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Communication

Ocean Temperatures Do Not Account for a Record-Setting Winter in the U.S. West

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Abstract: The record-setting winter of 2022–2023 came as an answer to both figurative and literal prayers for political leaders, policy makers, and water managers reliant on snowpacks in the Upper Colorado River Basin, a vital source of water for tens of millions of people across the Western United States. But this "drought-busting" winter was not well-predicted, in part because while interannual patterns of tropical ocean temperatures have a well-known relationship to precipitation patterns across much of the American West, the Upper Colorado is part of a liminal region where these connections tend to be comparatively weak. Using historical sea surface temperature and snowpack records, and leveraging a long-term cross-basin relationship to extend the timeline for evaluation, this analysis demonstrates that the 2022–2023 winter did not present in accordance with other high-snowpack winters in this region, and that the associative pattern of surface temperatures in the tropical Pacific, and snow water equivalent in the regions that stored and supplied most of the water to the Colorado River during the 2022–2023 winter, was not substantially different from a historically incoherent arrangement of long-term correlation. These findings suggest that stochastic variability plays an outsized role in influencing water availability in this region, even in extreme years, reinforcing the importance of other trends to inform water policy and management.

Keywords: Upper Colorado River Basin; snowpack; precipitation; sea surface temperatures; natural variability

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Citation: LaPlante, M.D.; Deng, L.; Dalanhese, L.; Wang, S.-Y. Ocean Temperatures Do Not Account for a Record-Setting Winter in the U.S. West. *Atmosphere* **2024**, *15*, 284. https://doi.org/10.3390/atmos15030284

Academic Editors: Christof Lüpkes, Kimitaka Kawamura and John Walsh

Received: 16 November 2023
Revised: 29 January 2024
Accepted: 30 January 2024
Published: 26 February 2024

1. Introduction

The Colorado River spans seven states in the Western United States, providing water for agriculture, industry, and municipalities from two major basins: the Lower Colorado River Basin and the Upper Colorado River Basin (UCRB), the latter of which comprises 17,800 square miles and provides about 90 percent of the river's total streamflow [1]. About 83 percent of UCRB discharge comes from fall, winter, and springtime precipitation [2], especially that which is initially stored in the snowpack of the Southern Rocky Mountains [3], which typically accumulates from November to April, when UCRB snowpacks peak (Figure 1k, black dashed line).

Evidence suggests that anthropogenic global warming may be contributing to an amplification of wintertime precipitation variability, resulting in more extreme events across the U.S. West [4,5], but an overall reduction in streamflow in the UCRB has been observed [6], and continued streamflow declines are expected with additional warming [7], substantially as a result of diminished snowpack [8]. Under these circumstances, much attention has been given to the challenge of enhancing the predictability of patterns of precipitation and runoff in the UCRB, as such information will likely be of critical importance to water users and water managers [9]. Across much of the rest of the West, such predictions are driven largely by known associations between tropical Pacific sea surface temperatures and wintertime precipitation [10], especially the various phases of the El Niño Southern Oscillation (ENSO). But while the impacts of certain types of El Niño and La Niña events on California [11], the broader Southwest [12], and the Pacific Northwest [13] are well-studied and broadly predictable, wintertime precipitation in the liminal UCRB has not been shown to be directly correlated with ENSO or other well-known patterns or modes in the world's oceans [14], seemingly rendering the most reliable pathway toward snowpack prediction untenable for this particular region of the American West, both in historic observations and model simulations [15]. Nonetheless, in the wake of the anomalously cold and pluvial winter of 2022–2023, which brought snowpack totals that neared or exceeded observational records across the UCRB, there was bountiful lay [16] and scientific [17] speculation that the record-breaking snowpack might be attributed to, and thus might have been predicted by, seasonally precursive sea surface temperatures.

