Relief from summer warming: Devils Postpile National Monument's cold air pool supports a refugium-based conservation strategy

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Abstract

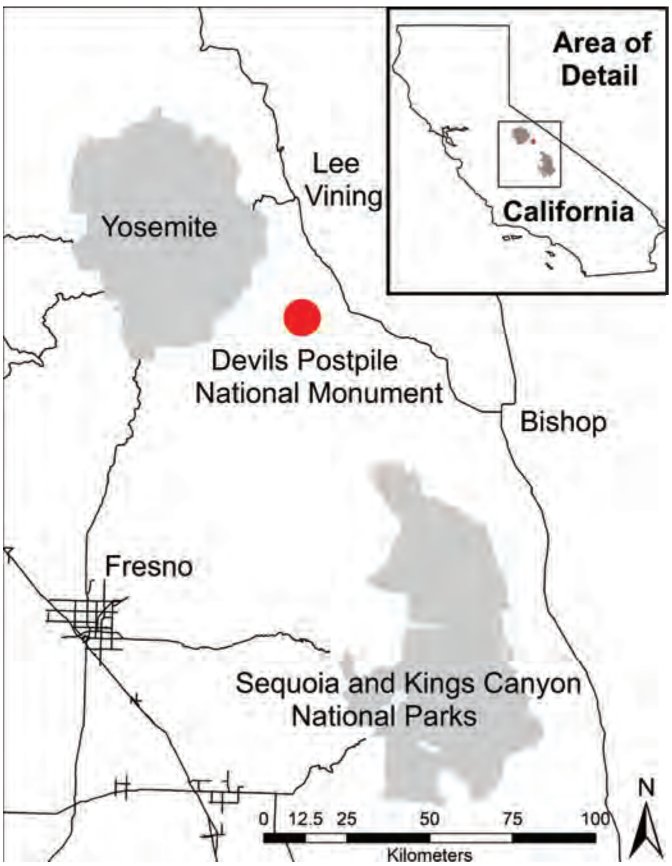
Cold air pooling (CAP) occurs in low-lying areas where cold, dense air collects during nighttime hours, producing colder temperatures than surrounding higher elevations. Devils Postpile National Monument (DEPO) is confined by steep mountain ridges, which promote cold air drainage into lower-elevation meadows and river valleys. These low lying areas where CAP occurs could help facilitate a potential refugium from some of the greatest impacts of regional climate warming. A strong focus on CAP occurrence is part of a seven-step climate change refugia conservation cycle, outlined in Morelli et al. (2016), that DEPO has instituted, wherein resource management seeks to identify and focus on parts of the landscape that may be sheltered from the intensity and pace of rapid climate change. Locales that harbor persistent CAP may provide vulnerable species and ecosystems a sort of refuge, allowing more time to adapt to new conditions. Central to DEPO's strategy is better monitoring and understanding of CAP occurrence. Based on observations from 10 years of temperature loggers in and around DEPO, CAP operates reliably throughout the year, and especially during summer. Importantly, CAP has occurred strongly during recent unusually warm years. These findings reinforce the value of monitoring and ongoing analysis as a way to guide conservation and adaptation using potential climate change refugia. As with this co-developed park–university investigation, other land managers could consider climate refugia-oriented management as a viable conservation and adaptation strategy.

Introduction

Microclimates are a conspicuous feature of mountainous terrain, vitally important in supporting biodiversity (Bennett and Provan 2008; Keppel et al. 2012). Valleys and other topographic hollows and low areas experience cold air pooling (CAP; Whiteman 2006), driven by meteorological patterns that promote nighttime infrared cooling (Burns and Chemel 2014). The shallow temperature inversion that accompanies CAP conditions affects the exchange of heat, moisture, momentum, and pollutants with the free atmosphere above. Importantly, during CAP situations, temperatures in these low areas may be decoupled from those aloft and throughout the broader region (Lundquist and Cayan 2007; Daly et al. 2010). Areas with CAP may serve as a refugia for certain species during warm periods (Dobrowski 2011), buffering the intensity and pace of contemporary climate change, so that species and ecosystems have more time to adapt to new conditions (Morelli et al. 2016, 2020). Refugia from climate warming in mountain landscapes have become extremely important in light of evidence that mountain zones will likely experience warming that is amplified over that in low-elevation zones (Pepin et al. 2015).

Devils Postpile National Monument (DEPO), a 320-ha National Park Service (NPS) unit, is located in the central Sierra Nevada range along the Middle Fork of the San Joaquin River (Figure 1). Much of DEPO is dominated by mixed conifer forest composed of red fir (*Abies magnifica*), white fir (*Abies concolor*), Jeffrey pine (*Pinus jeffreyi*), and lodgepole pine (*Pinus contorta*; Caprio and Webster 2006). DEPO has warm, mostly dry summers and cold, wet winters. This area is at the biogeographic crossroads where species from Sierra Nevada and Great Basin communities both occur (https://urldefense.com/v3/__https:/ucjeps.berkeley.edu/eflora/geography.html), increasing biodiversity in flora and fauna (Arnett et. al 2014). Along with the diverse natural resources

FIGURE 1. Location of Devils Postpile National Monument (DEPO).



and wetland habitat in Soda Springs Meadow (SSM; Figure 2), the cold night and morning temperatures experienced by DEPO staff and visitors inspired a focus on this area to monitor and study recurrent, strong nocturnal temperature inversions that develop there. The investigation into CAP structure and dynamics complements ongoing efforts at DEPO to implement the seven-step climate change refugia conservation cycle introduced by Morelli et al. (2016) and explore the potential of the national monument to function as a climate change refugium and understand the role of CAP.

DEPO and the seven-step climate change refugia conservation cycle

In August 2017, eighteen scientists and managers, including staff from the National Park Service, gathered at DEPO for a 1.5-day workshop to discuss the state of knowledge regarding SSM, identify gaps, and evaluate attributes of SSM and the potential that it might serve as a refugium for native biota under a warming and drying climate (Buhler et al. 2019; Figure 3). Given the ecological and physical characteristics that indicate its potential as a climate change refugium, participants suggested that SSM might be managed as such by following the seven-step conservation cycle (Morelli et al. 2016) illustrated in Figure 4.

This process began by defining the purpose and objectives for management of a climate change refugium (Step 1). In DEPO's case, this was developed through the workshop discussion and supported by program documents, including the General Management Plan (National Park Service 2015) and Foundation Document (National Park Service 2017a), that articulate the park's purpose,

FIGURE 2. Middle Fork of the San Joaquin River and Soda Springs Meadow (SSM). Photo taken from Granite Dome at an elevation of 2500 m.
MONICA BUHLER / NATIONAL PARK SERVICE

significance, and fundamental resources and values (FRVs). The FRVs include the significance of sustaining a free-flowing river, mineral springs, wetlands, riparian areas, and other water-dependent features and communities. Of note, DEPO is a valuable component of the San Joaquin River watershed, which supports and maintains unusually rich ecological diversity reflective of its location at the intersection of two biogeographic regions. Within DEPO, the most prominent wetland is the 5-ha SSM at an elevation of approximately 2286m, which was identified as the focus of the management objectives.

