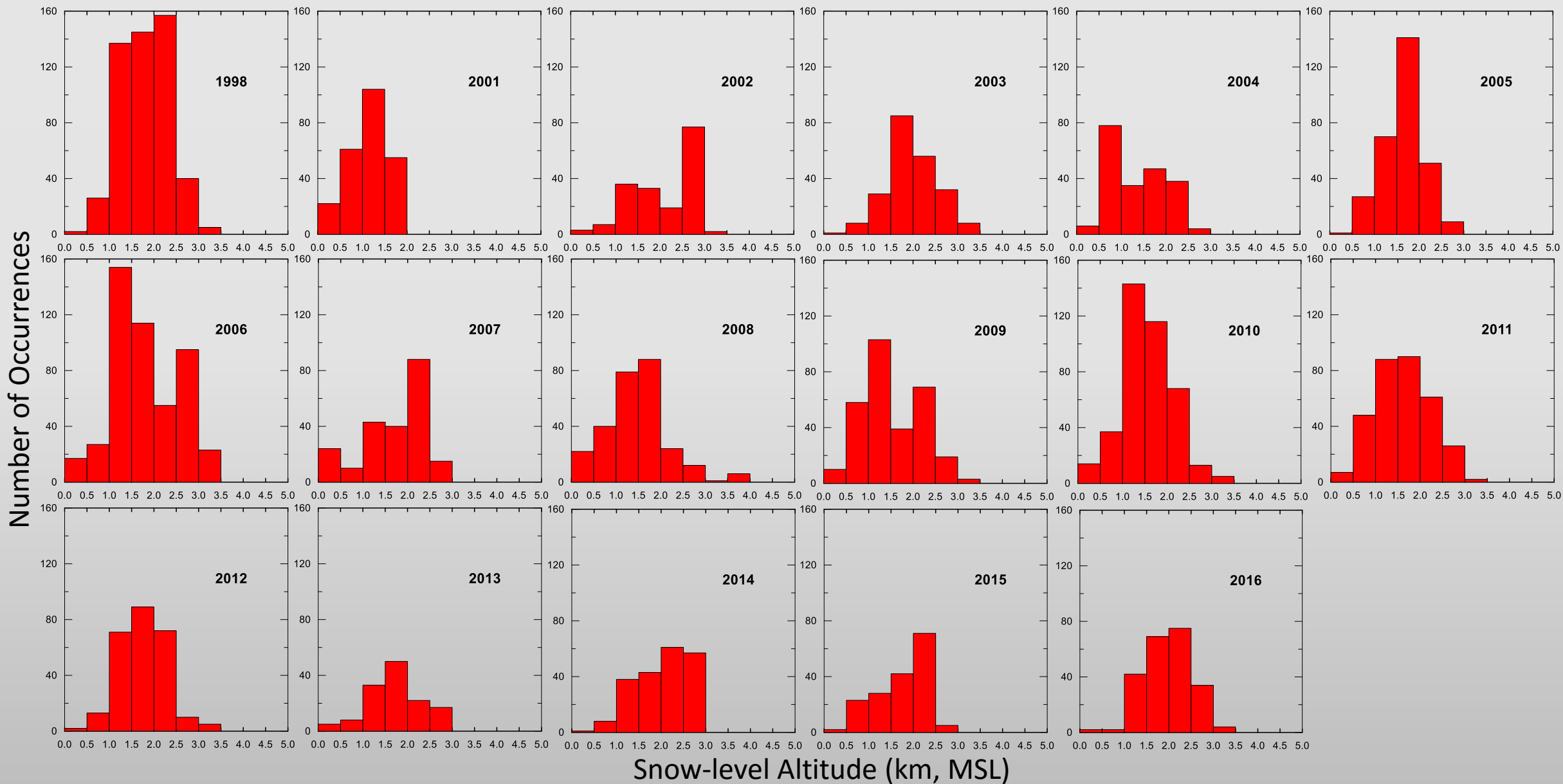
- El Niño did not produce higher snow levels at coastal locations either
- Differences between CZC and STR somewhat surprising (especially for 2013 and 2014) given the relatively small distance (37 km) between two observing sites

Results: Cazadero



- 17-year time series of snow levels measured at Cazadero (CZC)
- Black line and plus symbols denote yearly means
- Not much info available from means given large intra-annual variability in the snow level