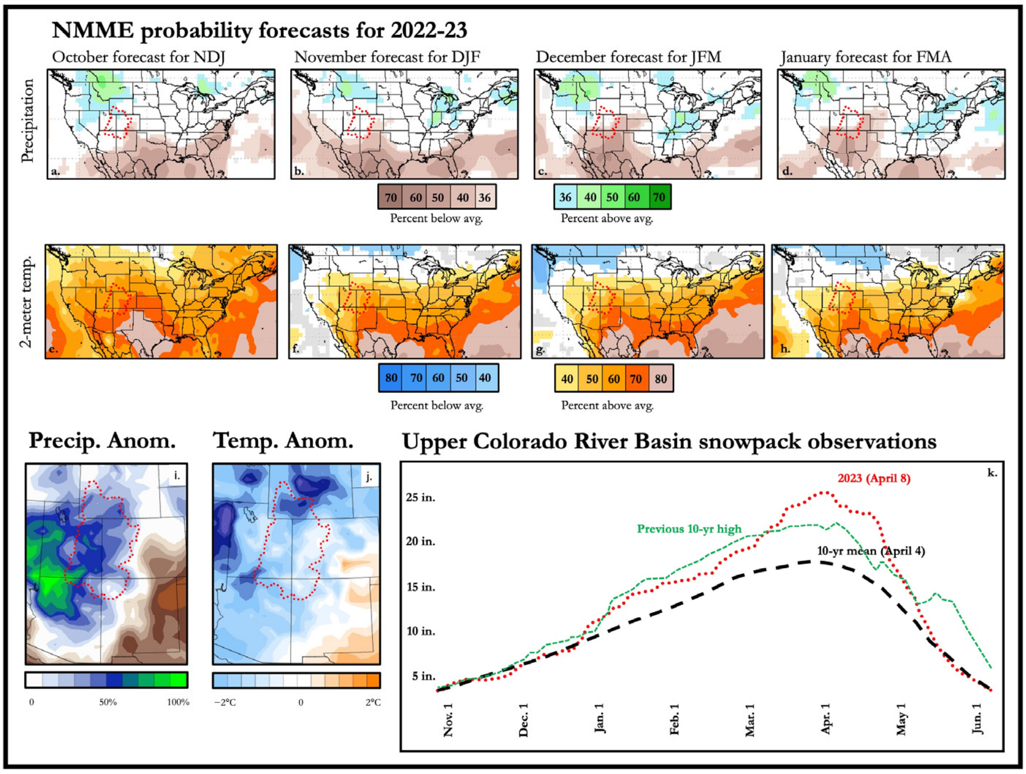

Figure 1. (**a**–**d**) The North American Multi-Model Ensemble's Probability Anomaly Correlation-calibrated forecasts from October, November, December and January of 2022–2023 for NDJ, DJF, JFM, and FMA, respectively. The Upper Colorado River Basin is depicted by a red dotted line, demonstrating a lack of robust predictions for a pluvial winter. (**e**–**h**) Same, for 2 m temperatures, demonstrating moderate confidence for an anomalously warmer winter. (**i**,**j**) ERA5 estimates of total precipitation and 2 m temperature anomalies. (**k**) Observed snow water equivalent in inches for the Upper Colorado River Basin in 2022–2023 (red dotted line), the previous 10-year high (green dashed line), and the average from 2014 to 2023 (black dashed line) from the United States Natural Resources Conservation Service.

The 2022–2023 winter and its resulting snowpack were not anticipated by the North American Multi-Model Ensemble's (NMME) Probability Anomaly Correlation-calibrated precipitation forecasts from October, November, December or January of 2022–2023 for NDJ, DJF, JFM, or FMA, respectively (Figure 1a–d). In most of the UCRB during those months, the NMME forecast suggested no substantially greater probability of either an anomalously wet or anomalously dry winter. In the same timeframes, the NMME offered slightly more firm predictions for 2 m temperatures, but these forecasts offered an above-average likelihood of anomalously warm conditions across the UCRB (Figure 1e–h). As precipitation and temperature are the key elements for snow accumulation, together these forecasted variables indicated a greater likelihood of lower-than-average snowpacks across the UCRB.

Contrary to these forecasts, the UCRB received substantially above-expected precipitation and substantially below-expected temperatures (Figure 1i,j). Accordingly, by early January, UCRB snowpack (Figure 1k, red dotted line) had begun to positively diverge from historical averages (Figure 1k, black dashed line). Basin-wide snowpack reached the average annual peak (15.6 inches) on 26 February, approximately 37 days ahead of when the high-snowpack mark is typically reached. The 2022–2023 snowpack maxed out on 7 April at 23.23 inches, 150 percent of the 10-year average and a record against observations going back to 1987, the first year in which UCRB-wide reports were available from the NRCS [18].

By expanding the limits of known variability, strongly anomalous events offer the intriguing possibility of aiding in the identification of trends and teleconnections that might otherwise go unnoticed [19]. The record-setting winter of 2022–2023 provided such an event, with snowpack totals nearing or overcoming observational records across the UCRB, and collectively exceeding any year in decades of observations. Thus, it is reasonable to ask whether the winter of 2022–2023 could have been predicted, particularly in association with the fluctuations of sea surface temperature anomalies (SSTAs) in the tropical Pacific, which are a key driving force for atmospheric circulations and moisture transport across much of the rest of the Western United States [20].

