AGU ADVANCING EARTH AND SPACE SCIENCE

Earth and Space Science

RESEARCH ARTICLE
10.1029/2022EA002630

Intensified Warming and Aridity Accelerate Terminal Lake Desiccation in the Great Basin of the Western United States

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Key Points:

- MODerate-resolution Imaging Spectroradiometer data products provide a unique way to assess individual vulnerabilities of terminal lakes as temperatures rise in the US West
- Surface and air temperatures in the Great Basin (GB) are rising dramatically, with a sharp rise in the rate of increase observed beginning ~2011
- ET is generally lower in the GB, exacerbated by drought restrictions on surface evaporation, likely reinforcing regional warming

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Hall, D. K., Kimball, J. S., Larson, R., DiGirolamo, N. E., Casey, K. A., & Hulley, G. (2023). Intensified warming and aridity accelerate terminal lake desiccation in the Great Basin of the western United States. *Earth and Space Science*, *10*, e2022EA002630. https://doi.org/10.1029/2022EA002630

Received 22 SEP 2022
Accepted 15 DEC 2022

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Funding acquisition: Dorothy K. Hall

Abstract

Terminal lakes in the Great Basin (GB) of the western US host critical wildlife habitat and food for migrating birds and can be associated with serious human health and economic consequences when they desiccate. Water levels have declined dramatically in the last 100+ years due to diversion of inflows, drought and climate change. Satellite-derived environmental science data records (ESDRs) from the MODerate-resolution Imaging Spectroradiometer (MODIS) (snow cover, evapotranspiration (ET) and land surface temperature (LST)), enable a unique approach to evaluate the effects of aridification on terminal lakes and to study their individual vulnerabilities. Surface and air temperatures in the GB are rising dramatically, with a sharp rise in the rate of increase observed beginning around 2011, while the number of days of snow cover is declining especially in the western mountainous part of the GB as exemplified in Mono Basin, California. Rising temperatures coincide with fewer days of snow cover, a decrease of inflow to the lakes and greater evaporation of water from the lakes. MODIS ESDRs show strong and statistically significant increasing surface temperature (LST) in the GB, a reduction in the number of days of snow cover, and mixed results in ET. ET declined slightly in the more arid parts of the GB due to greater moisture restrictions to evaporation from extended drought, while ET increased in the more-vegetated, wetter, mountainous northeastern parts as temperatures have risen. Severe and costly ecological, human health and economic consequences are expected if the lakes continue to decline as predicted.

Plain Language Summary

Terminal lakes in the Great Basin (GB) of the western US host critical wildlife habitat and food sources for migrating birds and can be associated with costly human health and economic consequences when they desiccate. Toxic minerals in the expanding lakebeds may become airborne during windstorms, contributing to air pollution. Satellite data products (snow cover, evapotranspiration and surface temperature) have enabled a unique understanding of the dynamics of aridification in the GB and associated effects on terminal lakes which are usually saline. Surface temperature is rising dramatically, with a sharp rise in the rate of increase observed beginning around 2011, while snow cover is declining especially in the western mountainous part of the GB as exemplified in Mono Basin, California. Evapotranspiration has declined slightly in lower elevation parts of the GB likely due to a decrease in vegetation there, while it has increased in the wetter, mountainous eastern part as temperatures have risen. Though we recognize that 21 years is not adequate for assessing trends, it is clear that increasing temperatures, greater evaporation of lake water and decreasing number of days of snow cover are contributing to desiccation of terminal lakes, with severe environmental and human health consequences expected.

1. Introduction

A terminal lake has no outlets, losing water only through evaporation or groundwater seepage. Terminal lakes have been shrinking worldwide, and water levels have declined in at least the last 100+ years, primarily due to increasing societal water demand exacerbated by periodic droughts, lake and groundwater extraction, and climate change (Wurtsbaugh et al., 2017). In the western United States lakes have been losing water and shrinking dramatically, especially since the current drought began around the year 1999 (Piechota et al., 2011).

In the Great Basin (GB) of the western US, streamflow from snowmelt in the mountains is the main inflow to the terminal lakes which are typically shallow and have a large surface area. The amount of water flow into the

10.1029/2022EA002630

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lake basins is affected by many variables such as: volume of snow in the mountains, precipitation/drought and upstream diversions by humans. When the need for water by humans increases during drought conditions, the need for more water flowing into the lakes to maintain the health of the lakes also increases. Lower water levels are associated with increased salinity, altered food webs and reduction of invertebrate food sources for shorebirds and waterbirds.

Global climate models predict increasing temperatures and intensity of droughts in the western US (Cook et al., 2015; McKenzie & Littell, 2017), with a projected increase in the fraction of precipitation falling as rain versus snow, having the effect of decreasing snowpack water storage (Frankson & Kunkel, 2016; McCabe & Wolock, 2010; Snyder et al., 2019; Williams et al., 2022). Snowmelt is a more efficient mechanism for filling lakes than is rainfall (Berghuijs et al., 2014). The reduction of snowfall and number of days of snow cover results in lower albedo and greater absorption of solar radiation and heating at the Earth's surface (Déry & Brown, 2007; Kumar et al., 2020). Additionally, a snowpack helps to reduce lake warming in summertime because snowpack and water temperature are highly correlated in mountain lakes (Smits et al., 2020).

Rapid surface warming on inland lakes has been documented for all parts of the globe (O'Reilly et al., 2015; Zhang et al., 2014). For example, summer nighttime surface temperatures of large inland water bodies increased at an average rate of 0.45°C/decade between 1985 and 2009 in large lakes in California and Nevada (Schneider et al., 2009). In the latter part of the 20th Century and the beginning of the 21st Century, the surface water of lakes warmed at an average rate of 0.34°C/decade across the globe according to satellite measurements (O'Reilly et al., 2015).

Terminal lakes play a critical but understudied role as sites of rare biodiversity and unique chemical and ecological processes and as feeding areas for migratory birds (Haig et al., 2019; Larson et al., 2016; Senner et al., 2018). Migrating waterbirds rely on the network of terminal lakes on their journeys through arid continental interiors (Donnelly et al., 2020) because the lakes can provide a rich source of food and energy (e.g., brine shrimp and brine flies) for the birds (Oring & Reed, 1997; Sorensen et al., 2020). Ultrasaline terminal lakes can also host "extremophiles," organisms that have provided invaluable information on the evolution of life (e.g., Roberts, 2005).

Additionally, desiccating saline lakes can negatively impact human health when the dried lakebed is exposed to wind erosion, reducing air quality (Zucca et al., 2021). Unconsolidated, toxic (e.g., selenium, mercury, arsenic and other heavy metals) and hazardous (high-pH alkali) substances are prevalent in the lakebed sediments. Windstorms can transport these toxic and hazardous particulates for hundreds of kilometers.

Here, we evaluate specific factors that are driving the decline of GB terminal lakes, with a focus on three lakes that are widely separated within the GB and are largely fed by streams originating in snow-covered mountains: Lake Albert in Oregon, Great Salt Lake (GSL) in Utah and Mono Lake in California (Figure 1). The combination of consumptive water use, drought and climate warming is jeopardizing the viability of these lakes (Donnelly et al., 2020; Haig et al., 2019; Hall et al., 2021; Larson et al., 2016; Wurtsbaugh et al., 2017).

The drought in the Southwest US that has afflicted the region for over two decades is the driest 22-year period in the last 1,200 years (Williams et al., 2022). It is often referred to as a megadrought which may be defined as a dry period lasting two decades or longer (Cook et al., 2015; Williams et al., 2020, 2022).

Only through the use of satellite data can we evaluate the regional changes that are affecting the GB under drought conditions. Using continuous, 21-year environmental science data records (ESDRs) consisting of validated MODerate-resolution Imaging Spectroradiometer (MODIS) standard data products: snow cover, evapotranspiration (ET) and land-surface temperature (LST), along with ancillary data, we can gain an understanding of the individual vulnerabilities of GB terminal lakes and evaluate differences in the responses of each lake to the current megadrought. Other satellite records are available with longer data records suitable for assessing climate trends, but no other ESDRs provide comprehensive operational land parameter records with a high level of precision enabled from continuous MODIS operations on the Earth Observing System Terra satellite.