Steps 2 and 3 included an assessment of climate impacts and vulnerabilities, which were addressed in DEPO's Resource Stewardship Strategy (National Park Service 2017b) and focused on FRVs. Expected climate change impacts in the Sierra Nevada include generally warmer days and nights; more intense and longer-lasting heat waves; more frequent, larger, and longer-duration wildfires (Miller and Safford 2012); reduced snowpack (Dettinger et al. 2018); on-average higher but more erratic winter stream discharge and diminished summer stream discharge (Herbst et al. 2016); and occasionally intensified storms, floods, and droughts (Monahan and Fisichelli 2014). Step 3 further refined the management goals and objectives, articulating that SSM is a centerpiece in managing DEPO as a climate change refugium.

In Step 4, the group identified and mapped key refugia features and considered research and monitoring in progress at DEPO, which includes an ongoing CAP study as well as hydrology, vegetation, and air quality monitoring.

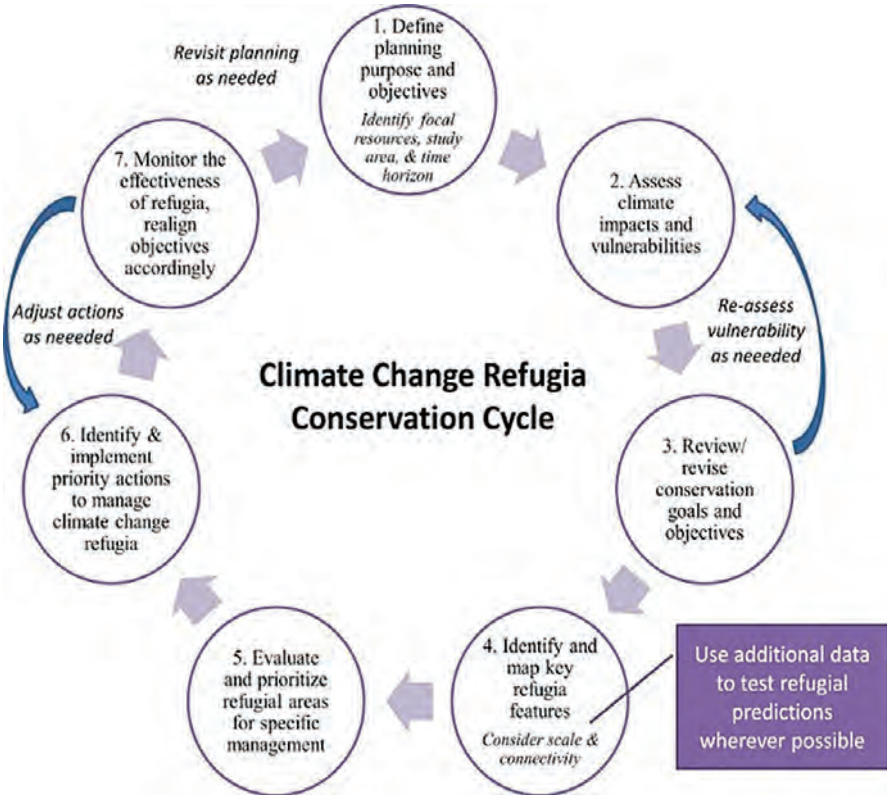


FIGURE 3. (top) August 2017 workshop discussing how to manage natural resources in DEPO under the growing influence of global climate change. SYLVIA HAULTAIN / NATIONAL PARK SERVICE

FIGURE 4. (bottom) DEPO management has adopted a climate change refugia conservation cycle (Morelli et al. 2016), in which the objective (Step 1) is to conserve species and ecosystems, whose implementation is supported by monitoring temperature variations and changes (Step 2) and identifying resilient CAP features (Step 4) that might provide a refugium from warmer temperatures.

Discussions of Steps 5 and 6 focused on the potential of managing SSM with a goal of *persistence*, that is, resisting change and retaining existing ecosystems *in situ* to the greatest extent possible, rather than the more common ecosystem management goal of *resilience,* wherein a system can absorb disturbance and reorganize but still retain ecological function (Walker et al. 2004). Managing for persistence generally relies on strategies to resist change through management intervention and conservation of target species and ecosystems (Ashcroft 2010; Weeks et al. 2018) and has been the main conservation strategy of NPS. Some approaches broaden the persistence strategy to include actions that enhance the ability of species, ecosystems, or environments (including social) to resist forces of climate change and maintain values and ecosystem services in their present or desired states and conditions (Peterson et al. 2011). Managing for resilience aims to enhance the capacity of ecosystems to withstand increasing effects without *irreversible* changes in important processes and functionality (Peterson et al. 2011). However, "agreement on definition is less important than how the range of meanings informs development of effective adaptation plans" (Peterson et al. 2011), and there are elements of both persistence and resilience strategies that are important management options for climate refugia. For example, removing conifers that are establishing in the meadow does not address the underlying conditions (e.g., altered hydrologic regime) that favor conifer establishment but could potentially help maintain the current meadow extent and area composed of herbaceous vegetation to persist, and delay its conversion to forest.

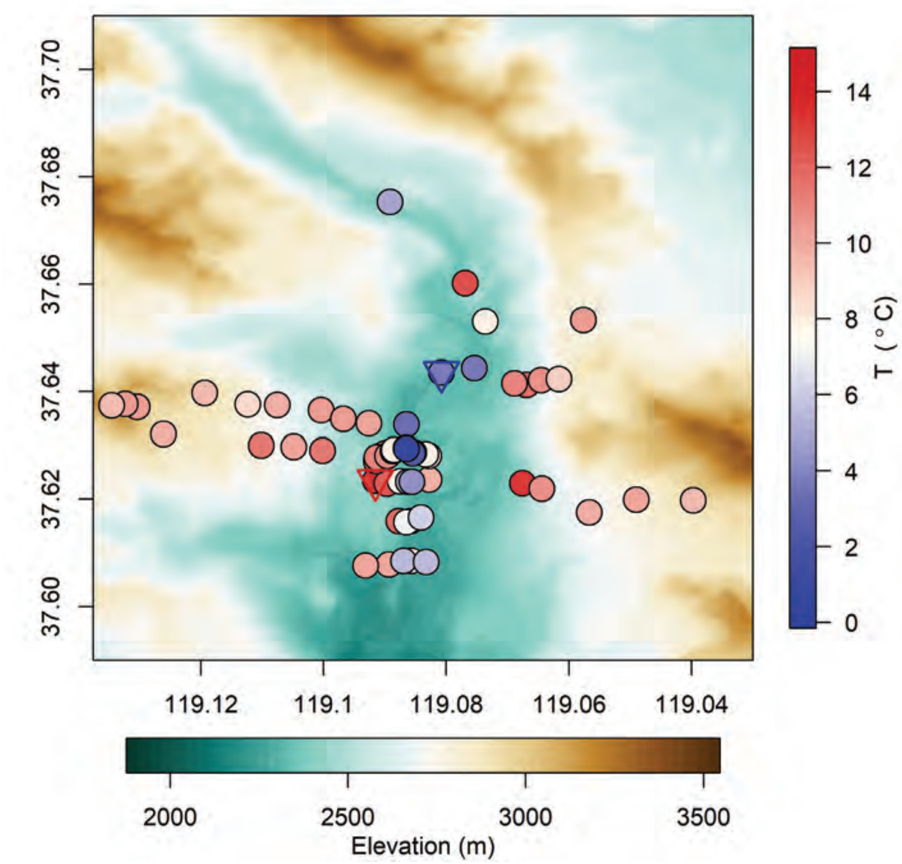
Straightforward initial strategies to resist adverse effects of climate change, such as those articulated in the United States Department of Agriculture (USDA) *Responding to Climate Change in National Forests* guidebook (Peterson et al. 2011) have been applied at SSM, and more are planned, to:

- Perform fuel reduction treatments around high-value riparian areas to prevent (temporary) habitat loss and aquatic habitat degradation from fire.
- Utilize prescribed fire to maintain native species and prevent tree encroachment.
- Use early detection of, and rapid response to control, exotic species.