To these ends, we sought to evaluate whether the associative patterns of tropical Pacific SSTAs and snowpack in the UCRB during the winter of 2022–2023 might provide an explanation for the record-setting observed snowpacks, potentially offering clarity to a history of otherwise incoherent patterns during other high-snow winters in this region. We then discussed the potential that multi-annual signals may be more valuable for snowpack prediction, and thus water management and planning, in the long-term.

2. Materials

To assess snowpack in the UCRB, we used observational snow-water equivalent (SWE) records from 121 stations spread across the basin from the United States Department of Agriculture Natural Resources Conservation Service (NRCS) from 1987 to 2023. (SWE is the depth of water that would cover the ground if the snow cover was in a liquid state.) Additionally, pursuant to a strong cross-basin relationship between snowpacks in the UCRB and the bordering Great Salt Lake region (explained in greater detail below), we utilized data provided by the Utah Climate Center representing the normalized water content of the 1 April snowpack for the GSL's three main subbasins: the Bear River, Weber River, and Jordan River catchments, from 1930 to 2023.

To review long-standing patterns that exist between UCRB snowpacks and other climate variables, we utilized the University of Maine Climate Change Institute (CCI) Climate Reanalyzer toolbox to deploy datasets from the European Centre for Medium-Range Weather Forecasts (ECMRWF), European Reanalysis V5 (ERA5) [21], including sea surface temperature (SST), geopotential height (GPH), 2 m temperature, and total precipitation (TP), which are available at $0.25^{\circ} \times 0.25^{\circ}$ resolution from the ECMRWF's Copernicus Climate Change Service but were re-gridded by CCI to $0.5^{\circ} \times 0.5^{\circ}$ using bilinear interpolation to reduce server load. ERA5 was chosen in part because the March 2023 release of 18 additional years of reanalysis data (1940 to 1958) offered a temporal record of 83 years, coinciding with the majority of the NRCS/GSL-derived snowpack time series of 93 years. In the region being accessed, the accuracy of precipitation estimates for ERA5 against station observations has been demonstrated to have a similar coefficient of determination to the amalgamated in situ, and remote observations incorporated in the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset (R_2 values of 0.6 and 0.63, respectively) [22] but with a substantially longer record of monthly values (83 vs. 42 years). ERA5 sea surface temperature estimates have also been demonstrated to achieve an overall agreement with in situ observations from the National Data Buoy Center in the Pacific Ocean, and while ERA5 accuracy varies under different conditions, it appears to be most accurate in the tropics, which is the oceanic focus of this analysis [23]. To affirm the reanalysis results, we additionally employed NOAA's Extended Reconstructed SST (ERSST) gridded observation dataset, version 5, a global ($2^\circ \times 2^\circ$) monthly analysis from 1854 to the present, derived from the International Comprehensive Ocean-Atmosphere Data Set, with missing data backfilled via statistical methods [24].

To evaluate upper tropospheric synoptic airflow and energy transfer, we utilized the Japan Meteorological Agency's (JMA) Climate System Monitoring tools for depicting outgoing longwave radiation anomalies (OLRAs) per Chodi and Harrison, 2013, who demonstrated that warm ENSO phases coinciding with positive OLRA were mostly likely to result in seasonal weather anomalies in North America [25], as well as stream function anomalies (SFA), which can be used to identify upper-level atmospheric patterns such as ridges and troughs in the jet stream, and wave activity flux anomalies (WAFA), which are useful for looking for migratory wave disturbances [26], as recorded by JMA observations and the JMA-55 reanalysis ($0.56^\circ \times 0.56^\circ$).

3. Methods

Across the UCRB, snowpack historically begins to accumulate in mid-to-late October. The median peak in the UCRB's subbasins ranges from 8 March in the Lower San Juan Basin to 12 April in the Colorado Headwaters Basin, with an average annual snowpack in most of the subbasins peaking within 10 days of 1 April. Between 2014 and 2023, the average snowpack peak was 4 April, and the 2022–2023 winter was not unusual in this regard; the basin-wide peak that year was observed on 8 April (Figure 1k). We considered all full months between the snow onset and peak, November through March (NDJFM), as the snowpack-accumulation season.