2. Study Area and Background

The study area consists of most of the GB of the western US and includes the basins of Lake Abert (2,753 km^2), GSL (39,732 km^2) and Mono Lake (AKA Mono Basin, 1,791 km^2) (Figure 1). The GB is a closed catchment of ~500,000 km^2 area located in Nevada, Utah, Oregon and California. This general area has been afflicted by enhanced adiabatic warming and resultant aridification since the end of the Pleistocene, but the rate of change has

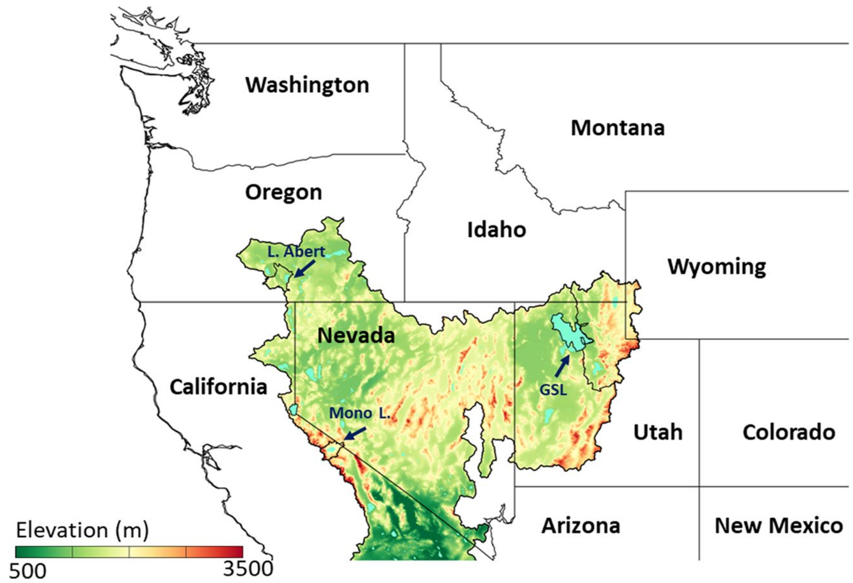

Figure 1. The boundaries of the Great Basin (GB) and the basins of Lake Abert, Oregon, Great Salt Lake (GSL), Utah and Mono Lake, California, in the western United States are outlined in black on this map of part of the western US. Arrows point to the study lakes. Only the effective area of the GSL basin, where all the streamflow enters the lake, is outlined. The digital-elevation model in the GB was obtained from the USGS GTOPO30 digital-elevation model (USGS GTOPO30 DEM, 2019). Boundaries of the basins of Lake Abert, GSL and Mono Lake were obtained from shape files from the USGS National Map (2019).

increased in at least the last few decades (Ficklin & Novick, 2017). Evaporation of lake water in the GB increased between 1985 and 2018 by ~1.5%/decade because of increasing air temperature and atmospheric vapor pressure deficit (Zhao et al., 2022). The focus herein is on the time period from Water Year (WY) 2001–2021 which is also mostly coincident with the timing of the current drought that began around 1999. The most severe drought area is largely centered over the US Southwest, including much of the GB (Dannenberg et al., 2022; Williams et al., 2022).

2.1. Lake Abert, Oregon

Lake Abert (42.66°N, 120.23°W) is in the northwestern part of the GB in south-central Oregon (Figure 1). The lake gets most of its water from the Chewaucan River, which drains snow-covered mountain ranges to the west of the lake, as well as small tributaries in the lower part of the Chewaucan watershed (Larson & Eilers, 2014; Larson & Larson, 2011; Moore, 2016). However, upstream diversions are common. For example, it was documented by Phillips and Van Denburgh (1971) that only about half of the flow of the Chewaucan River at Paisley, Oregon, reached Lake Abert during the 50 years between 1913 and 1963.

The highest "recent" surface-water elevation of Lake Abert was 1,298.6 m in 1958 (Larson & Eilers, 2014; Phillips & Van Denburgh, 1971). At the opposite extreme, Lake Abert was dry or nearly dry during the Dust Bowl era in the 1920s and 1930s, reaching a low of ~1,294.0 m in 1937 and again in June of 2014 (Larson & Eilers, 2014; Phillips & Van Denburgh, 1971), and the surface-water elevation has continued to decline.

There is an inverse relationship between surface-water elevation and salinity in terminal lakes (Figure 2). During the 21-year study period, salinity increased to a high of 250 g/kg in 2014 and 2015 in Lake Abert, but then decreased as the volume increased in 2017, then increased again until it reached a new high of ~280 g/kg in 2021 as the volume decreased (Figure 2). In 2014 when the salinity was very high, the water turned bright red because of the presence of ultrasaline-tolerant bacteria-like archaea microbes, such as *Halobacterium*, which contain a red photosynthetic pigment (Larson et al., 2016).

2.2. Great Salt Lake, Utah

Great Salt Lake (GSL) (41.12°N, 112.48°W), in the eastern part of the GB (Figure 1), is the largest saline lake in North America though in the summer of 2019 the extent of the lake was only 2685 km^2 according to

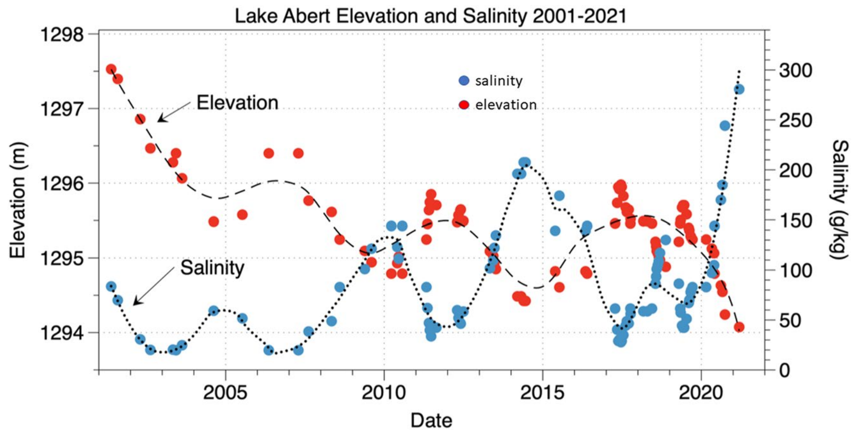

Figure 2. Lake Abert, Oregon surface-water elevations and estimated salinity in g/kg, WY 2001–2021. Elevation data were obtained by volunteers reading a staff gage installed along the eastern shore of the lake. Salinity was measured from water samples using an optical refractometer. Because there were gaps in the salinity measurements, a second-order polynomial equation of salinity versus elevation ($R^2 = 0.85$), was used to estimate salinity for every date on which there was an elevation measurement ($n = 47$). Some years show multiple elevations and salinities that were acquired in different seasons. Data used to create these plots are available in Table S3 in Supporting Information S1.

measurements using 30-m resolution Landsat data by Hall et al. (2021), and the lake has continued to shrink. Since the middle of the 19th Century, the volume and area of GSL have decreased by ∼50% and the lake-water elevation has dropped by ∼3.6 m with a concomitant increase in salinity (White et al., 2014a, 2014b, 2015; Wurtsbaugh et al., 2017) (Figure 3). While upstream water diversions are the primary reason for the lowered lake levels since the mid-1800s, the continued desiccation of the GSL is exacerbated by increasing air and surface temperatures, and intensifying climate aridity, along with a trend toward earlier snowmelt and greater evaporation in the Wasatch and Uinta Mountains (Cook et al., 2004; Hall et al., 2021; Wurtsbaugh, 2017).

The waters of the Bear, Jordan and Weber rivers, the primary tributaries to GSL, originate in the snow-dominated Wasatch and Uinta mountains to the east and northeast of the lake. Every year, an estimated 3.3 trillion liters of water are diverted from the streams feeding the GSL (Derouin, 2017) to support agricultural, industrial and municipal water uses in the basin. Upstream diversions, warmer temperatures, reduced snow cover and greater evaporation in the GSL basin to the east of the lake (32,251 km^2), from which nearly all the inflow occurs (the effective area of the GSL basin), are contributing to the ongoing trend toward lower water levels (Hall et al., 2021).

As the volume of the lake decreases and more lakebed is exposed, there are serious environmental and potential human health consequences as discussed further in the Discussion section. GSL is an important stopover for millions of migratory water birds (Audubon, 2022), however, the sustainability of the birds' primary food sources, brine shrimp and brine flies, is jeopardized when the salinity increases to levels that are toxic to the invertebrates.

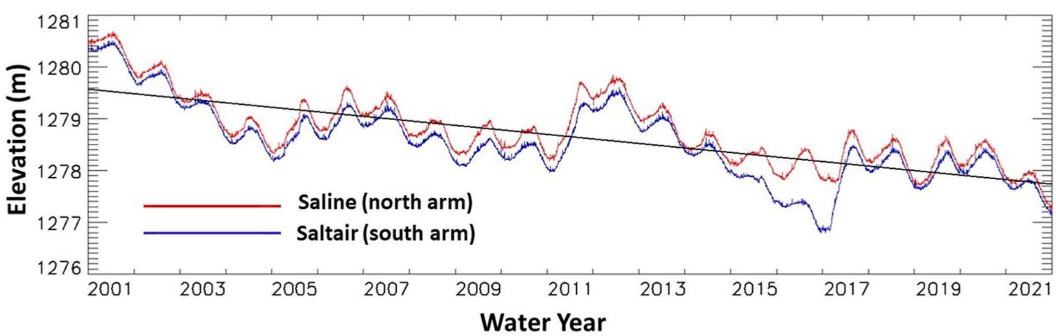

Figure 3. Daily mean surface-water elevations of the north and south arms of Great Salt Lake as measured at Great Salt Lake near Saline, UT (USGS Site Number 10010100) and Great Salt Lake at Saltair Boat Harbor, UT (USGS Site Number 10010000), respectively (USGS, 2022b). The black line represents the trend, in m/yr, derived from an average of the elevations from the north and south arms of the lake (USGS, 2022b). Extended from Hall et al. (2021).

2.3. Mono Lake, California

Mono Lake (37′58′N, 119′08′W) is located on the western edge of the GB, on the eastern side of the Sierra Nevada Mountains in California (Figure 1). The highly alkaline lake (Nielsen & DePaolo, 2013) provides habitat and food for numerous water birds, most of which are migratory. Many of these birds feed on the unique *Artemia monica* brine shrimp that are endemic to Mono Lake (Conte et al., 1988; Mason, 1966). While most terminal lakes in the GB are located at lower elevations and are shallow, Mono Lake, one of the highest large terminal lakes in North America at 1,944.5 m as of July 2022 (MLC, 2022a, 2022b), is relatively deep (up to ∼48 m) (Melack, 1983; Vorster, 1985), but still declining; it was 51 m deep in the 1960s (Mason, 1966).

