# Supporting Information for "Illuminating snow droughts: The future of Western United States snowpack in the SPEAR large ensemble"

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## Introduction

We include additional text and figures to complement the understanding in the main text and also include a data accessibility section.

**Text S1: Historical Changes in Temperature and Precipitation Extremes**

To give a more complete picture of how the climatology has already changed across the historical period (1930-2011), in addition to snow droughts, we assessed changes in extreme precipitation and monthly high and low temperatures. We found that generally winter meteorological drought had not changed significantly while temperatures increased. This is consistent with increases in warm snow droughts and not dry ones. We found changes in all-type wintertime precipitation droughts (D2+) simulated by SPEAR were only significant in the Lower Colorado region, with an average increase of 16% while other regions averaged between 1% and 3% increases, see Figure S3(a). The increase in the Lower Colorado as measured by SPEAR is consistent with findings in Livneh which saw a 48% increase in meteorological drought, significantly more than all other observed regions.

We assessed changes in temperature on the monthly scale as well and found that significant increases are expected across WUS. Instead of looking at average daily minimum or maximum temperatures, we examined monthly maximum and minimum temperatures from SPEAR and Livneh, with the goal of capturing extremes. For example, a severe multi-day heat wave in January has the potential to melt snowpack very quickly but might fail to show up in a 30 day average. We found strong evidence in both SPEAR and Livneh that extreme heat events had increased in frequency while extreme cold events had decreased. In SPEAR, monthly extreme heat under SPEAR increases on average between 59% and 73% (Figure S2(b)), while in (c) W2+ minimum temperatures decrease by between 41% and 60% on average. Furthermore, the occurrence of D2+ minimum temperatures decreases 18-21% as shown by panel (d). We see strong agreement between Livneh and SPEAR which further lends confidence to SPEAR's ability to capture extreme values in WUS climatology.

Interestingly the Livneh dataset shows that the Pacific Northwest seems to have experienced the least amount of warming and got significantly wetter over the historical period, which we attribute to internal climate variability as it is still within the SPEAR ensemble range. The Pacific Northwest saw the only decrease in meteorological drought, the smallest increase in monthly maximum temperatures, and the smallest decreases in monthly minimum temperatures. The colder, wetter climatology can explain how the PNW was the only region to see a decrease in D2+ SD frequency over the historical period (see Figure 3) and perhaps explains the deviation in the early 2000s of Livneh snow drought frequency from the SPEAR ensemble in Figure 5.

**Data Availability** Our code for this project can be found in the Snow Droughts repository (https://github.com/Julians42/Snow_Droughts) which is registered under doi: 10.5281/zenodo.7130302.

**HUC2 Shapefiles** The HUC2 shapefiles used to group data by HUC2 are available via FTP from NOAA's ESRL: You can access the shapefiles by connecting to: ftp1.esrl.noaa.gov, username: anonymous, your email address as password and port: 22. Files are titled WBD_{XX}_HU2_Shape.zip for each region XX in 1-18. We ended up including these in our dataset - see doi: 10.5281/zenodo.7121527.

**Livneh Dataset** The livneh dataset is also available online via https://psl.noaa.gov/data/gridded/data.livneh.html, and can also be accessed via FTP at: ftp2.psl.noaa.gov, logging in with username anonymous and your email as the password and port 22 for public connection.

**SPEAR Data Online:** SPEAR-MED data is partially available directly through GFDL's online server, found https://www.gfdl.noaa.gov/spear_large_ensembles/ for the entire globe. The website provides the opportunity to download monthly mean historical temperature and precipitation data, alongside temperature and precipitation data under RCP5-8.5 by decade.

**SPEAR Data via Zenodo:** GFDL does not provide monthly snow data for either the historical or future simulated events, nor does it provide any data for RCP2-4.5, nor does it provide temperature maximum or minimum values which we use for analysis in the supplemental. Only 4/15 of the data we used was available directly from GFDL, and as it's filed by decade across the whole globe, it would require roughly a 120 GB download.