The physical science focus in this paper is on Step 4, which aims to identify and map key refugia features. As noted in Morelli et al. (2016), "first approximations of refugia can be identified based upon the physical and biotic processes that buffer climate change. . . ." Specific attributes of SSM suggest that the area may serve as a climate refugium, even though air and water inputs into the meadow will likely be warmer as the climate warms. SSM's mitigating attributes include ample shading (because of a north-to-south-trending canyon), steep elevational gradients, a river fed by high-elevation snow melt, complex topography, substantial tree canopy, and CAP.

To understand the importance and role of CAP as an attribute of a possible climate change refugium, we investigated its structure and occurrence using an extensive set of observations from an array of temperature sensors (Figure 5), described below. Gonzalez et al. (2018) emphasized the importance of this kind of research: "Spatial analyses that identify vulnerable areas and potential refugia can guide prioritization of locations for habitat conservation, fire management, invasive species control, and other actions under climate change … so achieving the mission of the US National Park Service to conserve resources unimpaired for future generations benefits from spatial data on climate change trends." The temperature records indicate that CAP is strongly present in parts of DEPO and may help to ameliorate impacts of extreme region-wide warmth, and thus support a persistence management strategy. Observing weather conditions and regularly monitoring meadow health, including species changes over time, is important because SSM may become increasingly vulnerable to incoming species, particularly in view of its biogeographic setting.

FIGURE 5. Topography and location of primary temperature sensors (circles) in and around DEPO. Early-morning (5am PDT) temperature (°C), averaged over all days in August, is indicated by blue-red station circles. The permanent DEPO weather station is indicated by the black square. Topography in the DEPO region is indicated by shaded topographic surface. Inverted triangles designate sites used to construct a fixed-elevation CAP index in Figures 6, 8, and 11.



Measuring CAP in DEPO

The study area includes DEPO and adjacent Inyo National Forest land (managed by the US Forest Service), encompassing approximately 2500ha at elevations between 2150–3170m. The temperature sensors are arranged on (roughly) north-to-south and east-to-west transects to sample temperatures throughout the entire vertical height range of the study area in and around DEPO.

Prior to the 2017 workshop, DEPO and its university partners had already launched a fine-spatial-scale temperature monitoring program, called the "DEPO array," to track and better understand CAP. The first temperature loggers were installed in 2008 along east-to-west-trending transects at incremental elevations according to a peer-reviewed study plan (National Park Service 2011). Two models of temperature loggers, Maxim iButtons (https://www.mouser.com/new/maxim-integrated/maxim-ibutton-devices/) and Onset Tidbits (https://www.microdaq.com/onset-hobo-tidbit-temperature-data-logger.php), were placed in trees following a protocol outlined by Lundquist and Huggett (2008). Maxim iButtons claim a +/– 1°C accuracy while the Onset Tidbits claim a 0.2 +/– 0.2°C accuracy, both of which are adequate given the magnitude of temperature difference between CAP and non-CAP conditions. Loggers are placed in white plastic funnels and installed on the north side of conifers above and below shady branches to shield them from direct solar radiation. To remain above snowpack, loggers are placed high enough in each tree (typically 5 meters above ground); in a few locations multiple loggers are installed on a single tree at incremental heights (e.g. 1m, 5m, 10m, 15m 20m) to gather data on the near-ground structure of CAP. The loggers recorded temperature at hourly and in some cases 30-minute intervals to capture diurnal patterns, along with variations in the timing of CAP formation and breakup. Transects were selected to follow slopes with similar forest cover and slope aspect (either east or west) to avoid confounding due to these variables. At its beginning in 2008, the DEPO temperature array included 38 sensors; at its zenith, it included 115. A large number (42) of these were lost in an unusually severe wind storm in 2011, when thousands of live, large-diameter trees blew down (Hilimire et al. 2013). Some sensors were replaced in the following years, and by the 2019–2020 period the array included 103 sensors at 66 different sites.

CAP occurrence during the warm season in DEPO

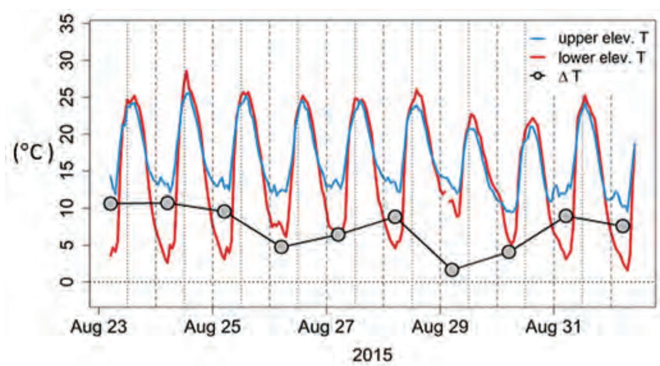
For most of our analyses, CAP was quantified using an index, ΔT, defined as the maximum temperature difference between a pair of loggers representing upper and lower elevations among all possible such pairs and hours of each day. This definition allows the CAP ΔT to result from different stations on any given day. Selection of the lower-elevation loggers was limited to those in SSM or in the adjacent low-lying area along the river channel having records longer than six years. As exemplified in the time series in Figure 6, the maximum ΔT generally occurs after midnight and before 7am. For simplicity and for selected illustrations, a version of ΔT is also employed by using temperatures from a single logger in SSM and one on the slope above.

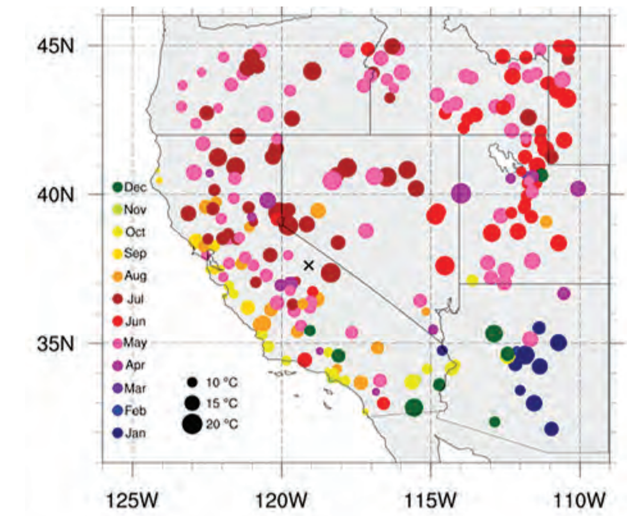
The observations in DEPO demonstrate that CAP occurs throughout the year. While some previous studies elsewhere emphasized CAP occurrence during the cool season (e.g. Daly et al. 2010; Morelli et al. 2016), an analysis of the amplitude of nocturnal cooling from weather stations across much of the far western states finds peak activity during spring–fall (Figure 7a). Although CAP occurs quite locally in topographically favored locations, the atmospheric drivers that enhance or diminish its occurrence may be much broader in scale. Figure 7b, showing correlations of DEPO CAP day-to-day fluctuations with a CAP index at weather stations across the Southwest, indicates that CAP variation operates over a rather broad regional footprint.