Most of the inflow to Mono Lake originates from runoff from three major perennial streams: Rush Creek, Lee Vining Creek and Mill Creek, contributing ∼53%, ∼33%, and ∼14% of the total runoff, respectively (Ficklin et al., 2013; Romero & Melack, 1996; Vorster, 1985). The lake itself does not receive much rainfall or snowfall directly because of its position in the rain shadow of the Sierra Nevada Mountains (NRC, 1987).

Beginning in late 1940, some tributaries to Mono Lake were diverted by the Los Angeles Department of Water and Power to augment the water supply of the City of Los Angeles, ∼500 km to the south. As a result, by January of 1982, the lake surface elevation dropped ∼14 m, to 1,942 m, the lake volume had decreased by 45% (MBC, 2022; Ficklin et al., 2013; Herbst, 2014), and the salinity doubled (MLC, 2022a, 2022b). The lower water levels in Mono Lake have had indirect negative effects, such as reduction of habitat and decline of food sources for migratory birds.

Because the viability of Mono Lake is impacted by upstream diversions, legislation was enacted in 1994 to reduce the impact by allowing the lake level to rise to 1,948 m. However, that elevation has not yet been achieved, partly due to the ongoing drought (Herbst, 2014).

3. Data and Methodology

In this work we use MODIS satellite data products and meteorological station data to assess the changes and trends in snow cover, snow-water equivalent (SWE), evapotranspiration (ET), and daytime and nighttime LST and air temperature over the 21-year study period (WY 2001–2021) for the western US with a focus on the GB as a whole and separately for the basins of Lake Abert, GSL and Mono Lake. Surface-water elevations of the lakes were derived from various sources and the surface areas of Lake Abert, GSL and Mono Lake were measured using remotely-sensed imagery and data products (described below). These geophysical parameter variables are considered essential climate variables that are key to tracking and understanding temperature, precipitation and hydrological change through time.

3.1. MODIS Satellite Data Products

The NASA standard data products used in this work: snow cover, LST and evapotranspiration (ET), are derived from the MODIS sensor on the Terra satellite. These complementary data products are well characterized and validated and cover key elements of the near-surface climate, water and energy budgets. The spatial resolutions of the products are well suited for investigations of the heterogeneous landscape. Data are available beginning 24 February 2000, and continue to the present, except during short-term outage periods caused by spacecraft maneuvers, temporary software or instrument issues or upgrades (LDOPE, 2022). The snow cover, LST and ET products have been validated at Stage 2. Stage 2 validation means that "Product accuracy is estimated over a significant (typically >30) set of locations and time periods by comparison with reference in situ or other suitable reference data." See CEOS-LPV (2022) for a detailed description of validation stages.

First we developed maps of mean annual snow cover, ET and LST for the GB for the study period (WY 2001–2021). To develop a mean snow-cover map from MOD10A1F, only "persistent" snow cover was mapped. Persistent snow cover in a pixel is defined herein as having at least seven consecutive days of snow cover in each of the 21 years, thus eliminating snow that might be present for less than 1 week in some or all years. In this work non-persistent snow cover is termed "ephemeral." Mean annual ET was calculated from all available 8-day MOD16A2GF products during the study period. LSTs from MOD21A1D and MOD21A1N for each non-cloudy pixel in each day of the study period were averaged to get a daily mean LST in each non-cloudy pixel. Daily data were then averaged for the study period to create the mean LST map.

3.1.1. Snow Cover

The MODIS Terra cloud-gap filled normalized-difference snow index 500-m resolution snow-cover map product, MOD10A1F (Hall & Riggs, 2020), from MODIS Collection 6.1 (C6.1) was used to provide a daily "clear-sky" snow map of the Lake Abert, GSL and Mono Lake basins and to calculate the number of days (#days) of snow cover for each pixel for every available day during the study period within GB as a whole and also for each of the three lake basins individually. Uncertainties in the snow-cover decisions in the cloud-gap filled maps that relate to the gap-filling methodology depend in part on the age of the observation, that is, the number of days since the last cloud-free observation of each pixel, and are discussed in detail elsewhere (Hall et al., 2010, 2019; Riggs et al., 2018). MOD10A1F was developed and produced at Goddard Space Flight Center and is distributed by the NASA Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, and may be downloaded from NSIDC.

3.1.2. Evapotranspiration

The 500-m resolution C6.1 NASA standard evapotranspiration (ET) Gap-Filled 8-Day Level 4 Global 500m product, MOD16A2GF (Running et al., 2021), was used to develop per-pixel ET maps in the GB for the study period. ET is the sum of water vapor fluxes from soil evaporation, wet canopy evaporation and plant transpiration from the dry canopy surface; the MOD16 algorithm uses daily meteorology reanalysis from the NASA Global Modeling and Assimilation Office Goddard Earth Observing System Forward Processor along with 8-day remotely sensed vegetation property dynamics from MODIS as key inputs (Mu et al., 2011). The MOD16 algorithm uses the Penman-Monteith model which is well suited for semi-arid dryland regions owing to explicit representation of vegetation canopy stomatal and surface restrictions to evaporation (Zhang et al., 2016).

First we used the 8-day total ET values to calculate a total annual ET value in mm for each of the 21 years of record; these data were then used to calculate the average annual ET for the study period. We also used the total per-pixel ET value in each WY to calculate the per-pixel change in ET (in mm). The MOD16 algorithm and ET product has been extensively validated over a global domain spanning multiple data years and diverse climate and vegetation conditions; the ET product accuracy and performance is comparable to daily ET measurements obtained from in situ tower eddy covariance measurements (Bajgain et al., 2020; Brust et al., 2021; Mu et al., 2011). MOD16A2GF data products may be downloaded from the NASA EOSDIS Land Processes DAAC at the EROS Data Center in Sioux Falls, South Dakota.

3.1.3. Land Surface Temperature (LST)

MODIS LST C6.1 data products, MOD21A1D (daytime) and MOD21A1N (nighttime) (Hulley & Hook, 2021a, 2021b; Hulley et al., 2017), are used to map daytime and nighttime LST trends in each pixel in the GB at 1-km resolution. The mean daily LST in the GB was derived by averaging the daily daytime (MOD21A1D, 10:30 a.m.) and nighttime (MOD21A1N, 10:30 p.m.) LST on a per-pixel basis. To fill in the gaps caused by clouds, we used a third order cubic polynomial of the LST data to develop basin trend plots.

We also used C6.1 MOD21C3 5-km resolution monthly LST products to look at day/night differences in LST trends in the GB for the study period. The monthly gridded product is computed by averaging the best quality data in the MOD21A1D (daytime) and MOD21A1N (nighttime) gridded data.

Additionally, we used the C6.1 LST products to measure the surface temperature trends of GSL and Mono Lake. For GSL, we developed a water mask consisting of pixels representing a minimum extent of the lake for the study period, to ensure that we would capture only water pixels even in drier years. For Mono Lake we used the USGS dynamic surface-water extent (DSWE) mask (USGS, 2022a) to determine the "high confidence water" for each year during the study period (see next section for a further description of the DSWE). We then measured LST only for the water pixels in each year. We did not measure the LST trend of Lake Abert because the lake was nearly desiccated in 2014, 2015, and 2021. There was not adequate water in the lake in those years to measure LST with confidence. All MODIS LST data products may be downloaded from the NASA Earth Observing System Data Information System Land Processes DAAC at the EROS Data Center in Sioux Falls, South Dakota.

3.2. Temporal Changes in Areal Extent of the Study Lakes

Landsat Collection-2 (C2) atmospherically-corrected Surface Reflectance data products were used to measure the length and width of Mono Lake on 30 July 2001 using Landsat-7, and on 24 July 2022 using Landsat-9. We then compared those results with results from Mason (1966) who measured Mono Lake in the early-to-mid 1960s (the exact date of the measurements is not known). We also used Landsat-8 Operational Land Imager (OLI) 30-m resolution imagery to measure the areal extent of GSL in 2020 and 2021. Interpretation was based on human visual analysis using spatial geographic software when there was no computer-assisted binary (land/water) classification to delineate lake extents. The details of the Landsat scenes that were used in this work are provided in Table S1 in Supporting Information S1.

The Landsat C2 Level-2 DSWE product (USGS, 2022a) was used to determine the surface water area of Lake Abert and Mono Lake and then to plot areal extent. The Landsat DSWE provides high temporal, moderate spatial resolution long-term data on terrestrial surface inundation using the Landsat at-surface reflectance product and a digital elevation model as inputs (Jones, 2019). A DSWE map for each lake was selected from late summer or early fall scenes in each year and used to calculate the extent.

3.3. Meteorological Station Data

We calculated a mean-daily air temperature of the GB for WY 2001–2021. There are 292 NOAA meteorological stations located within the boundaries of the GB; all daily minimum, T_{min}, and maximum, T_{max}, air temperatures were downloaded, however we did not use data from all 292 stations. Data from a station was accepted only if it had >272 days in which *both* T_{min} and T_{max} were available for at least 20 years of the 21-year study period. After filtering according to the restriction above, 164 stations were selected for use (Figure 5). Furthermore, for a day to be used in our calculation of mean-daily air temperature, 80% or more of the 164 stations had to report T_{min} and T_{max} on that day. Because the stations are not evenly distributed within the GB, the resulting "mean-daily air temperature" calculation is only an approximation of the actual mean air temperature on any given day, and the mean-daily air temperature of the study period in the GB. The air temperature data used in this study were obtained from NOAA National Centers for Environmental Information (NCEI, 2022).