We decided to crop all this data to make our work more easily reproducible, which is available under doi: `10.5281/zenodo.7121527`.

## References

Delworth, T. L., Cooke, W. F., Adcroft, A., Bushuk, M., Chen, J.-H., Dunne, K. A., … Zhao, M. (2020). Spear: The next generation gfdl modeling system for seasonal to multidecadal prediction and projection. *Journal of Advances in Modeling Earth Systems*, *12*(3), e2019MS001895. Retrieved from `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS001895` (e2019MS001895 2019MS001895) doi: https://doi.org/10.1029/2019MS001895

Huning, L. S., & AghaKouchak, A. (2020). Global snow drought hot spots and characteristics. *Proceedings of the National Academy of Sciences*, *117*(33), 19753-19759. Retrieved from `https://www.pnas.org/doi/abs/10.1073/pnas.1915921117` doi: 10.1073/pnas.1915921117

Walton, D., & Hall, A. (2018). An assessment of high-resolution gridded temperature datasets over california. , *31*(10), 3789–3810. Retrieved 2022-11-18, from `https://journals.ametsoc.org/view/journals/clim/31/10/jcli-d-17-0410.1.xml` (Publisher: American Meteorological Society Section: Journal of Climate) doi: 10.1175/JCLI-D-17-0410.1