We thus used April 1 as a marker upon which to base a normalized data time series representing the water content of the UCRB snowpack from 1987 to 2023 (Figure 2c, red dotted line). However, as observational records are historically sparse across much of the UCRB, we built upon the long-standing and close temporal coherence between the low-frequency variations of the Colorado River and the elevation of the Great Salt Lake [27], using data retrieved from the Utah Climate Center [28] and derived from Bean, et al. (2018) [29], representing the normalized water content of the 1 April snowpack for the GSL's three main subbasins: the Bear River, Weber River, and Jordan River catchments (Figure 2a, blue dotted lines) from 1930 to 2023 (Figure 2c, blue line). The overlapping SWE time series (from 1987 to 2023) for the UCRB and GSL strongly correlated, affirming that the well-established low-frequency coherence also applies to cross-basin snowpack. Both time series demonstrate a historically noisy pattern characterized by sharp changes of year-to-year variability in snowpack, but no statistically significant shifts occur in SWE over time. Linear regression was applied to extend the UCRB snowpack time series (Figure 2c, red dashed line).

We next evaluated the eight highest-snowpack years between 1940 (when the ERA5 dataset begins) and the present, excluding 2023. These years (starting with the highest estimated SWE) were 1952, 1993, 1997, 1982, 1984, 2005, 2019, and 2011. SSTAs from these years were collected into a composite, and a Pearson's one-point correlation map of SSTAs and SWE was generated for these years and 2022–2023. We repeated these processes for 2022–2023 and the eight other highest snow-accumulation seasons using the ERSST dataset.

The teleconnections that connect ENSO to weather regimes in other parts of the United States West are tied to the ability of persistent warm and cool phases to shift the position of the jet stream. As such, any connection between the ENSO and UCRB snowpack would include, as part of its fingerprint, a distinctive signal of connectivity near the 200–300 hPa pressure levels, where the jet typically resides. To this end, GPH anomalies were assessed for NDJFM of 2022–2023 using the ERA5 dataset for the 250 hPa pressure level, while stream function and wave activity flux were depicted for those months with JMA-55.

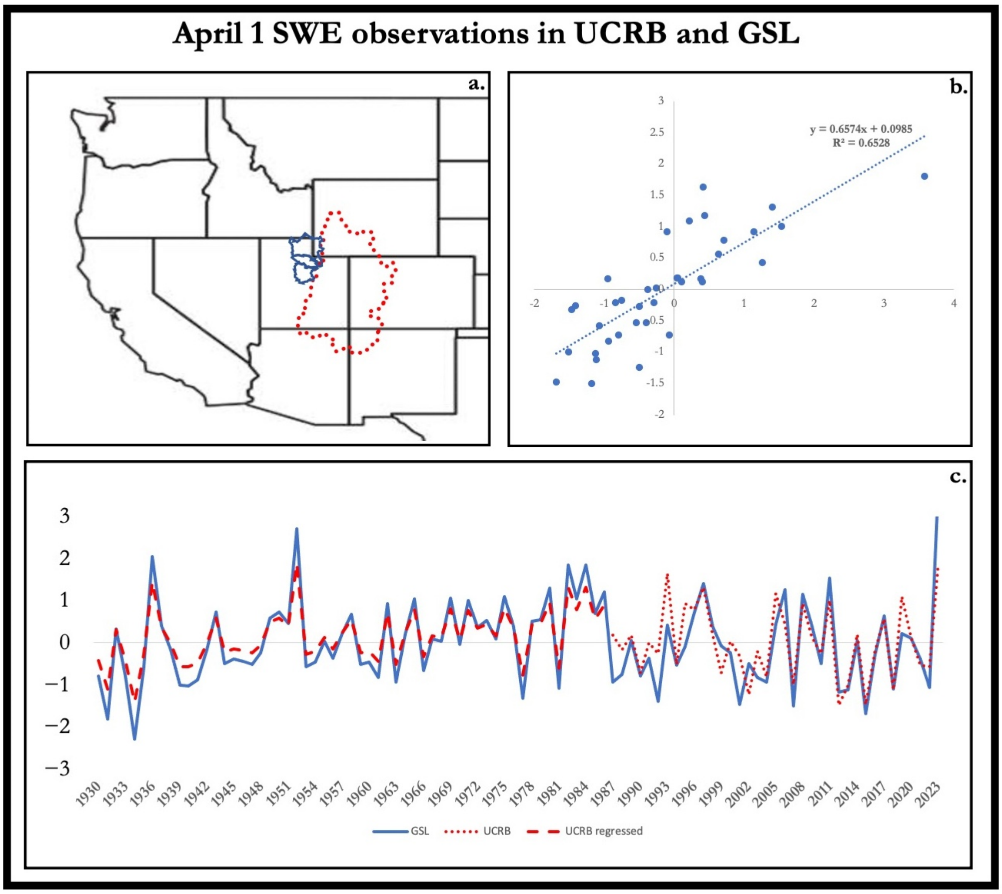

Figure 2. (**a**) The three major basins that supply the Great Salt Lake: the Bear River, Weber River, and Jordan River catchments (blue dotted borders), and the Upper Colorado River Basin (red dotted border). (**b**) Scatterplot showing the relationship between SWE in the GSL catchments and UCRB, along with the regression line (R_2 = 0.65). (**c**) A time series of SWE from the Great Salt Lake basins (blue line), the UCRB (red dotted line), and regressed values for the UCRB (red dashed line).