Related to the spatial coherence of nocturnal cooling events indicated in Figure 7b, the strong positive mode of CAP is associated with a high-pressure cell (Figure 8) that often envelops the entire West Coast, producing clear skies and warm days. DEPO's summer-accentuated CAP seems likely to involve its severe ridge-valley topography and north-to-south canyon orientation that provides evening and morning shading along with localized meteorological effects, but deciphering these would require comparative observations and modeling studies.

Here we focus on summer, because CAP occurs regularly then and is well developed with a typical amplitude of 5–8°C (Figure 9). Also, because summer is the time of greatest warmth, the refugium impacts of CAP on biota

FIGURE 6. Hourly time series of temperature (ºC) from selected lower (red) and upslope elevation (blue) sensors from the DEPO array. ΔT (black) represents the maximum nighttime or early-morning temperature difference between the upper- and lower-elevation sites identified in Figure 5.





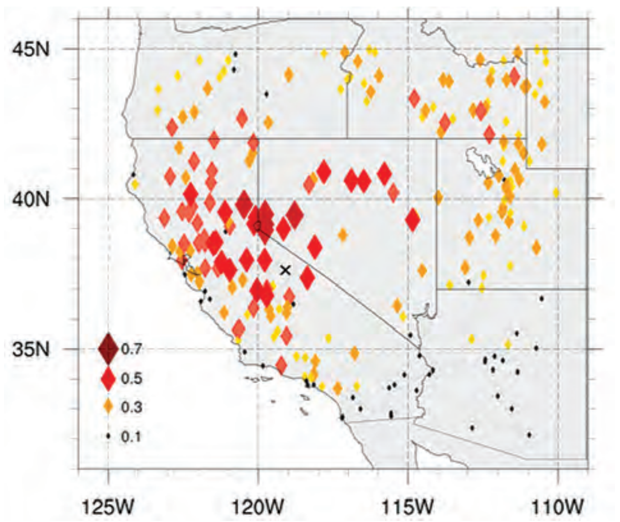


FIGURE 7a. (left) Month of peak in amplitude of $\Delta T_{diurnal}$.
FIGURE 7b. (right) Correlation, DEPO ΔT vs. ΔT_{night} during July–September. The $\Delta T_{diurnal}$ and ΔT_{night} indices of CAP were constructed from the differences in station temperature vs. atmospheric layer temperature, for nighttime minus daytime amplitudes and nighttime, respectively. Tmax and Tmin are from 234 Global Historical Climatology Network (GHCN) stations and North America Regional Reanalysis (NARR) average regional temperature data over the Southwest United States. Statistics are constructed from 2011–2016 daily data. NARR temperature is averaged over the domain 32N to 45N, and 125W to 110W, from higher, nearest pressure level from each station using standard atmosphere approximation. Stations were included having mean July $\Delta T_{diurnal}$ >5°C. DEPO location is indicated by "X." Correlation of July–September nighttime NARR layer temperature and DEPO upper-elevation temperature: 0.86; of DEPO weather Tmin vs lower elevation Tmin: 0.91; and of NARR layer Tmin minus DEPO weather station Tmin vs. DEPO ΔT: 0.76.

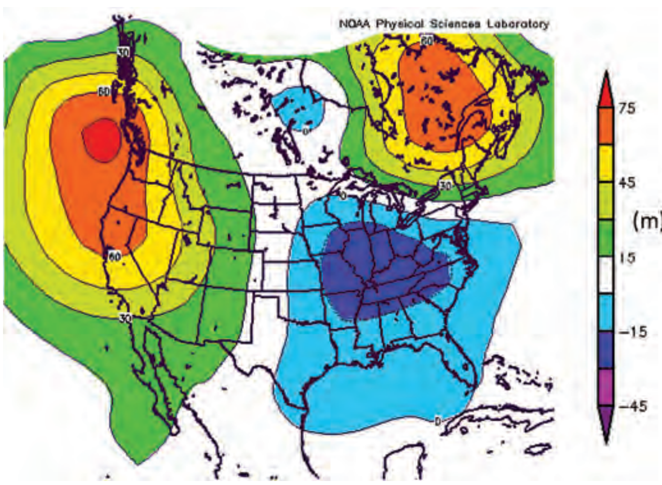


FIGURE 8. Anomalous mid-troposphere geopotential height (m) at 500 hPa level, averaged over 20 days within the period 2009–2018 with strongest CAP occurrence in DEPO during June–August, shows a high pressure ridge that occurs when CAP is strong. Anomalies are calculated from the 1980–2010 average. Map generated by software and data from National Oceanic and Atmospheric Administration (NOAA) Physical Science Division, Environmental Sciences Research Laboratory.

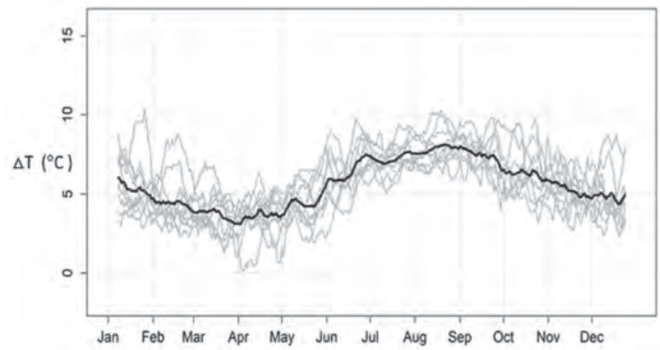


FIGURE 9. Annual cycle of CAP magnitude represented by temperature difference (ΔT °C) between upper elevation minus lower elevation at 5am PDT. Heavy line is the average of 15-day running mean ΔT(light lines) of each year from 2009–2018.

and ecosystems might be greatest during that season (Millar and Stephenson 2015). In addition to direct effects of drought, in terms of vegetation health and mortality, high temperatures and aridity produce increased pathogen impacts and fire danger (Williams et al. 2010; Dong et al. 2019). Thus, CAP during summer seems important in providing relief to biota from daytime heat stress. Often exceeding 6°C, summertime CAP magnitude amounts to about half of the daily range (maximum minus minimum) of temperature at upslope locations (Figure 6). Importantly, CAP magnitude (Figure 9) is typically considerably larger than the 1–3°C of modeled climate warming projected by the mid-21st century for much of California (Pierce et al. 2018).

Strong CAP episodes are driven by continental-scale atmospheric circulation patterns (Figure 8), a structure whose multi-day residence time anchors CAP persistence and would promote CAP occurrence over a western United States regional domain, as indicated in Figure 7b.