3.4. Snow-Water Equivalent (SWE) From SNODAS and SNOTEL

Snow-water equivalent (SWE) data were obtained from NOAA's National Weather Service National Operational Hydrologic Remote Sensing Center (NOHRSC) SNOw Data Assimilation System (SNODAS), which has provided an estimate of daily SWE for the western United States and elsewhere since 2003. SNODAS procedures assimilate satellite-derived, airborne, and ground-based observations of snow-covered area and SWE, then provide estimates of SWE and other parameters in support of hydrologic modeling and analysis (Carroll et al., 2001; NOHRSC, 2004; SNODAS, 2022). Daily SWE from SNODAS is generated on a 1-km spatial resolution grid and was analyzed for the GB for WY 2004–2021.

SWE data from the SNOTEL network were downloaded from the Natural Resources Conservation Service, National Water and Climate Center (NRCS, 2022). Two SNOTEL sites were selected within or as close as possible to the basins of Lake Abert and GSL, then averaged for each pair for each basin. Only one SNOTEL station was found close enough to Mono Basin to be useful. The stations are listed in Table S2 in Supporting Information S1.

3.5. Surface-Water Elevation

To determine the lake surface-water elevations, we used data from various sources. For Lake Abert, elevation data were obtained by reading a staff gage. For GSL, USGS Water Information System data were used (USGS, 2022b). For Mono Lake, data from the Mono Basin Clearinghouse (MBC, 2022) were used.

4. Results

There is quite a bit of complementary information in the MODIS maps of snow cover, ET and LST in the GB (Figure 6), and in their associated trends over the broader western US (Figures S1–S3 in Supporting Informa-

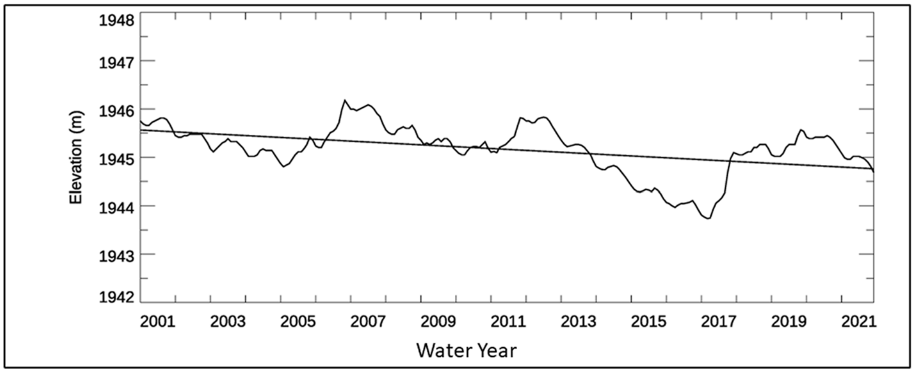

Figure 4. Plot of daily lake elevations of Mono Lake, WY 2001–2021. Source: Mono Basin Clearinghouse (MBC, 2022).

tion S1). Lower LSTs generally correspond with persistent snow cover and with higher ET rates, especially in mountainous areas on the periphery of the GB (Figure 6). In the GB as a whole and specifically in the Lake Abert, GSL and Mono Lake basins, there is a trend toward fewer days of snow cover and lower SWE, mixed (both increasing and decreasing) trends in land surface ET, and strongly increasing daytime and nighttime LST. In the following paragraphs we discuss trends in snow cover, ET and LST in the GB, and regional differences in their apparent response to drought conditions in different parts of the GB, as seen in the three lake basins for the study period.

Outside of the GB, in parts of Montana and Wyoming, there are areas indicating an *increasing* number of days (#days) of snow cover (Figure S1 in Supporting Information S1) especially in northern Montana, and roughly in the same location as the trends of *decreasing* LSTs seen in Figures S1 and S2 in Supporting Information S1. ET also tends to be reduced over much of the interior GB and California, where the extended drought has severely restricted water supplies available to support ET and vegetation growth (Dannenberg et al., 2022). Trends of decreasing ET from plants and soil in the GB and in California contrast with moderate increases in ET elsewhere as seen in Figure S3 in Supporting Information S1. In the Sierra Nevada Mountains in eastern California,

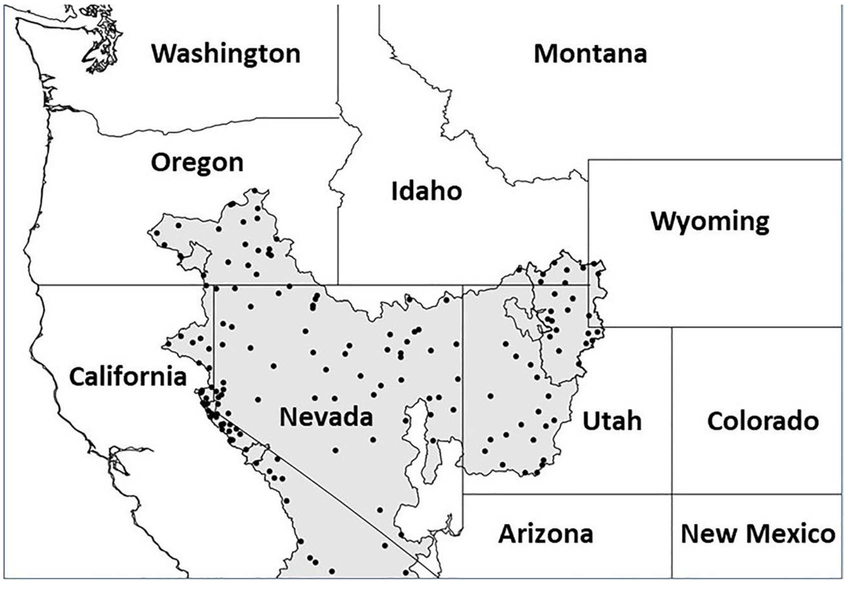

Figure 5. Black dots show locations of NOAA meteorological stations (total = 164) that were used to develop mean-daily average air temperatures in the Great Basin. Air temperature data were obtained from NOAA National Centers for Environmental Information (NCEI, 2022).

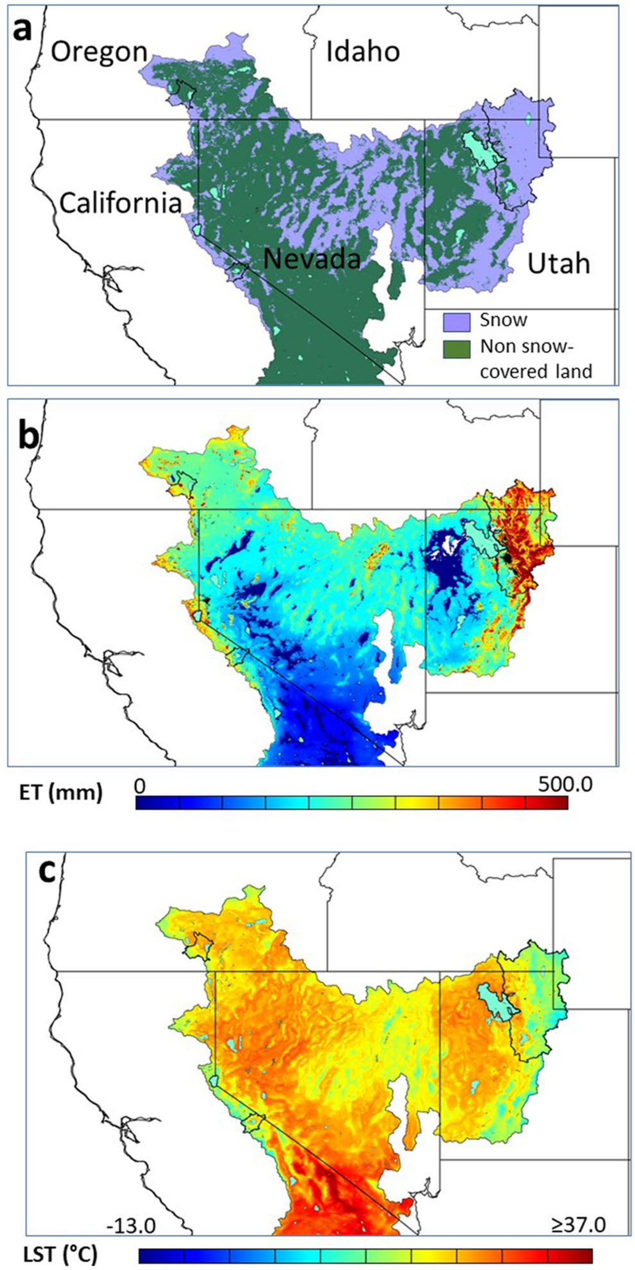

Figure 6. (a–c) MODIS-derived maps of the Great Basin (GB) in the western United States, WY 2001–2021; basins of Lake Abert, Oregon, Great Salt Lake, Utah and Mono Lake, California are outlined in black. Some of the larger lakes within the GB are shown in aquamarine. (a) Mean annual "persistent" snow cover from MOD10A1F; (b) mean annual evapotranspiration from MOD16A2GF; (c) mean annual land-surface temperature from MOD21A1D & MOD21A1N.

the number of days of snow cover are declining in much of the same area that shows the greatest decline in ET (Figures S2 and S3 in Supporting Information S1).