Results: Cazadero



Results: Cazadero

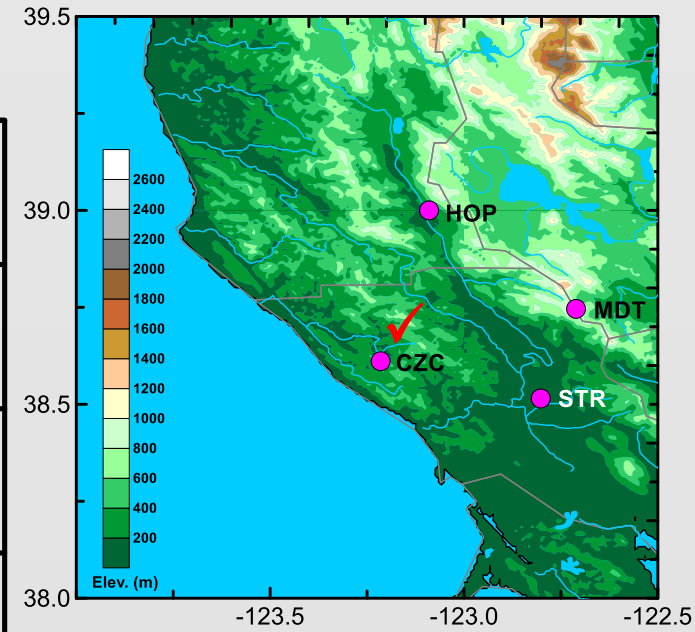
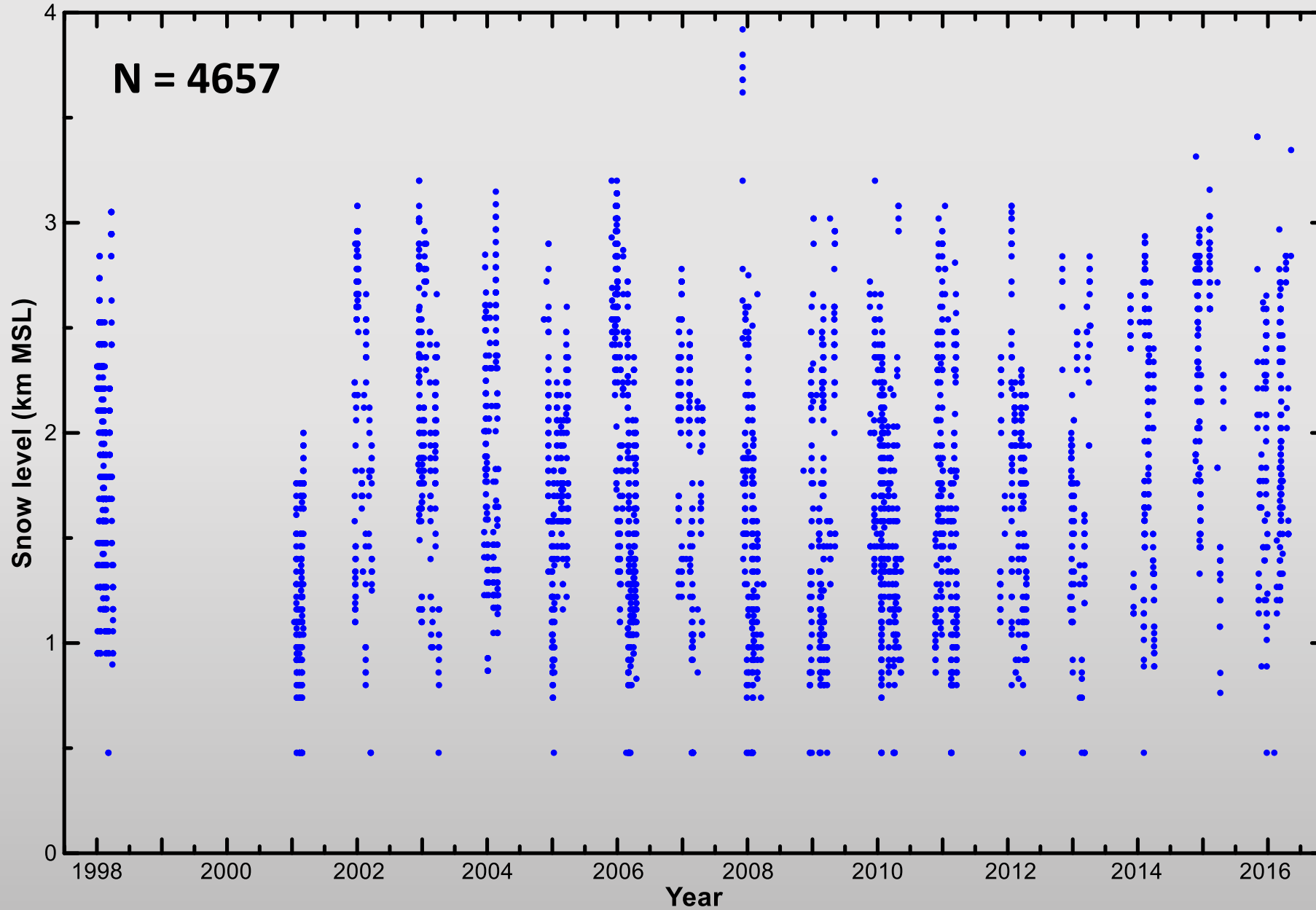
Snow level Altitude (km)	Number of half-hour periods	% of time snow level was in this range	Precipitation during these periods (mm)	% of total precipitation during these periods	Precip. rate (mm h ⁻¹)
0-0.5	133	2.86	149.352	1.44	2.25
0.5-1.0	388	8.33	492.506	4.75	2.54
1.0-1.5	1271	27.29	2311.654	22.30	3.64
1.5-2.0	1179	25.32	2768.346	26.70	4.70
2.0-2.5	1048	22.50	2688.844	25.93	5.13
2.5-3.0	565	12.13	1714.754	16.54	6.07
3.0-3.5	67	1.44	212.344	2.05	6.34
3.5-4.0	6	0.13	30.226	0.29	10.08
Total	4657	100	10,368	100	avg. = 4.45

Results: Cazadero

Snow-level Altitude (km)	Number of half-hour periods	% of time snow level was in this range	Precipitation during these periods (mm)	% of total precipitation during these periods	Precip. rate (mm h ⁻¹)
0-0.5	133	2.86	149.352	1.44	2.25
0.5-1.0	388	8.33	492.506	4.75	2.54
1.0-1.5	1271	27.29	2311.654	22.30	3.64
1.5-2.0	1179	25.32	2768.346	26.70	4.70
2.0-2.5	1048	22.50	2688.844	25.93	5.13
2.5-3.0	565	12.13	1714.754	16.54	6.07
3.0-3.5	67	1.44	212.344	2.05	6.34
3.5-4.0	6	0.13	30.226	0.29	10.08
Total	4657	100	10,368	100	avg. = 4.45