Notably, days when daytime temperatures are warmest usually have clear skies (Figure 10) which promotes nocturnal cooling driven by outgoing terrestrial radiation (Burns and Chemel 2014). CAP on these warmest days is

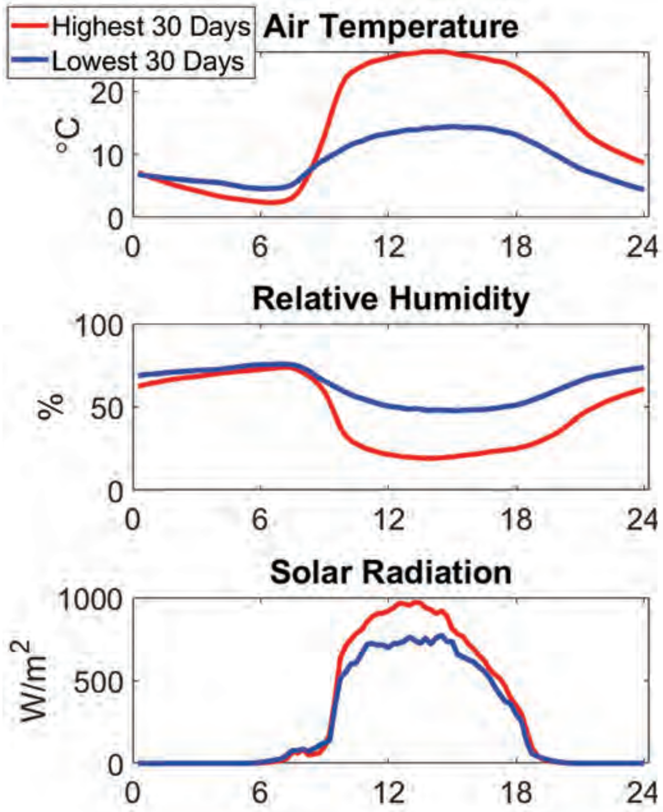


FIGURE 10. Average temperature (ºC), relative humidity (%), and incoming solar radiation (W/m2) on the 30 days during June–August with highest (red) and lowest (blue) ΔT. From 2009–2018 SSM weather station (Figure 5) observations; temperature 3.45m above ground, humidity and solar radiation 6.25m above ground. Days with strong CAP are notably warmer in daytime, somewhat drier, and have greater incoming solar radiation than cases with weak CAP.

thus quite strong; examples for days in June–August are shown in Figure 11. Conversely, on cooler summer days, CAP was somewhat weaker than long-term averages (not shown).

Typically, warm air develops in late morning (Figure 11), making the meadow 1–2°C warmer than locations upslope, but this usually erodes in the late afternoon followed by CAP formation in late evening. CAP begins to develop in the evening and strengthens steadily through early morning. The temperature inversion and strong CAP occurs until about 8am (PDT), when it abruptly dissipates as daytime heating commences. Thus, CAP persists, albeit with variable amplitude, for about half the day.

The DEPO temperature array reveals that CAP is formed by a relatively thin lens of cool air, ranging from 50–300m deep. CAP thickness is gauged by the difference in elevation between the coolest early morning temperatures occurring in the San Joaquin River valley and warmest temperatures at the top of the inversion. Differing CAP conditions are shown by vertical profiles of early morning temperatures from the DEPO array

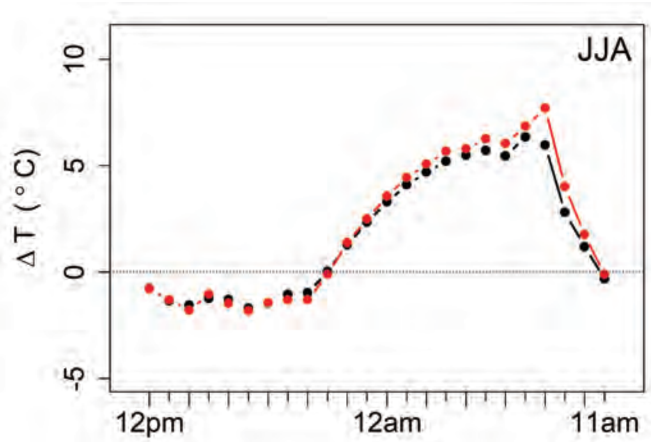


FIGURE 11. Hourly ΔT, upper vs. lower elevations in DEPO, during June–August (JJA). Average over entire 10 years is shown in black, and average over the 30 warmest days in JJA is shown in red. Both sample sets evidence steady development of CAP beginning in early evening and building to a peak in the morning, followed by rapid dissipation after 9am.

for two days in August 2015, plotted in Figure 12. One profile is the morning of 28 August 2015, when CAP is well developed, and was preceded by a very warm afternoon. The other profile, illustrating unusually low CAP development, is on the following morning of 29 August 2015, a day when the West Coast was overtaken by a broad low-pressure system (not shown) when the atmosphere was relatively unstable.

Strong CAP occurrence in DEPO during recent warm summers

Over the period since the 1970s the western United States experienced rising temperatures (Williams et al. 2020). Although much attention has been given to warming in winter and spring (Wang et al. 2017), summer mean temperatures over the Sierra Nevada also registered substantial warming since 1970 (Figure 13). And recently, a series of unusually warm years occurred, to the point that over the recent 10 years (2010–2019), the regional average temperature exceeded the 50-year (1970–2019) mean by 1°C.

The degree to which CAP decouples local climates from regional conditions could greatly impact ecosystems. A critical point is whether CAP operates effectively during unusually warm periods. DEPO temperatures span the recent decade, allowing investigation of CAP occurrence during warm and somewhat cool summers. The years 2016 and 2017 produced anomalously warm regional average summer temperatures, and 2010 and 2011 were relatively cool (Figure 13). Notably, the 2010–2011 cool and 2016–2017 warm summer anomaly signatures were features that enveloped much of the western United States with markedly different eastern North Pacific–Western North America atmospheric circulation patterns

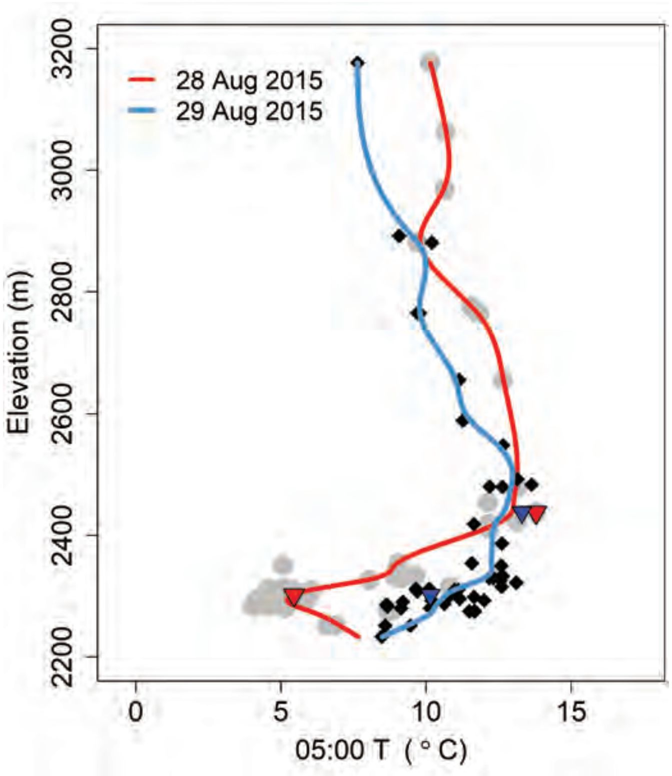


FIGURE 12. CAP in the DEPO region is a lens of cool air lying along the river valley/meadow capped by warmer temperatures upslope, shown by profiles of temperature (ºC) at 5am PDT 28 August 2015, a day with relatively well-developed CAP, and 29 August 2015, a day when the atmosphere was well mixed, dominated by a low-pressure system. The elevation of fixed-location temperatures used in some of the analyses is indicated by inverted triangles.