4.1. Trends in Snow Cover and Snow-Water Equivalent (SWE) for the GB

For the GB as a whole, there is an average of 12.4 fewer #days of snow cover (Figure 7a) over the 21-year period. The decline in snow cover is widespread, though most pixel trends are not statistically significant ($\alpha = 0.05$) (Figure 7b). In the areas of persistent snow cover as defined in Section 3.1 (see Figure 6a) there was an average

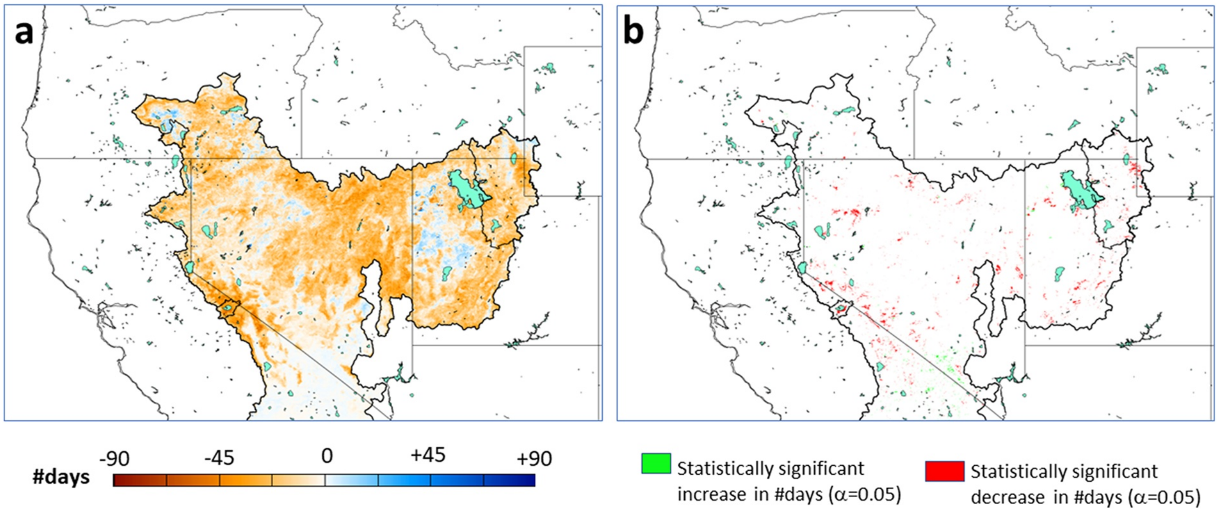

Figure 7. (a) Change (per pixel) in number of days of snow cover for the Great Basin (GB) derived from the MODIS standard snow-cover product, MOD10A1F. (b) Green or red pixels within the boundary of the GB show statistical significance at $\alpha = 0.05$. Within the GB, the boundaries of the basins of Lake Abert, GSL and Mono Lake are outlined in black. Some of the larger lakes in the western US are shown in aquamarine. A water mask shows large lakes and reservoirs both inside and outside the study domain.

of 18.4 fewer #days of snow over the study period. The lack of statistical significance is likely because inter-annual (climate) variability in snow cover is much larger than the long-term trend, which contributes to lower trend significance. However, the widespread trend pattern of fewer #days of snow cover is consistent with rising temperatures and declining lake levels. Areas where there was a lack of change and even weakly increasing in #days of snow cover in central to western Utah (white to light blue pixels in Figure 7a) are located at lower elevations (Figure 1), where snow cover is not persistent.

In all three lake basins there are declines in #days of persistent snow cover (Figures 8a–8f). This decline is particularly notable in Mono Basin with an average of 28.4 fewer days of snow cover (Table 1). Though most of the pixels in the basins do not show statistically significant trends in #days of snow cover, there are some clusters of pixels showing statistically-significant trends ($\alpha = 0.05$) in Mono Basin (Figure 8f), and in the GSL basin especially south and east of the GSL (Figure 8d).

The total mean change in SWE (2004–2021), determined from SNODAS data (SNODAS, 2022) in the GB was found to be −3.7 mm and is statistically insignificant. Larger changes in SWE were observed at the SNOTEL stations that are associated with the three lake basins (listed in Table S2 in Supporting Information S1).

Lake Abert and Mono Lake basins show 21-year declines in SWE at the SNOTEL stations, with slopes of −0.4 cm/yr (mean SWE from the Strawberry and Summer Rim SNOTEL sites) to −0.2 cm/year (SWE from the Virginia Lakes SNOTEL site), respectively. Though there is an increase in SWE (0.5 cm/yr) from an average of the Franklin and Tony Grove SNOTEL sites of the GSL basin, the historical record from 1979–2021 shows a general SWE decline in all three basins.

4.2. Changes in ET

Results derived from the MOD16A2GF standard ET data products show weak but insignificant trends of decreasing ET in much of the GB (Figures 9a and 9b) except in the eastern part where the ET increased over the study period. The mean change in ET in the GB over the 21-year record was +3.1 mm, but with much larger spatial variability ranging up to +100 mm in the eastern GB, contrasting with a decrease in ET in the southern and western regions. Most of the trends in ET are not statistically significant ($\alpha = 0.05$) with the exception of the positive trends in the higher elevation areas of the Wasatch Mountains in the eastern GB (Figure 9b). Widespread neutral or slightly-negative ET trends largely occur in lower elevation areas characterized by sparse dryland vegetation.

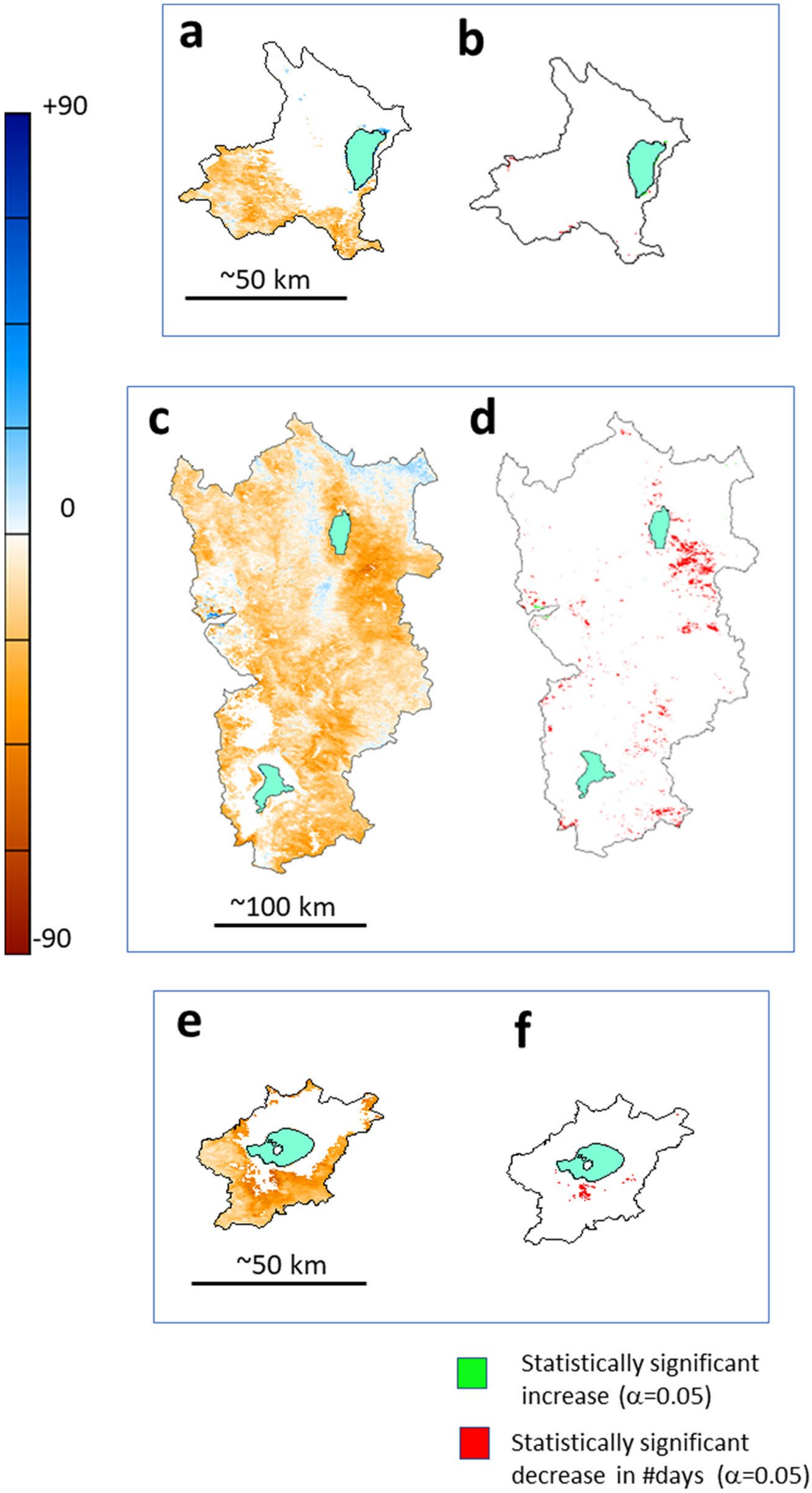

Figure 8. (a–f) Change (per pixel) in number of days (#days) of "persistent" snow cover (as defined in Section 3.1) in the basins of (a) Lake Abert, (c) Great Salt Lake and (e) Mono Lake, derived from the MODIS standard snow-cover product, MOD10A1F. Statistical significance ($\alpha = 0.05$) maps of trends in #days of snow cover for (b) Lake Abert, (d) Great Salt Lake, and (f) Mono Lake are also shown.