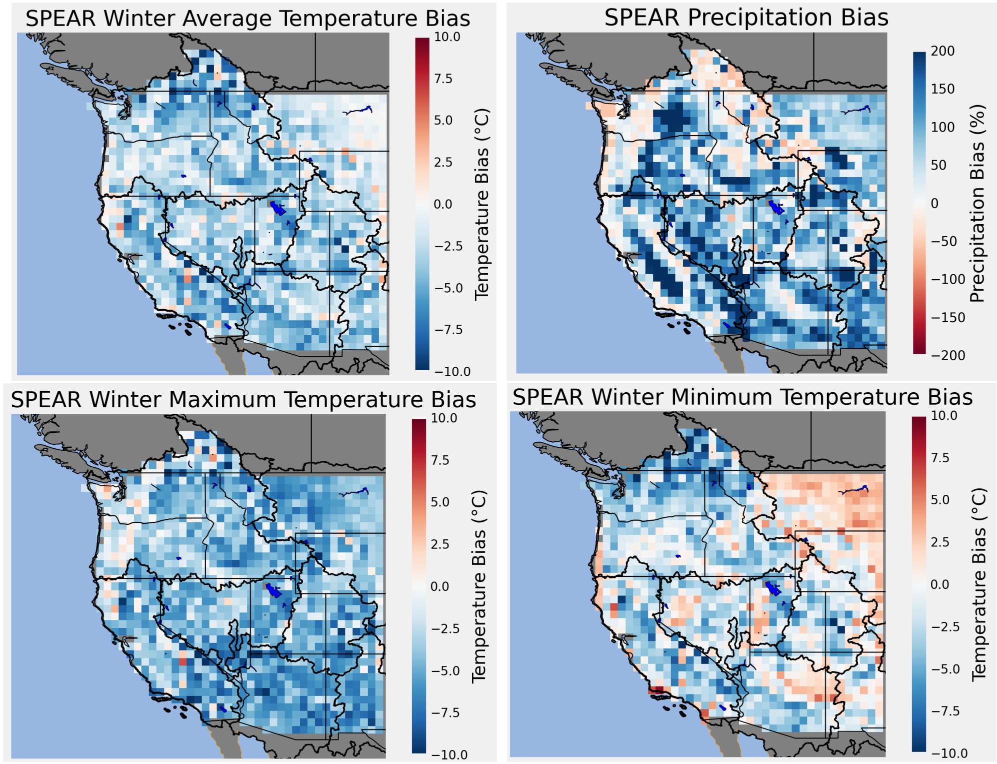


**Figure S1.** 90-Year Winter Temperature and Precipitation Biases. Clockwise from top left, (a) mean temperature bias, (b) precipitation bias, (c) minimum temperature bias, and (d) maximum temperature bias. The mean temperature bias was computed by taking the difference between the average the maximum and minimum temperatures of SPEAR and Livneh. We see that overall SPEAR has a slight cold and wet bias across much of the Western United States. The wet bias is consistent with Delworth et al. (2020). By examining the maximum and minimum temperature biases we see that SPEAR has a significant cold bias for maximum temperatures across the entire WUS, while it has a systematic cold bias for minimum temperatures over mountainous regions and slight warm bias over the rest of the WUS. We expect that some of the bias can be explained by the differences in model resolution: SPEAR is on a 1/2° grid while Livneh is on a 1/16° grid. We also note that Livneh has a particularly high lapse rate of 6.5°C/1000m which may contribute some additional bias (Walton & Hall, 2018).

**Snow Drought Classification by ZSWE Score**

| Drought Severity | Description | ZSWE Range | Probability of more Extreme |
|---|---|---|---|
| D4 | Exceptional Drought | ZSWE ≤ -2.0 | 0.023 |
| D3 | Extreme Drought | -2.0 < ZSWE ≤ -1.6 | 0.055 |
| D2 | Severe Drought | -1.6 < ZSWE ≤ -1.3 | 0.097 |
| D1 | Moderate Drought | -1.3 < ZSWE ≤ -0.8 | 0.21 |
| D0 | Abnormally Dry | -0.8 < ZSWE ≤ -0.5 | 0.31 |
| NN | Near Normal | -0.5 < ZSWE < 0.5 | -- |
| W0 | Abnormally Wet | 0.5 ≤ ZSWE < 0.8 | 0.31 |
| W1 | Moderate Wet Spell | 0.8 ≤ ZSWE < 1.3 | 0.21 |
| W2 | Severe Wet Spell | 1.3 ≤ ZSWE < 1.6 | 0.097 |
| W3 | Extreme Wet Spell | 1.6 ≤ ZSWE 2.0 | 0.055 |
| W4 | Exceptional Wet Spell | 2 ≤ ZSWE | 0.023 |

**Figure S2.** List of drought classification abbreviations, a text description for each, and the corresponding ZSWE values that are given the classification. We include for reference the probability of a random historical month being classified in that category or one that is more extreme, either dry or wet. We primarily use the D2+ classification for snow droughts which includes D2, D3, and D4 drought severity. This table is identical to one used by Huning and AghaKouchak (2020) and attempts to mimic frequencies of hydrological drought given by the US Drought Monitor.