(not shown). The average difference between the summers of 2010–2011 and the summers of 2016–2017 was about 1.5°C.

Distributions of each day's CAP, represented by the maximum of the daily upper- vs. lower-elevation temperature from the DEPO array during June–August, were calculated for the cool and the warm years and plotted in Figure 14. These distributions indicate that although nighttime temperatures in SSM and the valley of the San Joaquin River were somewhat warmer, CAP was well developed during these two warm summers. In fact, the magnitude of cooling in DEPO's lower elevations relative to temperatures upslope was actually greater during the warm years than the cool years. On average, ΔT was 2°C greater during these two warm summers than the 2010 and 2011 cool summers. Notably, during the warm 2016 and 2017 summers, most days registered ΔT of 6°C or greater, and very few days of less than 3°C.

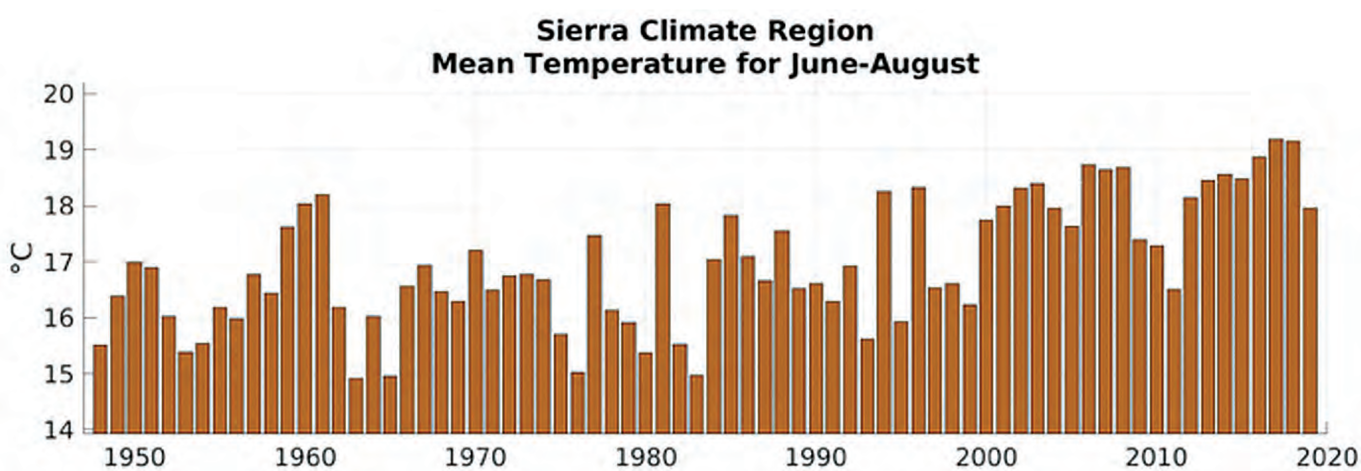
Summary and conclusions

Within DEPO's management plan to apply a seven-step climate refugia conservation cycle (Morelli et al. 2016), the understanding of CAP occurrence and structure is central to the identification of possible refugia that constitutes Step 4 in this process.

A high-density, but relatively low-cost, monitoring effort has yielded a valuable payoff. Ten years of fine spatial- and temporal-scale co-produced observations from the DEPO temperature array reveal very consistent formation of CAP along the San Joaquin River channel and SSM, which is well developed in summer. CAP occurred on most days, usually for about 12 hours. CAP developed in the evening and persisted through morning of the following day, forming as a relatively thin layer of cold air between 50–300m thick.

Two noteworthy findings support the possibility of a CAP-driven refugium from climate warming in DEPO's SSM. First, as measured by the temperature decline from the inversion top to the valley below, CAP strength was at its maximum during summer months (Figure 8). Second,

FIGURE 13. June–August time series of mean temperature (ºC) for the period 1948–2019, averaged over the Sierra Nevada, illustrates recent warm summers. From California Climate Tracker, Western Regional Climate Center. https://wrcc.dri.edu/Climate/Tracker/CA/



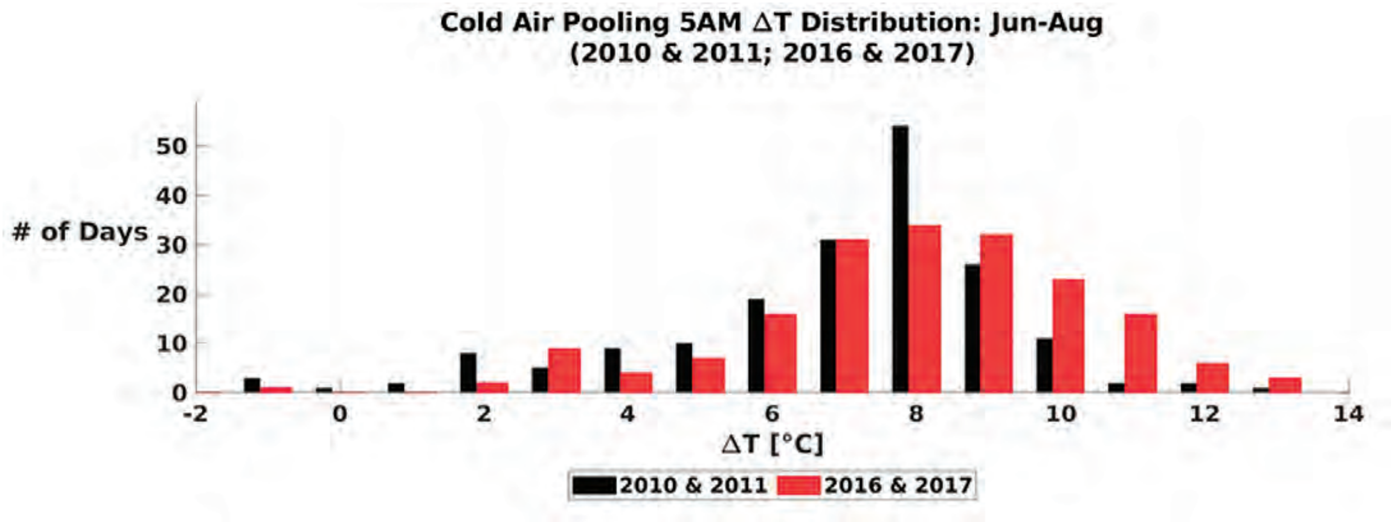


FIGURE 14. Distribution of June–August daily CAP strength, ΔT (ºC), the daily maximum upper- vs. lower-elevation temperature difference from hourly data, for all June–August days of the cool summers of 2010 and 2011 (black) and the warm summers of 2016 and 2017 (red).

while CAP varies from day to day and year to year, it actually occurred quite strongly during warmest days, even during summer heat waves and within summers when overall conditions were anomalously warm (Figures 10 and 14).