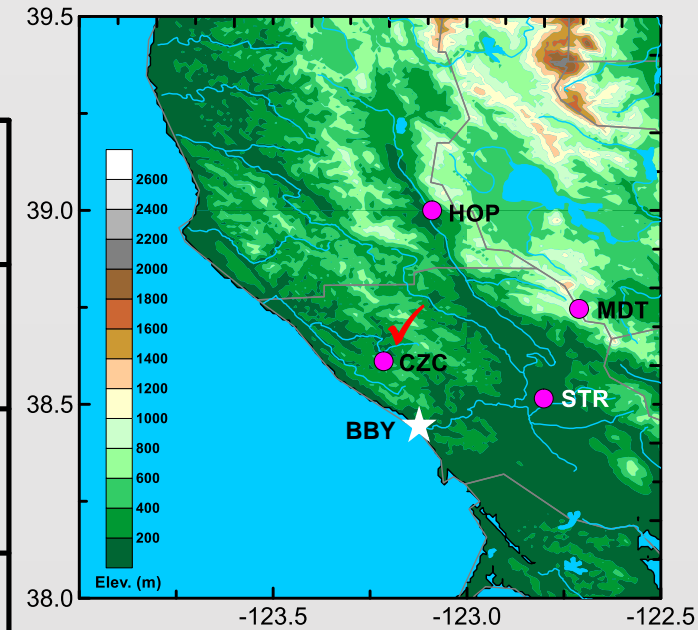
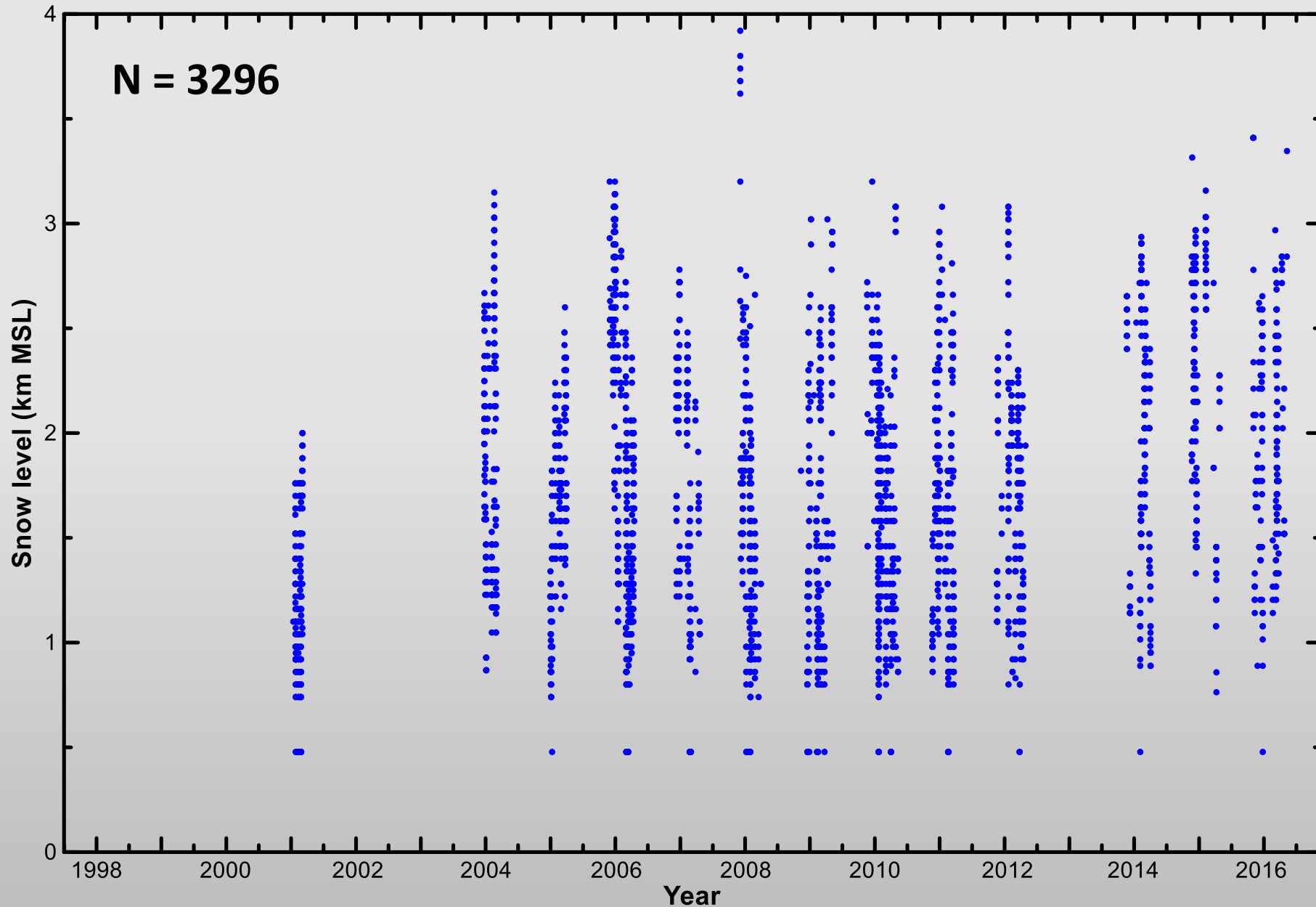
- 75% of the time the snow-level altitude is between 1.0 and 2.5 km at Cazadero, CA
- 75% of the precipitation occurs when the snow-level altitude was in this range.
- More than 97% of the time, the snow-level altitude is below 3000 m.
- The average precipitation rate systematically increases as the snow-level altitude increases