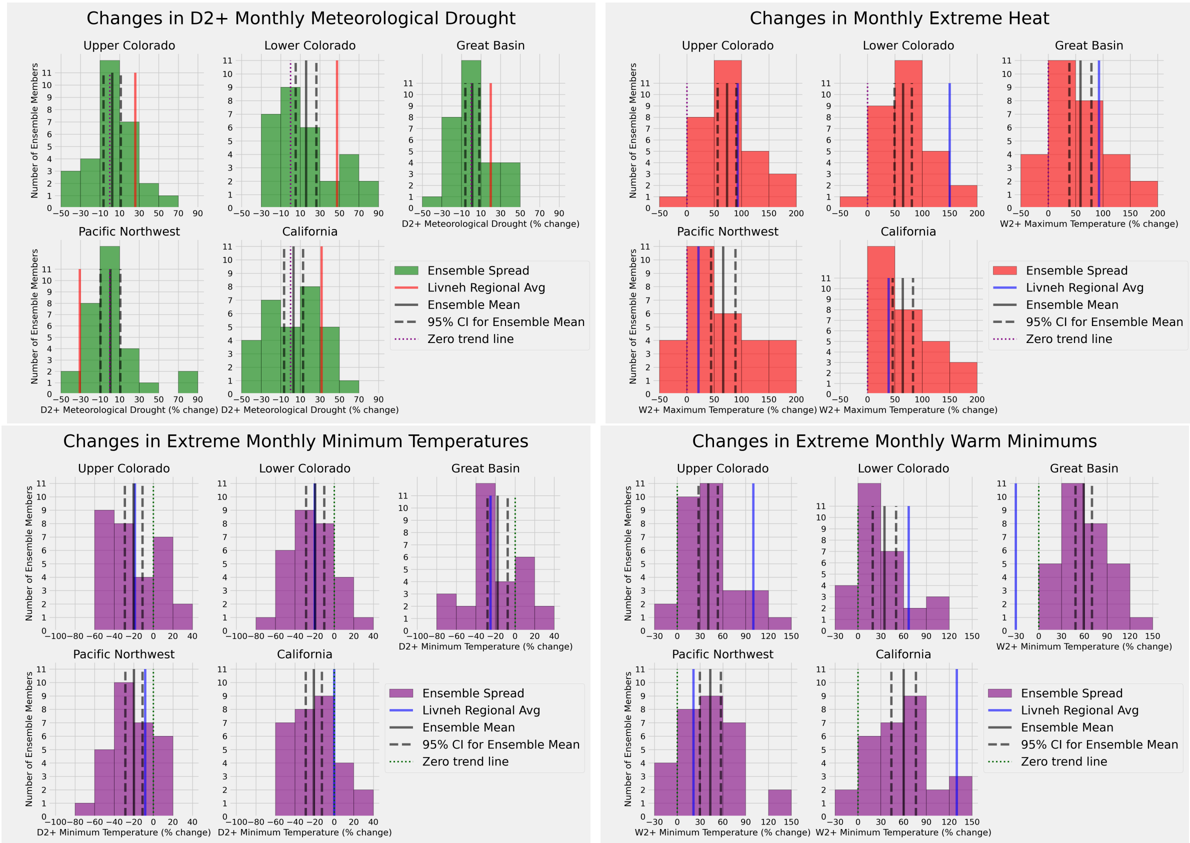


**Figure S3.** Changes in wintertime (Oct-Apr) historical precipitation and temperature extremes (clockwise from top left) in (a) D2+ Meteorological Drought, (b) W2+ monthly maximum temperatures, (c) D2+ average monthly minimum temperatures and (d) W2+ average monthly minimum temperatures. Here W2+ indicates that we are looking at positive z-scores, in this case extreme warm temperatures. The shaded histogram depicts the SPEAR ensemble distribution, with ensemble mean and confidence interval marked with vertical black dashed and solid lines, respectively. The observed value from the Livneh dataset is marked as a vertical line shaded red in (a) and blue in (b-d). A vertical dotted zero trend line is included for reference.