These results underscore the role of CAP in ameliorating daytime heat, particularly in the summer months when flora and fauna are most strongly affected by high temperatures and also exposed to reduced moisture availability. DEPO's strong summer CAP raises the possibility that substantial CAP may occur commonly in summer in other Sierra Nevada locales. A multitude of sites that foster nocturnal inversions and CAP in the Sierra Nevada have been identified from topographic indicators (Curtis et al. 2014). While the CAP process itself does not constitute refugia, the conditions that it provides may maintain refugia components such as wet meadows and riparian habitats. This decadal snapshot of fine-scale observations from DEPO has provided insights that should be a foundation for future understanding. Continued monitoring will quantify the pace of warming in future decades, whether CAP continues to occur, and how strongly. It appears that CAP in DEPO often represents CAP throughout a much broader region (Figure 7b), presumably because nocturnal inversions are promoted by large-scale drivers (Figure 9). Thus, results from this co-produced study and analysis are important both on site at DEPO and as a reference for land managers elsewhere who may be interested in assessing the value that CAP refugia could contribute to climate adaptation strategies.

Discussions and work continue on the seven-step climate refugia conservation cycle (Morelli et al. 2016; Figure 4). Besides anchoring Step 4 of the cycle, results of this study also contribute to Step 5, "evaluate and prioritize refugial area for specific management," and support prioritizing SSM as a refugial area and candidate for specific management. Progress on Step 6, "how to identify and implement priority strategies," resulted in an advanced monitoring protocol for SSM summarized in a formal memo that outlines a set of five broad strategies primarily focused on information gathering to help managers evaluate if NPS is achieving a persistence goal for the meadow (National Park Service 2020). Future evaluation will need to identify what factors are driving the system to a new state that could warrant alternative management actions. This ties to NPS policy emphasizing the need for thoughtful evaluation of potential resistance strategies as described in the NPS *Climate Change Response Strategy* (2010), where the necessary link between refugia science and management strategies is described in Goal 3, Objective 3.3j, emphasizes "the importance of verifying the scientific foundation of these concepts and to identify and evaluate their performance so that they may be applied appropriately in restoration and protection of park resources" (National Park Service 2010). Discussions regarding Step 7 include questions such as how and when to facilitate meadow structure and function versus species-specific conservation, and how to develop criteria to assess whether new colonizers are supportive of meadow function or are instead disruptive invasives. These questions, as well as other specifics on "resisting change," continue to develop as refugia science and case studies, such as this one at DEPO, expand.

Identifying, prioritizing, and protecting refugia are of increasing importance as land managers respond to accelerating change (Monahan et al. 2014). Even if refugia merely act as holdouts in the face of climate change

(Hannah et al. 2014), persistence of populations restricted to climate refugia likely will require their dispersal at some point. The shifts of biomes and species ranges that are occurring due to climate change increase the importance of national parks, which can offer a network of habitat refugia for climate-sensitive species that may utilize corridors to connected habitat, such as meadows across the landscape (Maher et al. 2017). Although specific climate refugia may not persist beyond the next several decades, their role in climate adaptation strategies could be vital in conserving habitats and providing seedbanks of flora and fauna for future restoration.

Allowing time for climate science learning and management to further evolve, "climate-change refugia may serve as a 'slow lane,' in that their relative buffering from climate change could protect native species and ecosystems from the negative effects of climate change in the short term, and provide longer-term havens from climate impacts for biodiversity and ecosystem function" (Morelli et al. 2020). Potential strategies may include managing high-value species in designated refugial networks and along connectivity corridors, assisted migration, and focused replanting of resilient species under projected changed climatic conditions, such as in burned area rehabilitation (Millar and Stephenson 2015). Importantly, there is a need to integrate climate refugia as a sensitive resource into wildfire response and to concurrently develop prescribed burn strategies to protect climate refugia for species and habitats, and as seedbanks for restoration.

Discussion at the 2017 workshop emphasized the value of current and future university and agency partnerships to provide interdisciplinary expertise and help sustain monitoring. It was recognized that monitoring was vital in identifying key refugial features (such as CAP) in Step 4 and assess the effectiveness of refugial attributes in Step 7, enabling the realignment of objectives at SSM accordingly. These points led to discussion of future opportunities for gathering and analyzing data, developing science communication materials, and sharing results and strategies. The DEPO CAP study and the aligned seven-step climate change refugia conservation cycle provides a case study at a manageable scale and underscores the value of science, as articulated in the presidential Antiquities Act proclamation of 1911 that created DEPO. At a time when land managers are called upon to respond to multiple climate impacts, it is hoped that the experience at DEPO will help to evaluate refugia management as a viable climate change adaptation strategy.

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References

Arnett, M., A.M. Huber, K.M. Stevenson, and S. Haultain. 2014. Vascular flora of Devils Postpile National Monument, Madera County, California. *Madroño* 61(4): 367–387.

Ashcroft, M.B. 2010. Identifying refugia from climate change. *Biogeography* 37(8): 1407–1413. https://doi.org/10.1111/j.1365-2699.2010.02300.x

Bennett, K.D., and J. Provan. 2008. What do we mean by 'refugia'? *Quaternary Science Reviews* 27 (27–28): 2449-2455. https://doi.org/10.1016/j.quascirev.2008.08.019

Buhler., M., S. Chau, M. Denn, D. Dulen, S. Haultain, and J. Nesmith. 2019. Developing a conservation strategy for Soda Springs Meadow: Results of a workshop held at Devils Postpile National Monument. Unpublished report. Mammoth, CA: National Park Service, Devils Postpile National Monument.

Burns, P., and C. Chemel. 2014. Evolution of cold-air-pooling processes in complex terrain. *Boundary-Layer Meteorology* 150: 423–447. https://doi.org/10.1007/s10546-013-9885-z

Curtis, J.A., L.E. Flint, A.L. Flint, J.D. Lundquist, B. Hudgens, E.E. Boydston, and J.K. Young. 2014. Incorporating cold-air pooling into downscaled climate models increases potential refugia for snow-dependent species within the Sierra Nevada Ecoregion, CA. *PLoS ONE* 9(9): e106984. https://doi.org/10.1371/journal.pone.0106984

Daly C., D.R. Conklin, and M.H. Unsworth. 2010. Local atmospheric decoupling in complex topography alters climate change impacts. *International Journal of Climatology*. 30: 1857–1864. https://doi.org/10.1002/joc.2007

Denn, M., J. Nesmith, S. Haultain, and M. Buhler. In draft. Soda Springs Meadow Management. Memorandum to National Park Service, Water Resources Division, Fort Collins, CO.

Dettinger, M.D., H. Alpert, J. Battles, J. Kusel, H. Safford, D. Fougeres, C. Knight, L. Miller, and S. Sawyer. 2018. *Sierra Nevada Summary Report. California's Fourth Climate Change Assessment.* Publication no. SUM-CCCA4-2018-004. Sacramento: State of California Governor's Office of Planning and Research, California Natural Resources Agency, and State of California Energy Commission.