Results: Cazadero



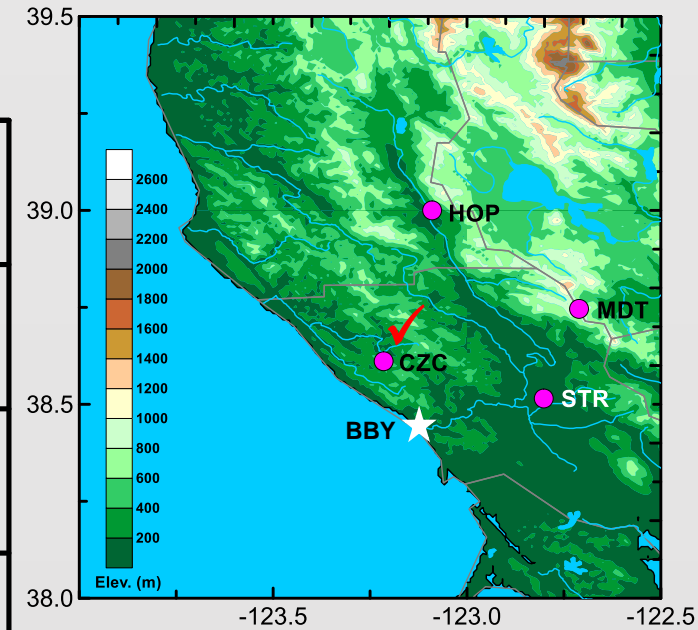
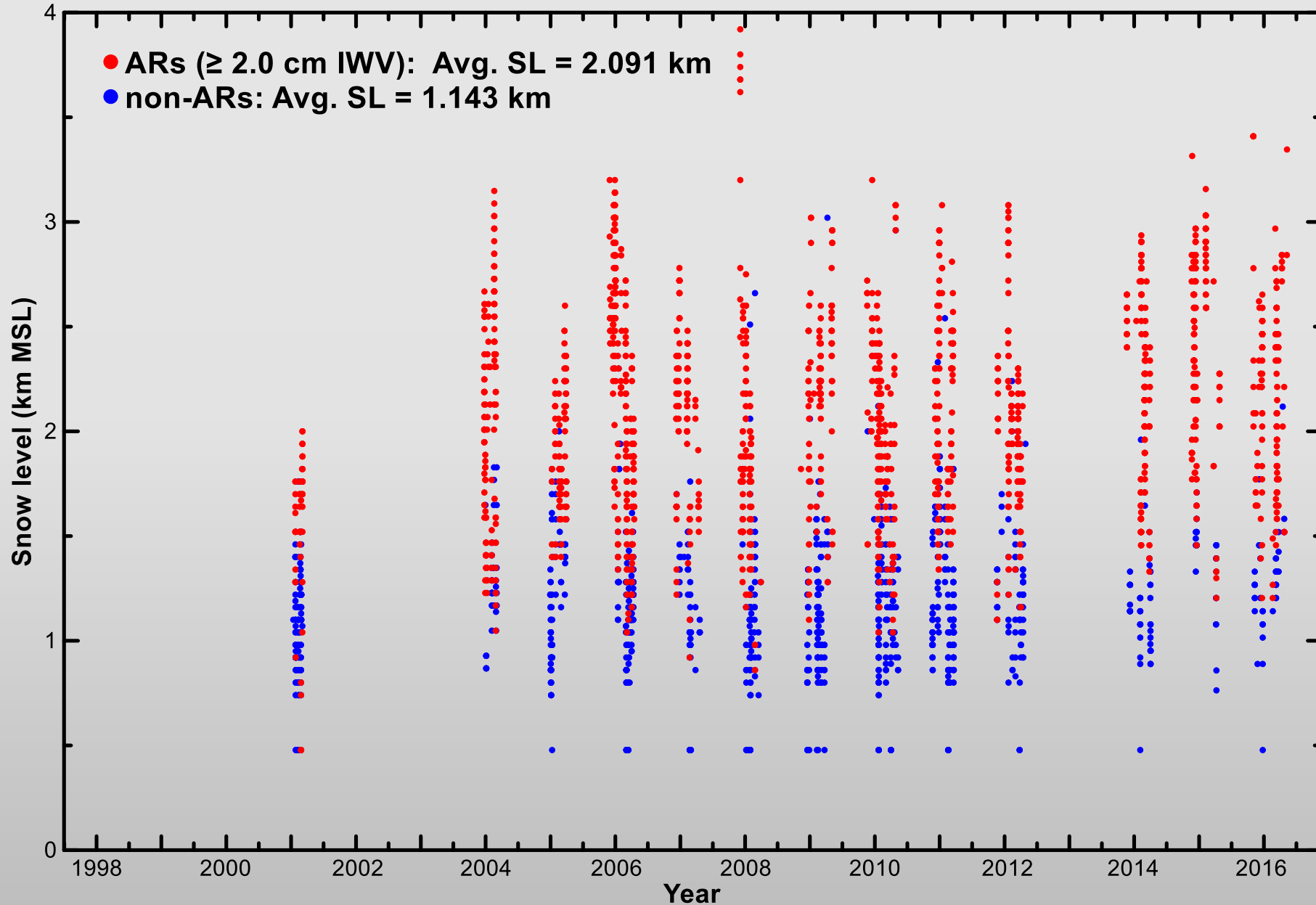
- 17-year time series of snow levels measured at Cazadero (CZC)