Prior research has suggested that precipitation in the U.S. Intermountain West, inclusive of the UCRB, is linked to the 10- to 20-year cycle of the Pacific Decadal Oscillation [30]. To assess the value of multi-annual signals on snowpack, we applied a bandpass filter of 5 to 20 years to the UCRB time series and applied a power spectral analysis to the time series.

4. Results

As depicted in Figure 3a, from 1941 to 2023 there has been no substantial correlative relationship between surface temperature anomalies in the tropical Pacific during the snow-accumulation season and the April 1 snowpack in the UCRB. Anomalies from NDJFM 2022–2023 (Figure 3b), show a canonical, albeit weak, La Niña arrangement, akin to the "type 3" cluster pattern identified by Johnson, 2013, in which an eastern-oriented cold tongue is met near Papua New Guinea and enveloped to the north and south by warm anomalies; Johnson found that the frequency of occurrence for this pattern was 6.6% between 1950 and 2011 [31]. This SSTA pattern is also apparent in the NDJFM of 1996–1997 and 2010–2011 (Figure 3c), potentially indicating that the eastern Pacific SST configurations may be conducive to the precipitation increases and temperature drops that create and maintain snowpacks in the UCRB (e.g., Yuan and Yan, 2013 [32]), a supposition that will be further explored below.

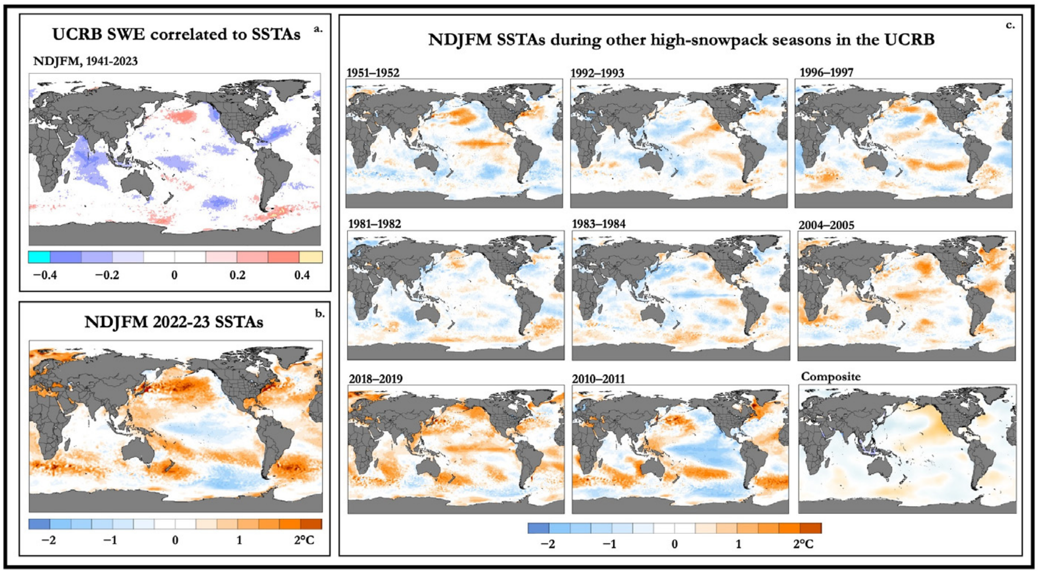

Figure 3. (**a**) April 1 snow-water equivalent in the Upper Colorado River Basin correlated to global sea surface temperature anomalies from the ERA5 dataset. (**b**) Monthly averaged SSTAs for the snow-accumulation season, leading to the extreme snowpack of 2022–2023. (**c**) SSTAs during the snowpack-accumulation seasons of the eight other highest-snowpack years, as estimated by Figure 2, and a composite of these exemplars (lower right).

However, as additionally shown in Figure 3c, the other six high-snowpack exemplars showed myriad other warm–cold juxtapositions, particularly in the ENSO-associated regions of the tropical Pacific, where warm anomalies (e.g., 1952 and 2019), and transitory phases (e.g., 1982 and 1993) have all coincided with high-snow years in the UCRB. Indeed, the record-setting winter of 2022–2023 came during a rapid phase change out of a rare "triple dip" La Niña [33], and in composite (lower right) SSTAs concurrent to high-snowpack years showed a lack of robust tropical signals, particularly in the ENSO-associated regions of the equatorial Pacific. Other features of the 2022–2023 NDJFM SSTA map, such as a region of intense warming in the Western North Pacific, also appear inconsistently in the other high-snow years in the eight other ERA5-generated maps of SSTAs, coinciding with high snowpacks in the UCRB and their composite.