Dobrowski, S.Z. 2011. A climatic basis for microrefugia: The influence of terrain on climate. *Global Change Biology* 17(2): 1022–1035. http://dx.doi.org/10.1111/j.1365-2486.2010.02263.x

Dong, C., G. MacDonald, G.S. Okin, and T.W. Gillespie. 2019. Quantifying drought sensitivity of Mediterranean climate vegetation to recent warming: A case study in Southern California. *Remote Sensing* 11(24): 2902. https://doi.org/10.3390/rs11242902

Gonzalez, P., F. Wang, M. Notaro, D.J. Vimont, and J.W. Williams. 2018. Disproportionate magnitude of climate change in United States national parks. *Environmental Research Letters* 13: 104001. https://doi.org/10.1088/1748-9326/aade09

Flint H.L., A.D. Syphard, M.A. Moritz, L.B. Buckley and I.M. McCullough. 2014. Fine-grain modeling of species' response to climate change: Holdouts, stepping-stones, and microrefugia. *Trends in Ecology & Evolution* 29(7): 390–397. https://doi.org/10.1016/j.tree.2014.04.006

Herbst, D., B. Medhurst, I. Bell, and M. Bogan. 2016. Observations of changing habitat and benthic invertebrate communities from the Sierra Nevada sentinel stream network during extended drought. PowerPoint presentation. University of California, Sierra Nevada Aquatic Research Laboratory. https://herbstlab.msi.ucsb.edu/pdfs/summary_SFS%20 2016%20Sentinel%20Streams%20Herbst.pdf

Hilimire, K., J.C.B. Nesmith, A.C. Caprio, and R. Milne. 2013. Field note: Attributes of windthrown trees in a Sierra Nevada mixed-conifer forest. *Western Journal of Applied Forestry* 28(2): 85–88.

Keppel, G., K.P. Van Niel, G.W. Wardell-Johnson, C.J. Yates, M. Byrne, and L. Mucina. 2012. Refugia: Identifying and understanding safe havens for biodiversity under climate change. *Global Ecology and Biogeography* 21: 393–404. https://doi.org/10.1111/j.1466-8238.2011.00686.x

Lundquist, J.D., and D.R. Cayan. 2007. Surface temperature patterns in complex terrain: Daily variations and long-term changes in the central Sierra Nevada, California. *Journal of Geophysical Research* 112: D11124. https://doi.org/10.1029/2006JD007561.

Lundquist, J.D., and B. Huggett. 2008. Evergreen trees as inexpensive radiation shields for temperature sensors. Water Resources Research 44(4): W00D04. https://doi.org/10.1029/2008WR006979

Maher, S.P., T.L. Morelli, M. Hershey, A.L. Flint, L.E. Flint, C. Moritz, and S. R. Beissinger. 2017. Erosion of refugia in the Sierra Nevada meadows network with climate change. *Ecosphere* 8(4): e01673. https://doi.org/10.1002/ecs2.1673

Millar, C.I., and N.L. Stephenson. 2015. Temperate forest health in the era of megadisturbance. *Forest Health Science* 349(6250): 823–826. https://doi.org/10.1126/science.aaa9933

Miller, J.D., and H. Safford. 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, U.S.A. *Fire Ecology* 8(3): 41–57.

Monahan, W.B. and N.A. Fisichelli. 2014. Climate exposure of US national parks in a new era of change. *PLoS ONE* 9(7): e101302. https://doi.org/10.1371/journal.pone.0101302

Morelli, T.L., C. Daly, S.Z. Dobrowski, D. M. Dulen, J.L. Ebersole, S. Stock, and S.T. Jackson. 2016. Managing climate change refugia for climate adaptation. *PLoS ONE* 11(8): e0159909. https://doi.org/10.1371/journal.pone.0159909

Morelli, T.L., C.W. Barrows, A.R. Ramirez, J.M. Cartwright, D.D. Ackerly, T.D. Eaves, J.L. Ebersole, M.A. Krawchuk, B.H. Letcher, M.F. Mahalovich, G.W. Meigs, J.L. Michalak, C.I. Millar, R.M. Quiñones, D. Stralberg, and J.H. Thorn, et al. 2020. Climate-change refugia: Biodiversity in the slow lane. *Frontiers in Ecology and Environment* 18(5): 228–234. https://doi.org/10.1002/fee.2189

National Park Service. 2010. *Climate Change Response Strategy.* Fort Collins, CO: National Park Service Climate Change Response Program.

National Park Service. 2011. Cold-air pool characterization, climate model down-scaling and baseline data acquisition for DEPO and UUMFSJ. National Park Service study proposal. D. Scott, comp.

National Park Service. 2015. *General Management Plan and Environmental Assessment, Devils Postpile National Monument.* Mammoth, CA: Devils Postpile National Monument.

National Park Service. 2016. *State of the Park Report for Devils Postpile National Monument.* State of the Park Series no. 26. Washington, DC: National Park Service.

National Park Service. 2017a. Foundation Document: Devils Postpile National Monument. DEPO 120/134151. Mammoth, CA: Devils Postpile National Monument.

National Park Service. 2017b: Resource Stewardship Strategy: Devils Postpile National Monument. IMammoth, CA: Devils Postpile National Monument.

National Park Service. 2020. Potential management actions at Soda Springs Meadow, Devils Postpile National Monument, to promote persistence of a wet meadow at the site under changing hydrological and climactic conditions. NPS Water Resources Division memorandum to Devils Postpile National Monument.

Pierce, D.W., J.F. Kalansky, and D.R. Cayan. 2018. Climate, drought, and sea level rise scenarios for the fourth California climate assessment. In *California's Fourth Climate Change Assessment.* Publication no. CCCA4-CEC-2018-006. Sacramento: State of California Governor's Office of Planning and Research, California Natural Resources Agency, and State of California Energy Commission.

Pepin, N., R. Bradley, and H. Diaz. 2015. Elevation-dependent warming in mountain regions of the world. *Nature Climate Change* 5: 424–430. https://doi.org/10.1038/nclimate2563

Peterson, D.L., C.I. Millar, L.A. Joyce, M.J. Furniss, J.E. Halofsky, R.P. Neilson, and T.M. Morelli. 2011. *Responding to Climate Change in National Forests: A Guidebook for Developing Adaptation Options*. General Technical Report. PNW-GTR-855. Portland, OR: US Department of Agriculture–Forest Service, Pacific Northwest Research Station.

Walker, B., C.S. Holling, S.R. Carpenter, and A. Kinzig. 2004: Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society* 9(2): 5. http://www.ecologyandsociety.org/vol9/iss2/art5/

Wang, K.J., A.P. Williams, and D.P. Lettenmaier. 2017. How much have California winters warmed over the last century? *Geophysical Research Letters* 44: 8893–8900. https://doi.org/10.1002/2017GL075002

Weeks, D., M. Denn, J. Wagner, K. Nydick, A. Demetry, J. Nesmith, S. Haultain, and E. Frenzel. 2018. Managing wet meadow systems at Sequoia and Kings Canyon National Parks in a changing climate. Unpublished report, 5 November. Fort Collins, CO: National Park Service Climate Change Response Program.

Whiteman, C.D. 2000. *Mountain Meteorology: Fundamentals and Applications*. New York: Oxford University Press.

Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. *Science* 368(6488): 314–318. https://doi.org/10.1126/science.aaz9600

Williams, A.P., C.D. Allen, C.I. Millar, C.I., T.W. Swetnam, J. Michaelsen, C. J. Still, and S.W. Leavitt. 2010. Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences USA* 107: 21289–21294. https://doi.org/10.1073/pnas.0914211107

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