Results: Cazadero



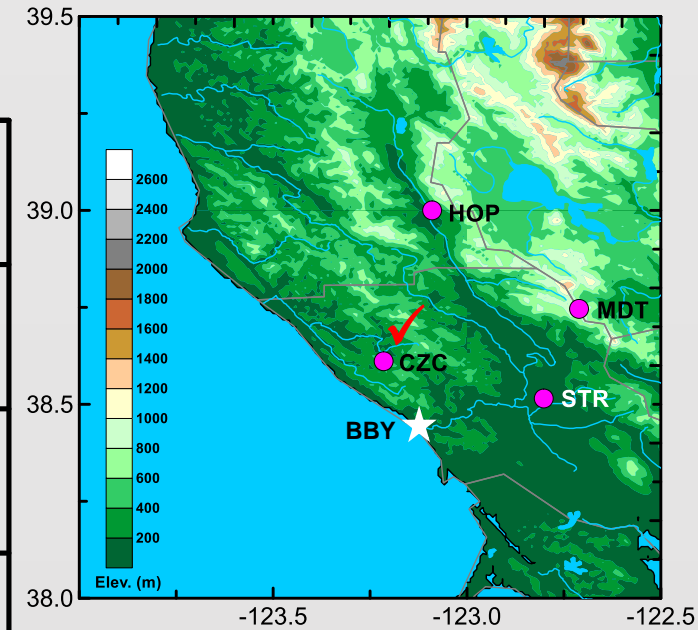
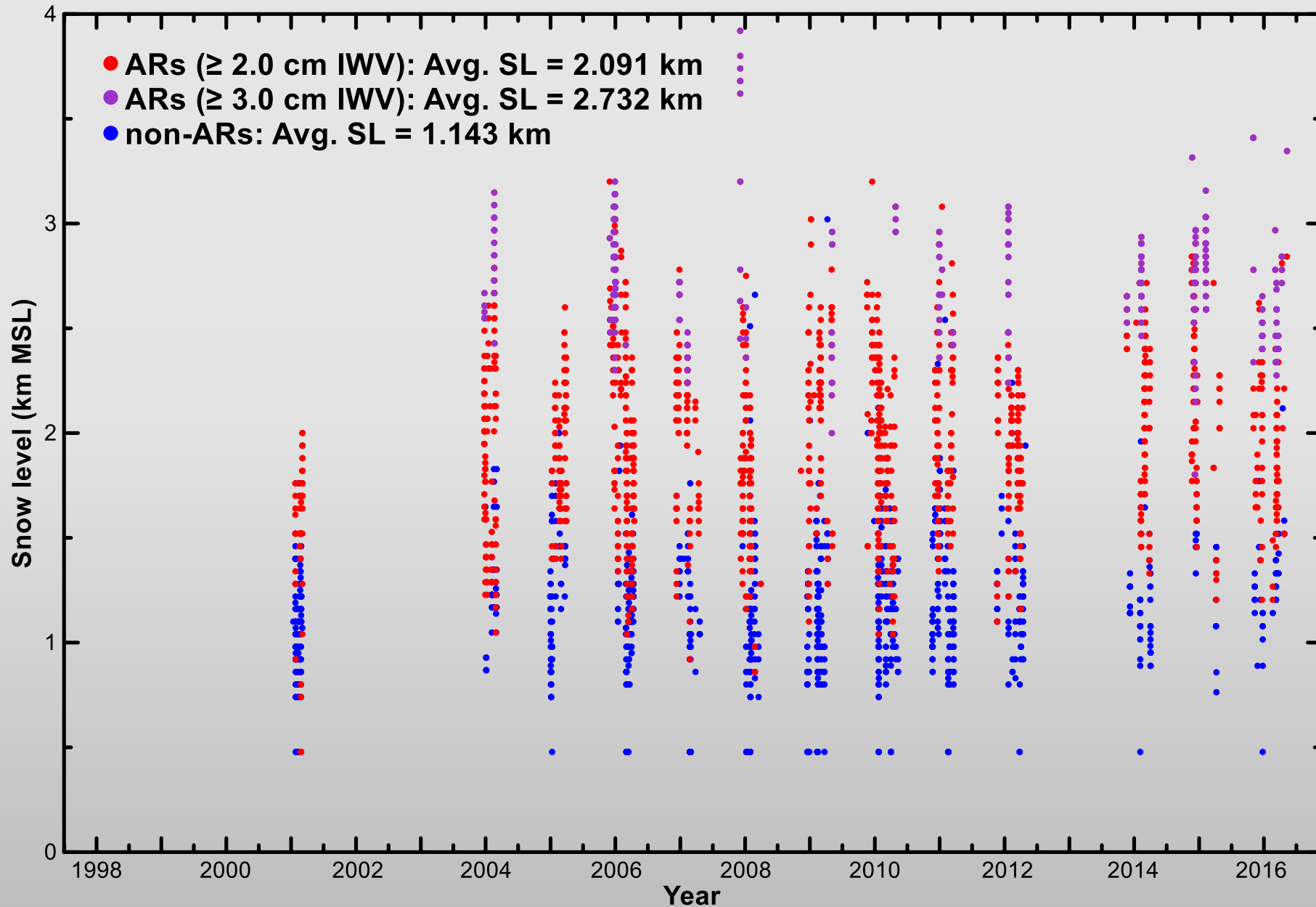
- 17-year time series of snow levels measured at Cazadero (CZC)
- Matched to times when GPS Integrated Water Vapor (IWV) was available at Bodega Bay (BBY) via the satellite-based GPS-Met technique.