Even when SSTAs do present in roughly similar configurations, the atmospheric outcomes are vastly dissimilar. For instance, the "type 3" La Niña pattern that was discernable during the snow-accumulation seasons of 1996–1997, 2010–2011, and 2022–2023 can be seen in Figure 4a–c, which depicts SSTAs for the middle month, January, of each of those seasons.

Notably, it is not just the presence of a cold phase in the eastern-to-central tropical Pacific, cupped by warmer-than-average waters to the north, west, and south of the cold tongue, that unites these "snapshots" of ocean temperature conditions, but also anomalous warming in the northwestern Atlantic, and a region of warmer-than-average temperatures stretching from the Argentine coast eastward to Cape Agulhas/Cape of Good Hope, in Africa. As seen in Figure 4d–i, the configurations of SFA, WAFA, and OLRA in these three instances were broadly dissimilar, and a pronounced wave train that resulted in a synoptic trough over the U.S. West in January of 2022–2023 (and which persisted through the entire snow-accumulation season of those years, not shown) was not matched in the 1996–1997 and 2010–2011 instances.

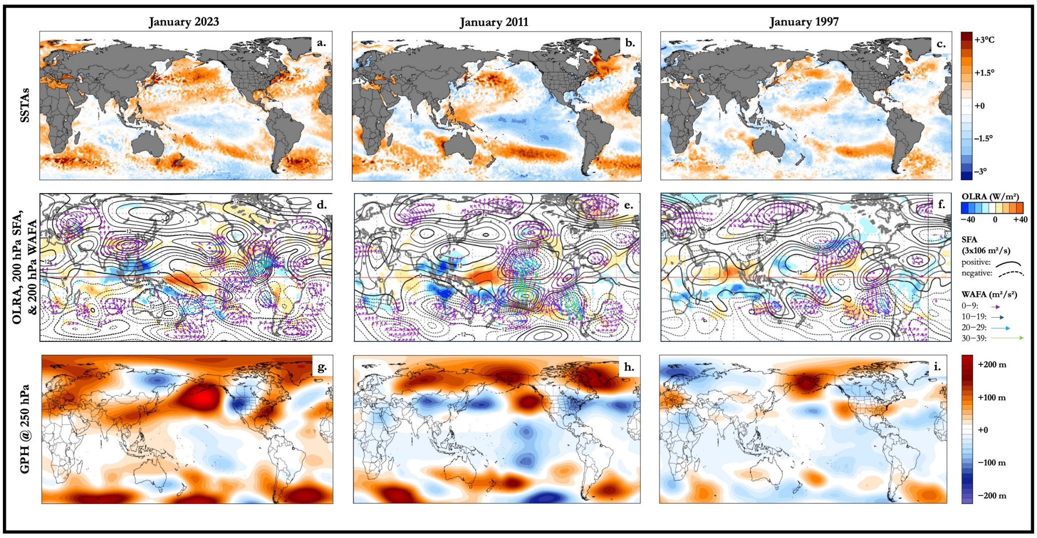

Figure 4. (**a**–**c**) From ERA5, sea surface temperature anomalies in January of 2023, January of 2011, and January of 1997—three high-snowpack years in the Upper Colorado River Basin that coincided with roughly similar configurations of SSTAs across the Pacific Basin. (**d**–**f**) For the same months, outgoing longwave radiation anomalies, stream function anomalies, and wave activity flux anomalies, from JMA. (**g**–**i**) For the same months, from ERA5, geopotential heigh anomalies at 250 hPa.

5. Discussion

In recent years, there has been a notable amplification of winter precipitation variation, resulting in more extreme events across the U.S. West [34]. Thus, the U.S. West appears to be one of the many regions of the globe that, pursuant to the increased water-holding capacity of warmer air [35,36], may be experiencing shifts in atmospheric circulation patterns, moisture availability, and temperature gradients, resulting in intensified short-term precipitation events [37]. In the U.S. West, these events have sometimes been ascribed to an intensification in the atmospheric rivers (aRs) that transport large quantities of water vapor from the tropics to the mid-latitudes, including the Western United States [38], and there has been widespread speculation that a "freight train of atmospheric rivers" was responsible for the extreme winter of 2022–2023 in the UCRB and wider west [39]. As the Pacific Ocean surface temperatures are a key driver of landfalling atmospheric rivers [40] and other teleconnective circulations that impact meteorological regimes across much of Western North America, it is sensible to examine whether the SSTAs that existed during the snow-accumulation season of 2022–2023 followed patterns that have previously been associated with high-snowfall years in the UCRB.