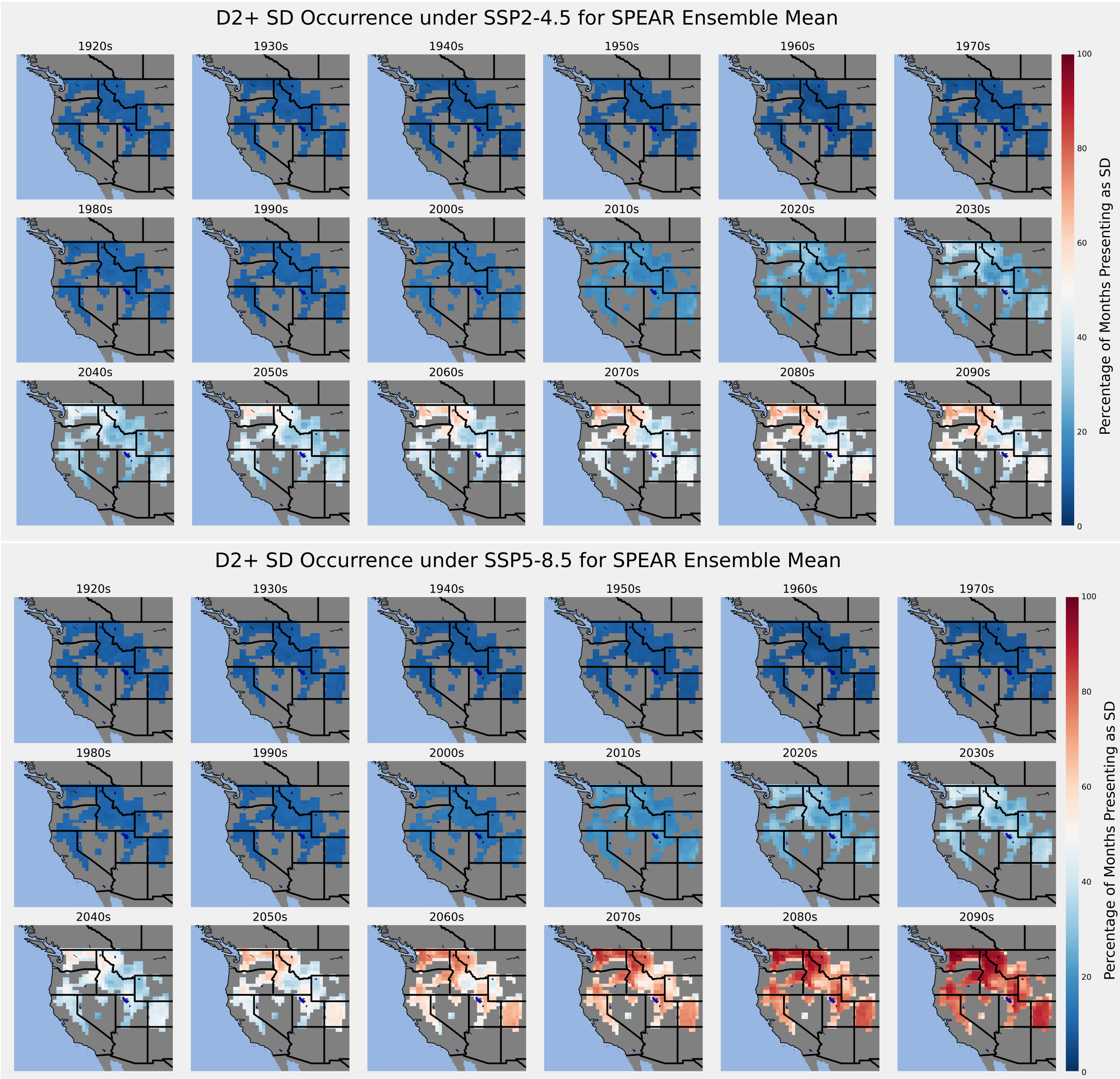


**Figure S4.** Panel plots for all 18 study decades between 1920 and 2100 for the SSP2-4.5 and SSP5-8.5 D2+ SD classification frequencies for the SPEAR ensemble mean. This figure emphasizes just how dramatic SPEAR expects the increase in D2+ SD occurrence to be, as the natural variability of the 20$^{th}$ century is barely distinguishable when placed on the same color scale as changes in the 21$^{st}$ century.