Results: Cazadero



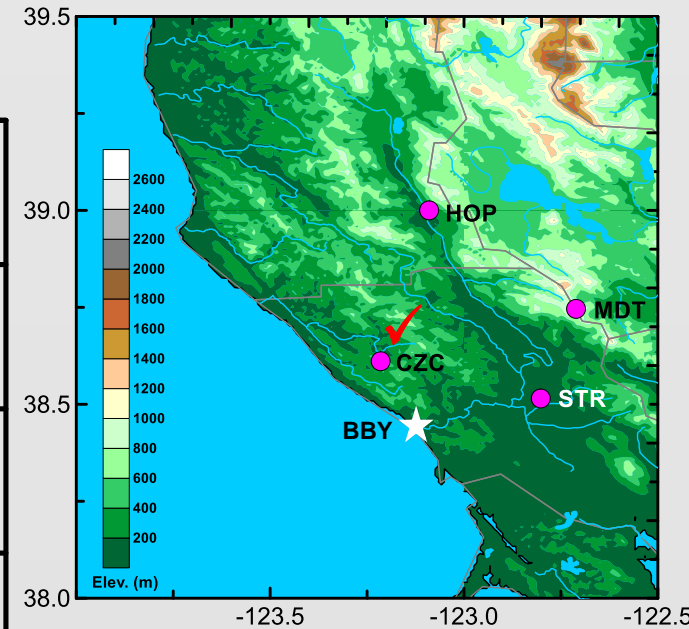
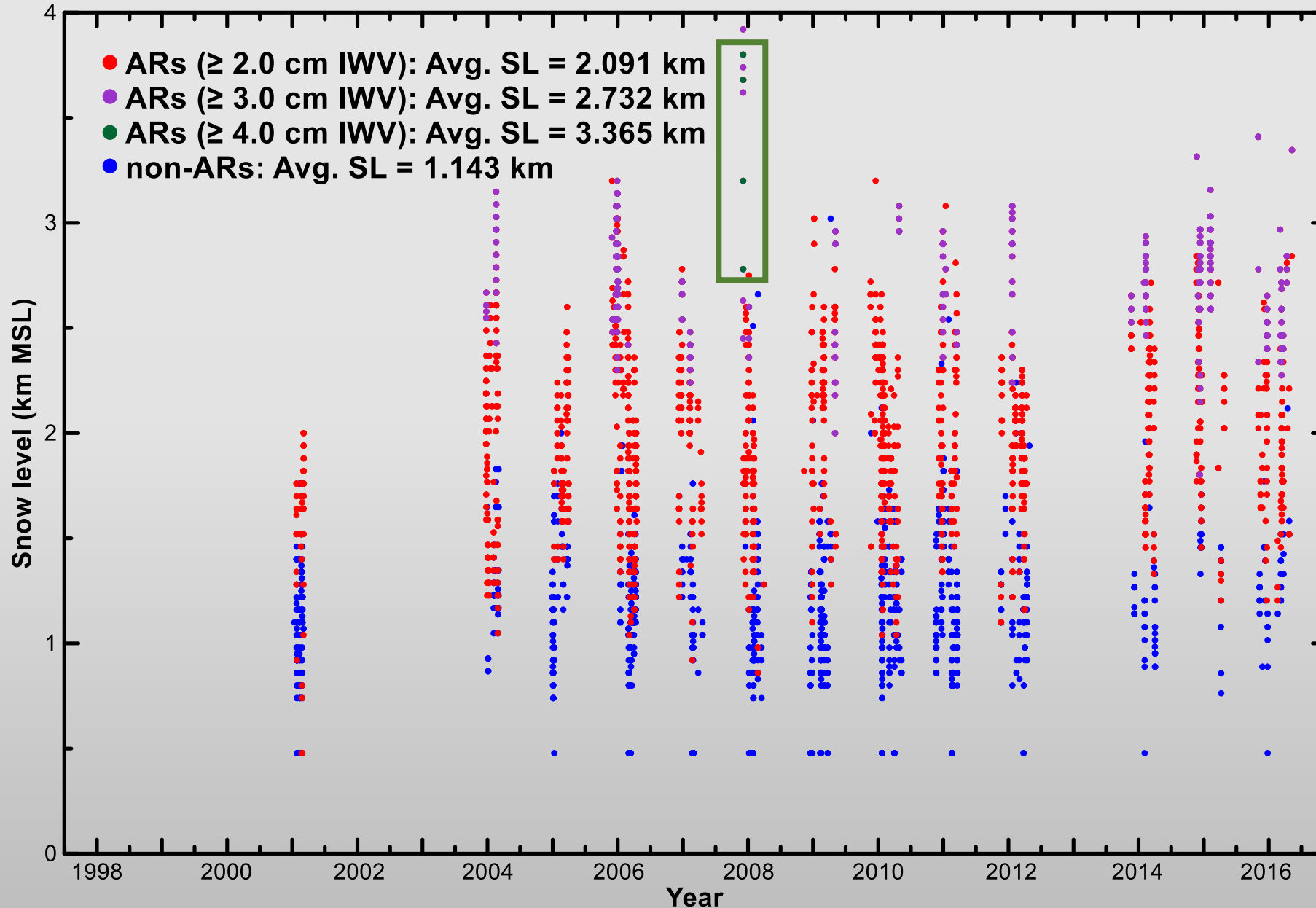
- 17-year time series of snow levels measured at Cazadero (CZC)
- Matched to times when GPS Integrated Water Vapor (IWV) was available at BBY
- ARs in red using 2.0 cm IWV threshold