This analysis, however, aligns to a globally familiar story: while anthropogenic climate warming may intensify interannual climate variability [41], perhaps in the case of the winter of 2022–2023, by amping up the presence and transport of moisture from the Pacific to the UCRB, underlying variability continues to be the dominant factor driving year-to-year fluctuations.

There are limits to this analysis, which derives several decades of UCRB snowpack data from in situ observations, but includes longer-term estimates from strong-but-not-flawless correlative relationship between GSL and UCRB snowpacks. Other variables used were derived from reanalysis, which can suffer from the same challenges of observational datasets (lack of observations, errors in observations), as well as shortcomings in assimilation and computational limitations [42]. Notwithstanding these caveats, this assessment affirms in several ways the general agreement that tropical SSTs do not drive predictable patterns of temperature and precipitation, which are the key elements of snowpack, in the UCRB, building upon this general understanding by demonstrating that it appears to hold true even in extreme cases, like in 2022–2023.

This poses a challenge to offering long-lead predictions for snowpack in a region that is vitally important for water resources in the United States, as stochastic forcings appear to remain the dominant drivers of snowpack. Thus, while it remains possible that specific patterns of SSTAs could be connected to UCRB snowpacks, the lack of coherent signals across many decades, and even under the extreme conditions of 2022–2023, suggests that water planning and management may be best informed by other signals. While this analysis is not intended to offer a complete answer as to what signals would be preferable, prior research has suggested that a multi-faceted, multi-annual set of oceanic precursors (including cool SSTAs in the tropical Pacific 1–2 years before, warm SSTAs in the Kuroshio-Oyashio region 2–3 years before, and the warm SSTs in the southern tropical Atlantic 3–4 years before) can improve the outlook for heightened drought threat [43], albeit this predictive matrix is for the conditions that are adverse to snowpacks and cannot be "opposite signaled" to predict the cold and pluvial conditions that lead to greater wintertime water storage in the UCRB.

However, it has also been shown that the Pacific Decadal Oscillation (PDO) strongly influences soil moisture in the UCRB, presumably in part via its influence on circulations that drive snowpacks [44], and that the Pacific Quasi-Decadal Oscillation (QDO) is an effective predictor of the elevation of the Great Salt Lake, which is fed by the same basins that were used to extend the snowpack proxy time series [45]. ARs, which have been demonstrated to play a concurrent role in past extreme precipitation events in the region [46] and are widely regarded and reported to have been a key factor in the extreme pluvial winter of 2022–2023 [47], have also been shown to exhibit a quasi-decadal frequency in the U.S. West [48].

Accordingly, it may be worth evaluating whether quasi-decadal fluctuations can be more useful for long-term water prediction. To these ends, we applied a 5-to-20-year bandpass filter to the UCRB snowpack time series, unveiling a pronounced quasi-decadal pattern (Figure 5a, black line), and a power spectral analysis revealed that the most substantial spectral density occurs in a period of roughly between 11 and 17 years (Figure 5b, pink shaded area). Repeating the process with the GSL SWE time series, from which the extended, pre-1987 UCRB SWE time series was regressed, resulted in an even stronger density at the same intervals (results not shown).

