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

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Received for peer review 31 May 2020; revised 12 November 2021; accepted 4 June 2021; published 15 September 2021

Conflict of interest and funding declarations. The authors declare they have no actual or potential competing financial interests. Support for DRC, JG, and DA was provided by California Energy Commission EPC-16-093, NOAA’s California and Nevada Applications Program award NA17OAR4310284, and the US Geological Survey/Department of Interior through the Southwest Climate Adaptation Science Center, G18AC00320.

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,
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,
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 (Dettlinger 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.

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...
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.

**Measuring CAP in DEPO**

The study area includes DEPO and adjacent Inyo National Forest land (managed by the US Forest Service), 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.
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 $\Delta T$ generally occurs after midnight and before 7am. For simplicity and for selected illustrations, a version of $\Delta T$ 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 envelopes 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

**CAP occurrence during the warm season in DEPO**

For most of our analyses, CAP was quantified using an index, $\Delta T$, 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 $\Delta T$ 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 $\Delta T$ generally occurs after midnight and before 7am. For simplicity and for selected illustrations, a version of $\Delta T$ is also employed by using temperatures from a single logger in SSM and one on the slope above.

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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 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 36).
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 10. Average temperature (°C), 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.

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.
lated 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, \( \Delta T \) 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 \( \Delta T \) 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,
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
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 refugial management as a viable climate change adaptation strategy.

Acknowledgments
DEPO temperature array data collection, organization, and analyses could not have been accomplished without Student Conservation Association (SCA) interns Eric Moore, Catie McCafferty, Larene Cameron, Andrew Osborne, Julie Chuong, James Benson, Marta Bravo, Nick Graver, Sophia Chau, Kyan Elep, Zoe Varner, Conner Rosenblatt, Danny Park, Austin Riley, Alissa Chrisekos, Peter Fahey, and Jillian Henrichon, and physical science technicians at DEPO, namely Maureen McGlinchy (who provided extensive data organization), Catherine Fong, and David Scott and Colin Leslie (for the initial installation of the loggers). In addition, Laurel DeHaan and Joshua Mumford provided data analyses and graphics. We thank two anonymous reviewers for thorough sets of constructive comments and edits.

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The journal continues The George Wright Forum, published 1981–2018 by the George Wright Society.

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Citation for this article
Cayan, Daniel R., Monica Buhler, Jordan Goodrich, Deanna Dulen, and Douglas Alden 2021. Relief from summer warming: Devils Postpile National Monument’s cold air pool supports a refugium-based conservation strategy. Parks Stewardship Forum 37(3): 592–603.

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