Results: Cazadero



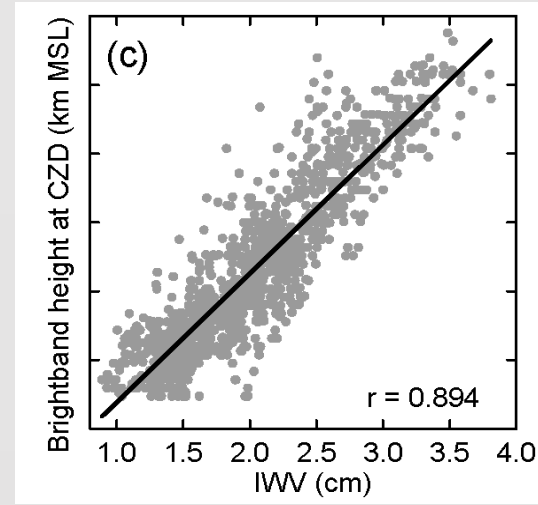
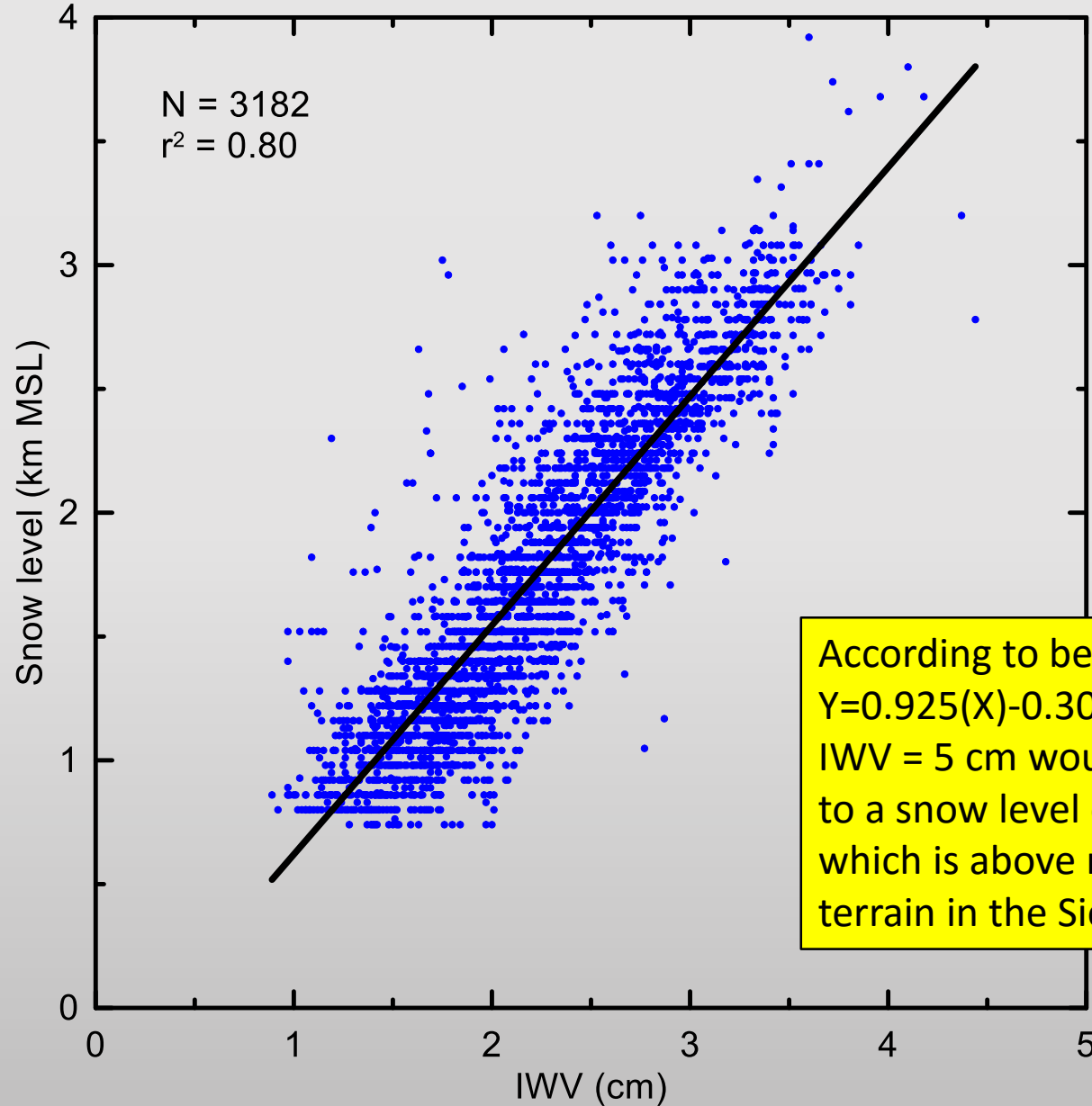
- 17-year time series of snow levels measured at Cazadero (CZC)
- Matched to times when GPS Integrated Water Vapor (IWV) was available at BBY
- ARs in red using 2.0 cm IWV threshold
- ARs in purple using 3.0 cm IWV threshold

Results: Cazadero



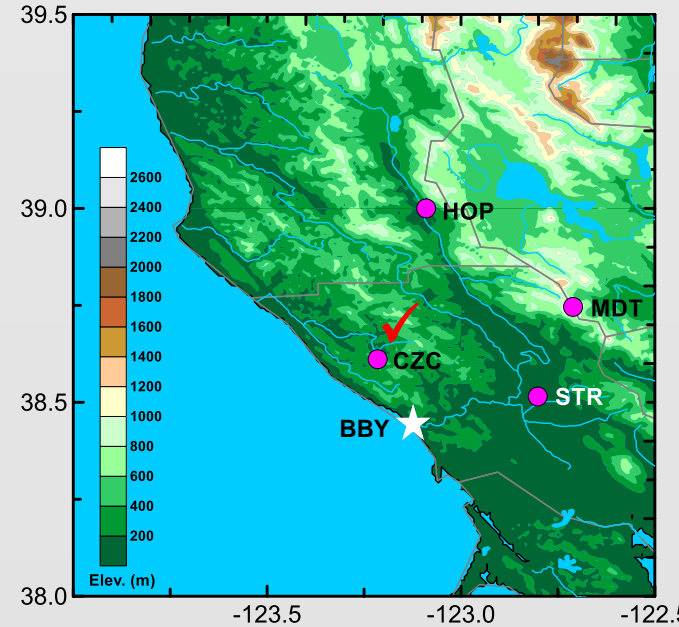
- 17-year time series of snow levels measured at Cazadero (CZC)
- Matched to times when GPS Integrated Water Vapor (IWV) was available at BBY
- ARs in red using 2.0 cm IWV threshold
- ARs in purple using 3.0 cm IWV threshold
- ARs in green using 4.0 cm IWV threshold

Results: Cazadero



Neiman et al., 2009
Water Management

According to best fit line,
 $Y=0.925(X)-0.305$, a value of
IWV = 5 cm would correspond
to a snow level of 4.3 km,
which is above most of the
terrain in the Sierra Nevada.