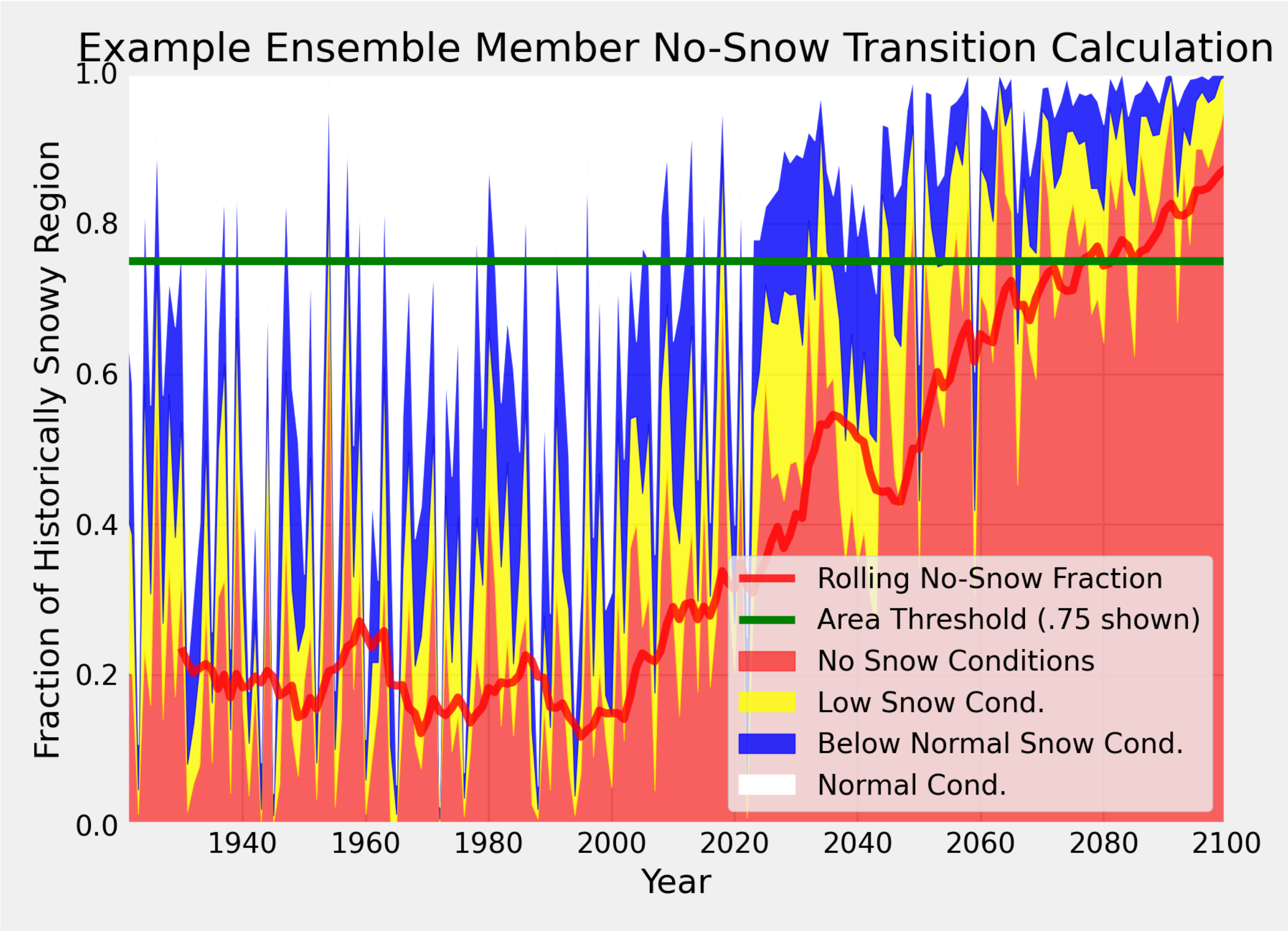


**Figure S5.** An illustration of how the no-snow transition is calculated as a function of the area threshold. This figure shows the fraction of the historically-snowy region experiencing no-snow (red), low-snow (yellow), below average-snow (blue), and near normal or above average snow (white). The dark red curve represents a 10 year moving average of the yearly no-snow values (in red), while the green horizontal line indicates the chosen area threshold, in this case $\mathcal{A} = .75$. For this particular region in one ensemble member, we see that the red curve crosses the green line for the last time in 2082. Thus, this ensemble member records a no-snow transition time of 2082.