10.1029/2022EA002630

Table 1
Change[a] in #Days of Persistent Snow Cover, in Each of the Three Lake Basins, WY 2001–2021, Derived From MOD10A1F

	Lake Abert	Great Salt Lake	Mono Lake
#days	−14.6	−14.1	−28.4

[a]Derived from the end points of the trend lines.

There was a small and generally insignificant change in ET in the basins of Lake Abert and Mono Lake, but an overall increase in ET in the GSL basin (Figures 9a and 9b and Table 2). Lake Abert basin showed a mean ET decrease of −5.2 mm over the period, with some pixels in the basin showing statistical significance ($\alpha = 0.05$) for increasing and decreasing ET, particularly in the southern half of the basin (Figures 9a and 9b). For the GSL basin, there was a mean ET increase of +28.1 mm, with 29.4% of basin pixels showing a statistically significant positive trend ($\alpha = 0.05$), mainly in the northern half of the basin, and only 1.1% of pixels showing a statistically-significant negative ET trend. For Mono Basin, there was little change in ET over the study period, with a mean change of +3.3 mm. Most of the pixels showed weak positive or negative changes that are statistically insignificant ($\alpha = 0.05$).

4.3. Changes in LST and Air Temperature in the GB

In Figure 10a, strongly increasing LST is evident, with a rate of increase of 1.0°C/decade and a total mean increase of 2.1°C over the study period, WY 2001–2021. These trends are statistically significant ($\alpha = 0.01$) for 99% of the pixels in the GB (Figure 10b). Though the earlier part of the data record, 2001–2011, showed increasing LSTs (0.1°C/yr), the latter part of the record, 2011–2021, showed a sharply greater rate of increase in LST (0.4°C/yr).

We also looked at the daytime and nighttime LST separately using the 1-km daily product (not shown) and 5-km gridded monthly LST product, MOD21C3 (Figure 11), and found an overall greater rate of warming during the daytime (0.6 ± 0.25°C/decade) versus nighttime (0.3 ± 0.12°C/decade) in the GB over the study period. Earlier in the record, the rate of LST increase was greater during the nighttime (see dashed lines in Figure 11).

4.3.1. Changes in LST in the Basins of Lake Abert, Great Salt Lake and Mono Lake

We also calculated trends in LST and total change in LST using the MOD21A1D and MOD21A1N products for each lake basin: Lake Abert, GSL and Mono Lake. In all three basins there was an overall increase in LST, both in the basins and in the lakes, with the greatest total mean change found in Mono Basin (2.9°C) (Tables 3 and 4). In all three basins, the daytime LST increased more than did the nighttime LSTs (Table 3). All of the trends are statistically significant ($\alpha = 0.01$). There were no trends of decreasing LST.

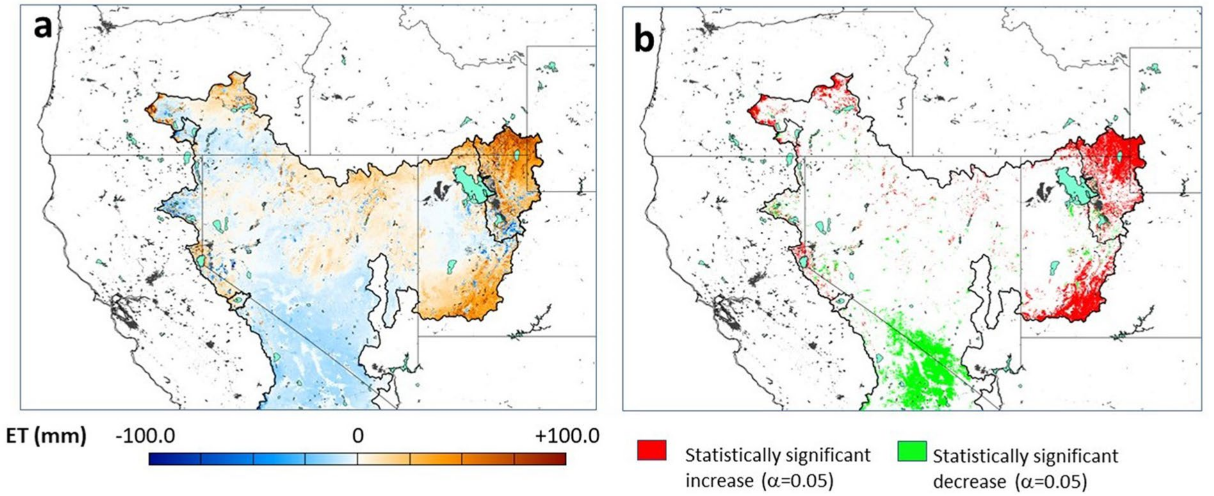

Figure 9. (a, b) Total change in evapotranspiration (ET) in mm, WY 2001–2021 for the Great Basin derived from the MODIS standard ET product, MOD16A2GF. The larger lakes are shown in aquamarine. There was no ET retrieval in the few pixels that are colored dark gray. A water mask shows large lakes and reservoirs both inside and outside the study domain.

10.1029/2022EA002630

Table 2
Mean Total Change[a] in ET in mm, WY 2001–2021, in the Basins of Lake Abert, Great Salt Lake and Mono Lake, Derived From MOD16A2GF

Lake Abert	Great Salt Lake	Mono Lake
−5.2	+28.1	+3.3

[a]Derived from the end points of the trend lines.

The lake surface-water temperatures also increased (Table 4). Though increases in LST were measured in Lake Abert, the lake dried up or nearly dried up in 2014, 2015, and 2021, thus the calculation of trends was not meaningful and the LST increase for Lake Abert is not shown.

4.3.2. Trends in Air Temperature

Air temperatures from 164 NOAA meteorological stations were also analyzed as described in the Methodology section. There is a total increase in mean air temperature for the GB of ∼1.0°C over the 21-year study period, with a slight decrease in temperature in the first half of the study period and a strong increase during the second half (Table 5). However, the stations are not evenly spaced throughout the GB, so these values are not a true mean-daily temperature of the GB (see station locations in Figure 5).

4.3.3. Lake Surface-Water Elevation and Extent Changes, WY 2001–2021

Lake Abert has experienced a strong trend toward declining elevation and increasing salinity (Figure 2). The lake elevation has dropped >3.0 m since 2001 when the elevation was 1,297.5 m; it was 1,293.6 m in 2021, and the lake was essentially dry by the summer of 2022, with 99% of the lakebed exposed. Changes in the areal extent of Lake Abert from 2000 to 2021 are shown in Figure 12a. Discharge from springs along the eastern side has kept the lake from completely desiccating in 2022 by maintaining a very shallow pool of water ∼1–2 km^2 in area according to field measurements by one of the authors (RL).

The GSL surface-water elevation dropped ∼1.84 m from 2001–2021 (USGS, 2022b). On 23 July 2021 the mean surface-water elevation dropped to its lowest recorded level: 1,277.5 m, and then continued to drop further (USGS, 2022b). Changes in the areal extent of GSL from 2000 to 2021 are shown in Figure 12b.

The lake elevation of Mono Lake dropped ∼0.80 m during the study period (Figure 4) (MLC, 2022a). The areal extent of the lake shrank as well, as compared to length and width measurements acquired in the 1960s (Mason, 1966) (Table 6). Changes in the areal extent of Mono Lake from 2000 to 2021 are shown in Figure 12c.

5. Discussion

5.1. Drought/Climate Aridity and Reduced Snow Cover

The GB is experiencing a more than two-decades-long drought that began in 1999–2000 (Williams et al., 2020). A number of recent studies have documented an intensifying climate aridity trend across the southwest US (e.g.,

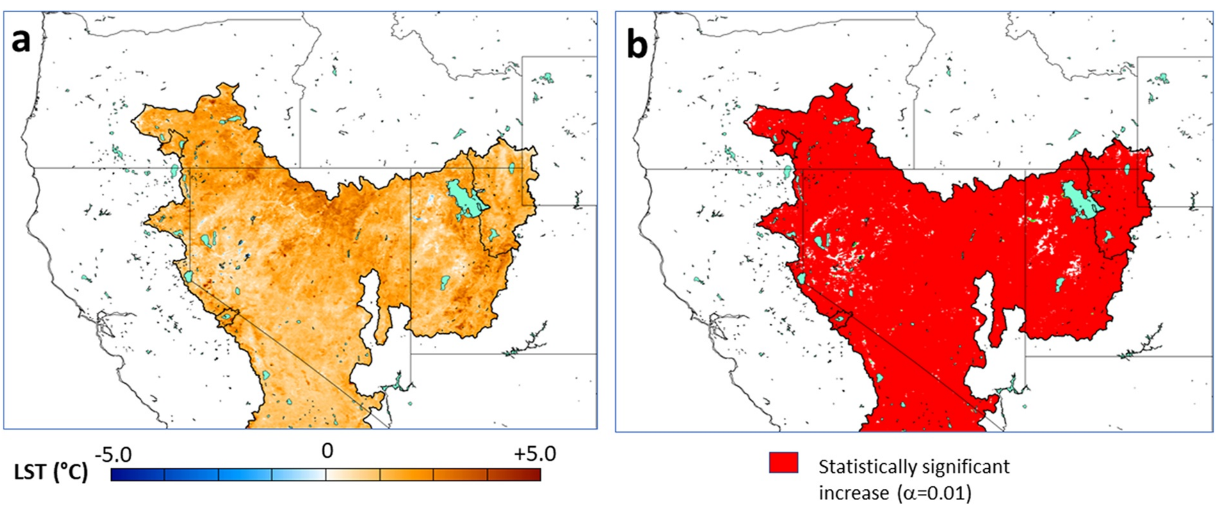

Figure 10. (a) Change in mean LST (average of daytime and nighttime LST) on a per-pixel basis. (b) Statistically-significant ($\alpha = 0.01$) trends in mean LST. There were no statistically-significant trends showing decreasing LSTs in the Great Basin. A water mask shows large lakes and reservoirs both inside and outside the study domain.