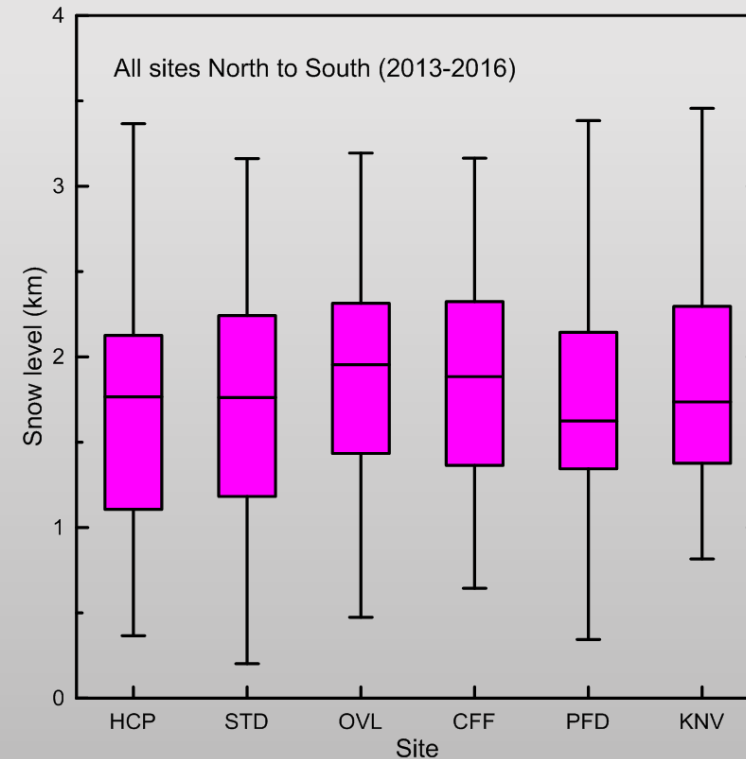
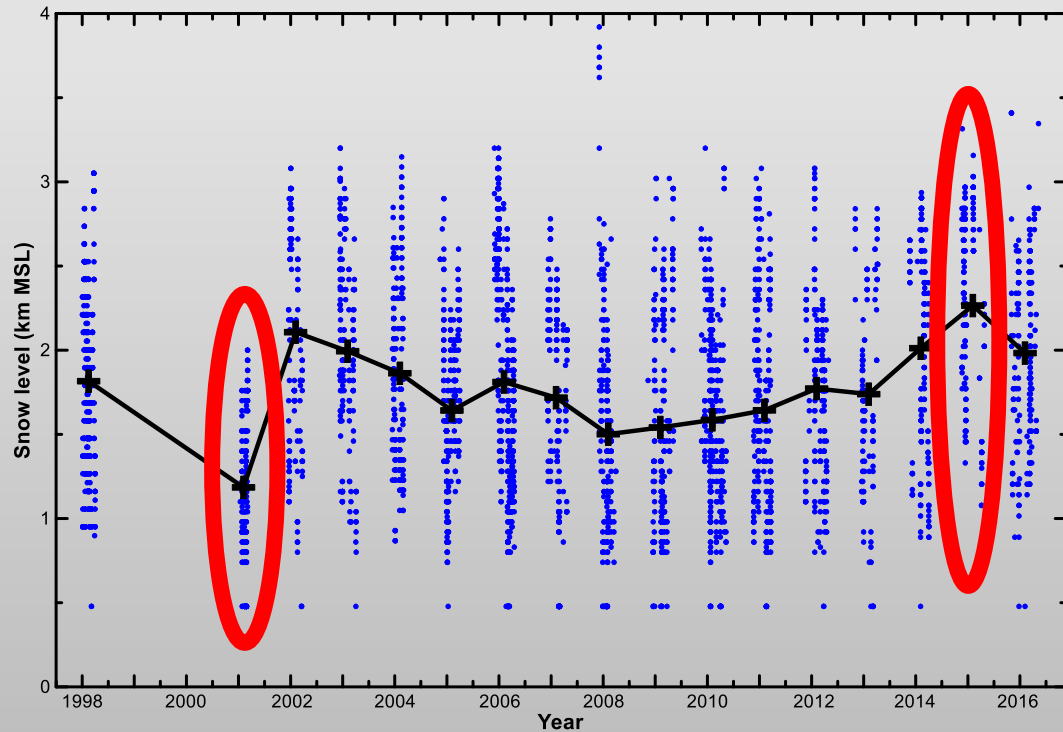
- 17-year time series of snow levels measured at Cazadero (CZC); snow cases removed
- Matched to times when GPS Integrated Water Vapor (IWV) was available at BBY
- Strong correlation between snow level and IWV

Summary

- Both the 1997-98 and 2015-16 El Niño winters did not produce anomalously high snow levels in the coast range or in the Sierra Nevada for the latter El Niño in comparison to the three previous drought winters.
- The 2014-15 winter had the highest snow levels in the Sierra Nevada, which exacerbated the drought because many Sierra Nevada locations did not receive a significant snowpack to draw on during the dry season.
- At a long-term coast range site (CZC), it appears there is an orographic “sweet spot” (75% of the time the snow level is in range of 1.0-2.5 km) with 75% of the precipitation occurring when the snow-level is in that altitude range.
- AR periods produce significantly higher (by 948 m at CZC) snow levels than non-AR periods, and the degree to which this occurs is highly correlated with IWV.
- Long-term operation and maintenance of the snow-level radar network in California will allow forecasters and other end users to determine the impact of climate change on the snow level, which in turn could require water managers to alter strategies in order to optimize the availability of water.

Future Work

- Storm track: use reanalysis data to investigate how the varying storm track impacts snow levels (start with 2001-coldest and 2015-warmest winters)
- Water vapor flux: Use AR water vapor flux to compare to snow levels to see if correlation is better/worse than using only IWV
- Latitudinal dependence: Investigate impact on snow level when all sites experience part of storm instead of compositing over several seasons



Thank you!