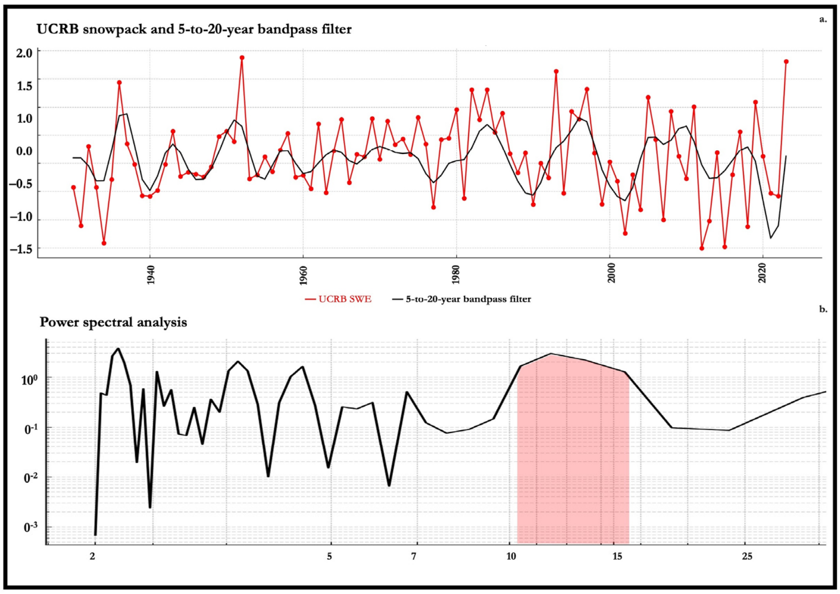

Figure 5. (**a**) Normalized Utah Colorado River Basin (red line) estimated snow-water equivalent, from observations (1987–2023) and regression (1930–1986). The 5-to-20-year bandpass filter of the UCRB time series (black line). (**b**) Power spectral analysis of the above time series plotted on a logarithmic scale at intervals of 2, 5, 7, 10, 15, and 25 years, showing a substantial spectral density at 11 to 17 years (pink shaded area).

While intriguingly pointing to the potential for multi-annual signals and quasi-decadal oscillations to inform water management, substantial additional research would be needed to make such associations useful to inform the decision-making of political leaders, policy makers, and water managers who are reliant on snowpacks in the Upper Colorado River Basin to serve the needs of tens of millions of people downstream. However, in lieu of the identification of the sort of robust, seasonally precursive signals that are helping to shape water resource decision-making in other parts of the U.S. West, this would appear to be a worthwhile area of exploration.

6. Conclusions

In the fall of 2021, water storage levels in the two major reservoirs fed by the Upper Colorado river had dropped below 40 percent capacity. With forecasts showing dry weather ahead, regional water planners were figuratively—and in many cases literally—praying for snow [49]. The much hoped-for deluge did not come for another two winters; however, when it did, water managers reliant on UCRB runoff were reluctant to disperse too much water, concluding that it was best to hold on to much of the aqueous bounty they had received, for they could not be sure when another massive snowpack would arrive [50], even as forecasts firmed for a "historically strong" El Niño [51], which often signals anomalously high precipitation in other parts of the U.S. West. This appears to be a wise approach, as this analysis suggests that we cannot now (nor perhaps ever) rely upon shorter-term signals to inform water policy and management for this region.

While this does not eliminate the possibility that significant signals may yet be identified, connecting precursive SSTs and the variables that most account for UCRB snowpacks, the record-setting winter of 2022–2023 appears to have closed yet another potential window of opportunity for identifying such connections. If this extreme winter had coincided with SSTAs, pressure anomalies, or circulation patterns that had been observed in other high-snowpack winters, it might be worthwhile to continue to pursue these elusive connections, as skillful forecasts at seasonal lead times can offer actionable information to water managers seeking to maximize savings and distributions for both short- and long-term benefit of myriad users [52]. However, our suspicion that much longer-term signals, such as those evidenced in the power spectral analysis on Figure 5b, which could be used to guide water-planning, does not necessarily suggest that water managers should only rely on these long-term trends for their decisions—although we do believe this is a possibility deserving of significant additional study. A third possibility exists: it may be true that UCRB snowpacks are of such stochastic nature that they will continue to defy prediction of any sort, in which case water managers in this liminal-yet-vital region may need to continue to do what many did in response to the 2022–2023 water year: banking snowmelt from bountiful years regardless of what ocean temperatures and other signals may seem to suggest about the coming winter.

Author Contributions: Conceptualization, M.D.L. and S.-Y.W.; methodology, M.D.L. and S.-Y.W.; validation, M.D.L., L.D. (Liping Deng), L.D. (Luthiene Dalanhese) and S.-Y.W.; writing, M.D.L. and S.-Y.W.; visualization, M.D.L. and L.D. (Luthiene Dalanhese); supervision, S.-Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the U.S. Department of Energy/Office of Science under Award Number DE-SC0016605 and the U.S. SERDP project RC20-3056. SYSW was also supported by the U.S. Department of Interior, Bureau of Reclamation with Grant No. R19AP00149. LD is supported by the National Natural Science Foundation of China with Grant No. 41875071. This research was further supported by the Utah Agricultural Experiment Station, Utah State University, and approved as journal paper number 9750.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used for this study are freely and publicly available. NMME forecast archive: https://www.cpc.ncep.noaa.gov/products/NMME/archive/; UCRB April 1 SWE: https://nwcc-apps.sc.egov.usda.gov/; GSL April 1 SWE: https://climate.usu.edu/service/droughtPredictionPages/snowpack.php; ERSST V5: https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html; ERA5: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form; JMA55: https://jra.kishou.go.jp/JRA-55/index_en.html. (All data was available and accessed on 19 February 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

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