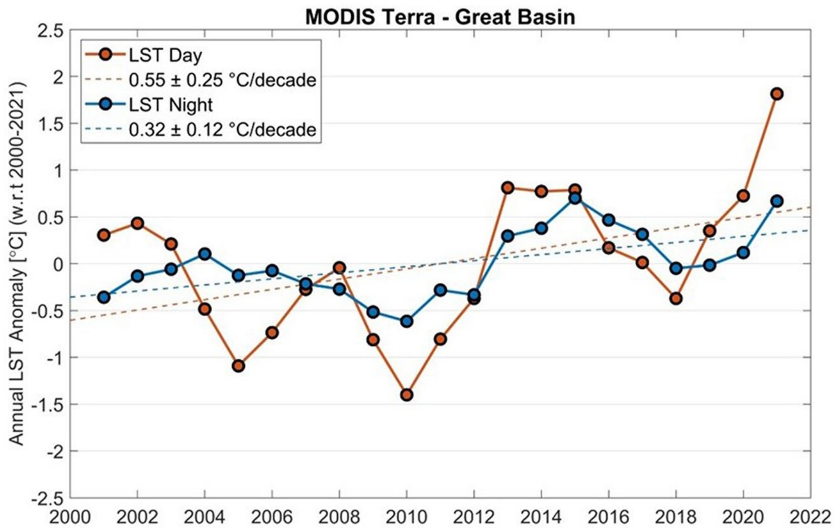

Figure 11. Annual average land-surface temperature (LST) anomaly (2000–2021) for daytime (red) and nighttime (blue) for the Great Basin, derived from the monthly climate modeling grid LST product, MOD21C3 (~5-km resolution).

Lian et al., 2021; Overpeck & Udall, 2020; Woodhouse et al., 2010). Since the aridity trend has been documented in prior studies, our paper focuses on other climate sensitive indicators available from the MODIS ESDRs and regional station networks, and documents regional environmental trends interpreted in the context of the increasing aridity trend.

The trends reported in our study are consistent with a warmer and generally drier climate, including increasing LST, reduced snow cover, shrinking lakes, and shifting ET patterns.

From WY 2001 through 2021, we found a mean LST increase of ~2.1°C ($\alpha = 0.01$) and a mean air temperature increase of ~1.0°C in the GB. The *rate* of increase of both air and surface temperature has increased since ~2011. If temperatures continue to increase as predicted, the outcome will be further reductions in regional snow cover, river flows and lake levels, contributing to further increases in atmospheric and soil aridity (Berghuijs et al., 2014; Milly & Dunne, 2020). Regional climate warming is also contributing to drier soil, forest mortality and wildfires (Overpeck & Udall, 2020; Udall & Overpeck, 2017). Part of the reduction in river flows is due to less snow versus rain and thus a reduction in snowmelt reaching streams (see Gordon et al., 2022; Stigter et al., 2018) and perhaps greater evaporative losses from ground previously covered by snow (Milly & Dunne, 2020).

Greater climate aridity may also be enhancing snowpack sublimation and associated SWE losses to a warmer/drier atmosphere, although total sublimation losses may be offset by reductions in snow-covered area and duration of snow cover (Sexstone et al., 2018). In a dry area such as the GB, sublimation is an especially important factor in the disappearance of snow as atmospheric aridity increases.

Persistent snow cover in the GB has declined by an average of ~18.4 days over the study period. Approximately 96.1% of the area of persistent snow cover (Figure 6a) experienced a reduction in #days of snow cover. However, in the GB and in a larger area of the western US, change in #days of snow cover is generally not statistically significant ($\alpha = 0.05$) (Figure S2 in Supporting Information S1). An exception is in north-central California and in the Sierra Nevada Mountains where there are clusters of statistically-significant ($\alpha = 0.05$) pixels showing declines in #days of snow cover (Figures S2a and S2b in Supporting Information S1).

Table 3
LST Increases in °C in the Three Lake Basins, and, in Parentheses, Rate of Increase per Decade, WY 2001–2021

	Lake Abert	Great Salt Lake	Mono Lake
Daytime °C (°C/dec)	3.4 (1.6)	3.1 (1.5)	3.9 (1.9)
Nighttime °C (°C/dec)	1.8 (0.8)	1.7 (0.8)	2.0 (0.9)
Mean °C (°C/dec)	2.6 (1.2)	2.4 (1.2)	2.9 (1.4)

5.2. Mixed Trends in Evapotranspiration (ET)

We found a positive trend in ET (3.1 mm total increase) overall for the GB (Figures 9a and 9b). In the most sparsely vegetated areas of the GB, such as in most of the lower elevation areas of central and southern Nevada, ET has a larger proportional contribution from soil evaporation (Brust et al., 2021).

Table 4
LST Increases in °C Showing Surface-Water Temperature Increases in GSL and Mono Lake, and, in Parentheses, Rate of Increase per Decade, WY 2001–2021

	Great Salt Lake	Mono Lake
Daytime (°C/dec)	1.4 (0.7)	1.8 (0.8)
Nighttime (°C/dec)	0.8 (0.4)	1.2 (0.6)
Mean (°C/dec)	1.1 (0.5)	1.5 (0.7)

Note. Rates of increase per decade are shown in parentheses.

However, the prolonged drought has extended the period of exceptionally dry soil conditions, reducing evaporation accordingly. This has contributed to overall reduction in ET in the drought-affected areas. This is a reinforcing feedback: lower ET results in a drier atmosphere (larger vapor pressure deficit and higher LST), with further ET reductions (Lian et al., 2021). The large areas of neutral and even decreasing trends in ET are consistent with the expected ET reduction from the extended drought in the GB. The lack of ET increase over much of the GB may contribute to higher LST since more net radiant energy is partitioned as sensible rather than latent heat, which would reinforce warming. Declining ET in parts of the GB and in California contrast with ET increases seen elsewhere in the western US where there are large areas of statistically-significant ($\alpha = 0.05$) increases in ET (Figure S3 in Supporting Information S1).

Positive, statistically significant ($\alpha = 0.05$) ET trends are seen along the mountainous edges of the eastern GB in the higher elevations of the Wasatch Mountains and the Colorado Plateau (Figures 1a and 9b). These areas have a cooler/wetter climate and greater vegetation cover compared to lower elevation areas in the GB. The generally greater moisture availability and increasingly earlier snowmelt may contribute to higher ET rates, especially in spring and early summer. Positive ET trends, particularly in the northern parts of the basin, also coincide with a small increase in irrigated cropland (Ketchum et al., 2020) which can elevate ET by enhancing cropland vegetation growth and reducing surface evaporative resistance relative to the surrounding natural semi-arid vegetation.

Over the study period, ET in the GSL Basin increased an average of ~28.1 mm. There may also be a secondary precipitation/temperature/snow/elevation effect on the ET trend in the GSL basin, where the higher elevation areas can maintain positive ET trends as the climate warms due to the more moderate temperatures and generally higher annual precipitation amounts, along with additional spring moisture inputs from seasonal snowmelt that can sustain ET.

5.3. Response of Lakes to Increasing Temperatures and Reduced Snow Cover

Warmer temperatures and associated greater atmospheric moisture demand are likely driving increasing rates of evaporation of water in lakes, since evaporation over a lake surface is largely unrestricted in summer (see interactive database of 1.42 million lakes worldwide (Zhao et al., 2022)). Positive trends in lake evaporation due to higher water surface temperatures are likely contributing to desiccation. We measured increasing surface water temperature in GSL and Mono Lake (Table 4). Schneider et al. (2009) reported that Mono Lake experienced a summer nighttime surface-water temperature warming of 0.2 ± 0.02°C/yr, 1992–2009, for a total increase of 2.6°C, over the 17-year study period. This may be compared with the LST warming that we measured on Mono Lake (1.5°C), though for a different time period, but overlapping with the Schneider et al. (2009) study period.

Additionally, as a snowpack declines in mountainous areas, higher air temperatures will warm the lake-surface water faster when less snowmelt flows into the lakes (Smits et al., 2020). The decline in seasonal snow cover is also likely contributing to LST warming at the higher elevations in the GB.

Table 5
Change in the Great Basin "Mean" Air Temperatures (°C) in the First Half of the Study Period, 2001–2011, in the Second Half of the Study Period, 2011–2021, and for the Entire Study Period, 2001–2021 (The Year 2011 Is Used in Both the First and Second Halves of the Study Period)

Time period	Rate of change (°C/yr)	Total change (°C)
2001–2011	0	−0.2
2011–2021	0.1	0.9
2001–2021	0.1	1.0

5.4. Deleterious Effects on Wildlife and Humans

Lake desiccation can be life threatening to humans and wildlife. Expansion of dry lakebeds allows toxic dust and particulate matter to be picked up by wind and become airborne, creating air pollution that includes heavy metals. Owens Lake, on the eastern side of the Sierra Nevada Mountains in California, became desiccated after the City of Los Angeles diverted inflow from the Owens River, which leads to the lake, to augment the city's water supply. Before that diversion project began in 1913, the lake covered an area of ~280 km^2 (Reheis, 2022); now it is mostly dry. "Saline dust" from the dried lake basin is a major source of PM10 dust pollution and has adversely affected vegetation and soils surrounding the lake (Zucca et al., 2021). The City of Los Angeles will spend billions of dollars over 25 years to minimize airborne "dust" from the Owens Lake basin (Wurtsbaugh et al., 2017).

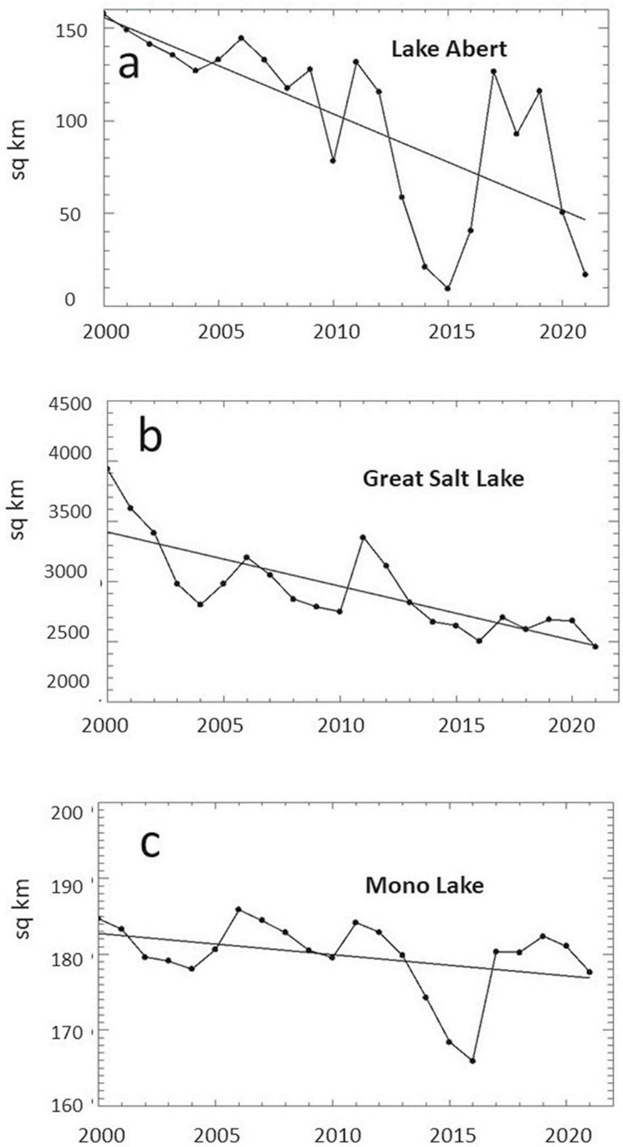

Figure 12. (a–c) Changes in the areal extents of (a) Lake Abert, (b) Great Salt Lake and (c) Mono Lake from 2000 through 2021. Lake Abert and Mono Lake extent measurements were derived from the USGS Dynamic Surface Water Extent product as described in the Methodology section (USGS, 2022a). The GSL measurements were made using Landsat-7 Enhanced Thematic Mapper Plus and Landsat-8 OLI imagery and extended from Figure 10a in Hall et al. (2021).

Table 6
Length and Width Measurements of Mono Lake as Measured by Mason (1966) and Using Landsat-7 (2001) and Landsat-9 (2022) Data Products as Described in Section 3.2

Date of measurement	Length	Width
Early-to-mid 1960s[a]	21.76 km	15.34 km
30 July 2001	20.97 km	13.59 km
24 July 2022	20.52 km	13.23 km

[a]An exact date of the measurements was not provided by Mason (1966).

Residents living near Mono Lake in California and GSL in Utah are also at risk for hazardous air quality due to the expanding lakebeds (MLC, 2022a; Reynolds et al., 2014; Stine, 1991). The population exceeds 2 million people in Salt Lake City and other rapidly-growing cities along the Wasatch Front, which are affected by the expansion of the shoreline of GSL (Putman et al., 2022). Furthermore, when the dust is deposited in the nearby snow-covered Wasatch and Uinta mountains to the east of GSL, it reduces the albedo of the snow surface allowing greater absorption of solar radiation that accelerates snowmelt (Skiles et al., 2018).

If the drought continues and perhaps even intensifies, water demand for irrigation and for urban areas will increase, thus there will be even less water available to flow into the lakes. In response to the increased aridity, water supplies may be increased by allowing more groundwater use and funding the construction of reservoirs, both of which would negatively affect downstream natural lakes. The need for water to flow into the GB lakes should, however, be considered in order to avert environmental and economic catastrophes, such as occurred with the desiccation of Owens Lake.

5.5. Changes in Lake Area and Depth

While the changes in areal extent of Lake Abert and GSL are dramatic (see Section 4.3.3), changes in the extent of Mono Lake are not as great because of its greater depth, together with legal actions enacted to slow its decline. Mono Lake is much deeper than the other two lakes and its shape does not lend itself to large changes in areal extent with small decreases in volume. However, at the end of the 2021 WY, the surface-water elevation of Mono Lake was 3.3 m lower than the surface-water elevation target of ∼1,948 m which would cover much of the exposed dry lakebed and allow a healthy ecosystem to thrive and protect wildlife habitat (MLC, 2022a).

There was a small spring-fed pool present in 2021 and 2022 in the lakebed of Lake Abert that provided some habitat for 5–10 thousand migratory waterbirds. But this was just a fraction of the hundreds of thousands of birds that use the lake (Larson et al., 2016) when water levels are higher.

6. Conclusion

Analysis of more than two decades of data from satellite-derived ESDRs developed from validated NASA standard data products (snow cover, LST and ET) from the Terra MODIS sensor, along with ancillary data, has enabled an in-depth evaluation of some of the environmental effects of the mega-drought on terminal lakes in the GB. Higher air and surface temperatures and a reduction in the #days of snow cover and lower SWE promote desiccation of terminal lakes, endangering human health, wildlife habitat, and risking dire economic consequences.

The basins of Lake Abert, Oregon, GSL, Utah and Mono Lake, California, located in different areas and different topographical and climate zones within the GB, are responding differently to intensifying warming and aridification. Though all show 21-year trends toward increasing temperatures and decreasing #days of snow cover, the ET results are mixed. The MODIS ESDRs used in this study only cover a 21-year period, although continuing satellite operations are approaching the 30-year threshold for defining Climate Normals, and will enable greater precision in documenting climate trends when more years of data become available.

Over the WY 2001–2021 study period, the GB experienced a ∼1.0°C increase in air temperature and a 2.1°C increase in LST, with a greater rate of increase in the latter half of the study period for both LST and air temperature. Mono Basin shows a slightly greater LST increase (2.9°C) than the Lake Abert (2.6°C) and GSL (2.4°C) basins. There appears to be a breakpoint around 2011 when the rate of warming in both LST and air temperature increases, for reasons that are unclear. A loss of #days of persistent snow cover is seen in the GB (18.4 days average) and in the individual lake basins. Mono Basin shows the greatest loss, for a total of ∼28.4 days, with the basins of Lake Abert and GSL showing more modest losses for a total of 14.6 and 14.1 fewer #days of persistent snow cover, respectively. In general, the GSL and Mono basins show positive ET trends, while Lake Abert shows slightly negative ET trends associated with increasingly sparse vegetation and warm, dry conditions. The overall change in ET for the GB is positive (3.1 mm), but relatively small due to heterogeneity in the sign and magnitude of the regional trends.

Lake Abert, the shallowest of the three study lakes, was almost fully desiccated in 2021 while GSL reached its lowest surface-water elevation ever recorded in 2021 and has declined further since then. Legislation prompted a slowing in the rate of decline of Mono Lake, but despite this it has continued to decline, and is ∼3.3 m lower than its mandated elevation.

If the climate in the US West continues to get warmer and drier, as predicted, the societal demand for water will also continue to increase. The example of Owens Lake, California, shows that the diversion of stream water from saline lakes comes at a huge cost to human health especially when a terminal lake is near a population center. Costly mitigation efforts are necessitated, though only after widespread adverse health impacts have been identified. Controlling upstream water diversions may help to alleviate severe and costly ecological and human health consequences associated with continued desiccation of terminal lakes in the GB and elsewhere.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All of the data used to undertake this research are freely available. The specific sources for the data are provided in the text and summarized below.
MODIS snow-cover [Dataset]: https://modis-snow-ice.gsfc.nasa.gov/?c=MOD10A1F
MODIS LST [Dataset]: https://lpdaac.usgs.gov/products/mod21a1dv061/ and https://lpdaac.usgs.gov/products/mod21a1nv061/
MODIS ET [Dataset]: https://lpdaac.usgs.gov/products/mod16a2v006/
Air temperature: NOAA NCEI [Dataset]: https://www.ncei.noaa.gov/maps/daily-summaries/
SNODAS [Dataset]:NOAA NOHRSC: https://nsidc.org/data/g02158/versions/1
SNOTEL [Dataset]: USDA NRCS: https://wcc.sc.egov.usda.gov/nwcc/rgrpt?report=precsnotelmon&state=CA, https://wcc.sc.egov.usda.gov/nwcc/rgrpt?report=precsnotelmon&state=OR&operation=View, https://wcc.sc.egov.usda.gov/nwcc/rgrpt?report=precsnotelmon&state=UT

Acknowledgments
The authors thank Dr. K. Arthur Endsley, Numerical Terradynamic Simulation Group, University of Montana, for his review of the MOD16A2GF evapotranspiration product results. This work was supported by NASA's Terrestrial Hydrology Program and Earth Observing Systems programs: 80NSSC22K0554, 80NSSC21K1927 and WBS number: 444491.02.01.04.52.

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