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Cascading Drought-Heat Dynamics During the 2021 Southwest United States Heatwave

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Key Points:

- The record-setting 2021 US heatwave struck at a time when surface conditions were anomalously dry, bright, and barren due to drought
- Satellite observations indicate that drought led to anomalous land-atmosphere fluxes
- Model simulations also indicate a small but systematic positive feedback of drought on heat

Supporting Information:

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

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Abstract In June of 2021 the Southwest United States experienced a record-breaking heatwave. This heatwave came at a time when the region was in severe drought. As drought alters the surface energy budget in ways that affect lower atmosphere temperature and circulations, it is possible that the combined drought-heat event was a cascading climate hazard, in which preexisting drought exacerbated the heatwave. We apply satellite observation and numerical experiments with the Weather Research and Forecasting (WRF) model to test for land-atmosphere feedbacks during the heatwave consistent with drought influence. We find a modest positive drought-heat effect, as WRF simulations that include the drought have marginally higher air temperatures than those that exclude the initial drought conditions, with more substantial effects in wetter, forested areas. Evidence of drought-heat-drought-coupled feedbacks was similarly modest in our simulations, as accounting for drought preconditioning led to a small reduction in simulated precipitation in the region.

Plain Language Summary In June 2021 the Southwest United States was hit by a record-breaking heatwave at the same time as a severe drought. In this study, we look into the response of both events effect on one another. The WRF computer model is designed to test the observed events besides the use of satellite images during the same time. We find a small positive response between the two events that was more considerable over wetter and green regions. We also find a decrease in rainfall over the study region as a response to the drought-heatwave conditions.

1. Introduction

In 2021 the contiguous United States (US) experienced its hottest summer on record. This included an extended high temperature period over the western United States, with distinct maxima in the Southwest in mid-June and northwest in late June, raging wildfires and widespread exceptional drought conditions. The overlapping occurrence of these multiple record-setting climate extremes marks the western United States summer of 2021 as a case of record shattering and compound climate hazards—phenomena that are increasing in frequency under climate change (AghaKouchak et al., 2020; Fischer et al., 2021; Zscheischler et al., 2018). Specifically, the colocation of an extreme drought present at the beginning of the summer and the first wave of record shattering temperatures in mid-June (Figure 1) raise the possibility that the two events were physically linked cascading hazards (Tilloy et al., 2019): Drought, through its influence on surface fluxes, might have triggered or intensified the heat wave, which in turn could exert a positive feedback on drought through increased evaporative demand or decreased precipitation.

The question of whether the Southwest drought and heat extreme were cascading extremes or simply an instance of a multivariate compound extreme event (Zscheischler et al., 2020), in which drought and heat had no direct physical influence on each other, is relevant to understanding how hot and dry extremes might interact in a changing climate. There is now robust evidence that compound dry-hot extreme events have increased due to anthropogenic warming in recent decades (Alizadeh et al., 2020; Sarhadi et al., 2018). Dryness and heat are often products of a common synoptic circulation, such that they can occur together without a direct physical link between the two. There is also evidence that land-atmosphere interactions during drought have led to hotter droughts in recent decades (Chiang et al., 2018), potentially increasing the intensity of heat extremes in a manner consistent with cascading hazards. Indeed, increases in the strength of negative correlation between temperature and precipitation over much of the globe point to a potential role of land-atmosphere feedbacks under climate change contributing to increased frequency of compound dry-hot extremes (Zscheischler & Seneviratne, 2017).

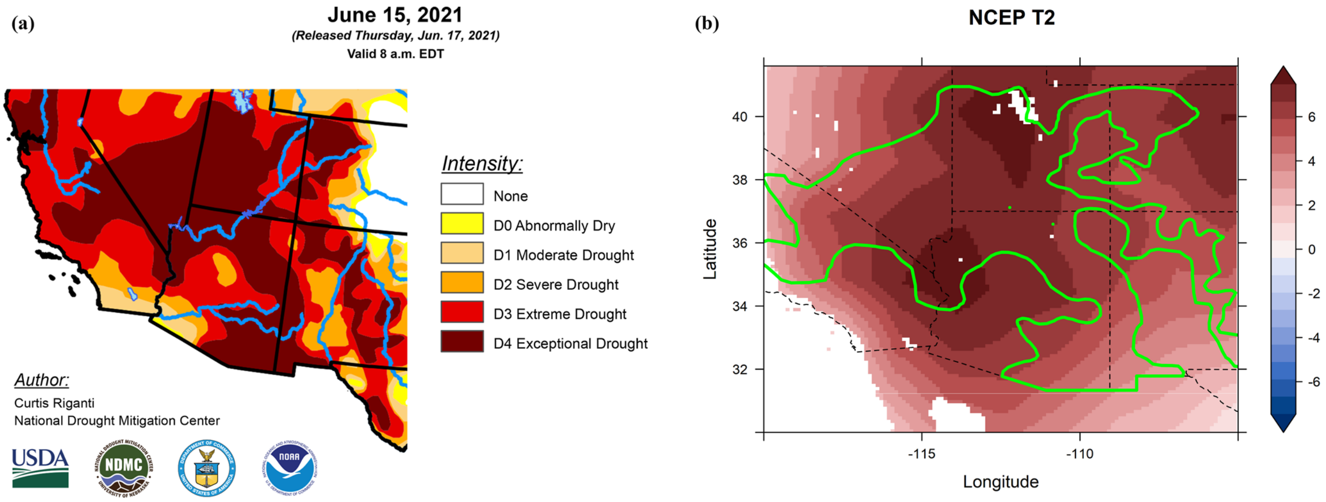

Figure 1. (a) Drought conditions identified by the United States Drought Monitor (USDM) for mid-June 2021. (b) The National Centers for Environmental Prediction (NCEP) 2 m air temperature composite anomaly for the period from 13 June 2021 to 19 June 2021 over the region of interest. The light green outline shows the USDM D4 (Exceptional Drought) region as identified in Figure 1a.

The importance of intensifying feedbacks between drought and heat, however, depends on context and can be difficult to quantify (Miralles et al., 2019). Hypothesized drought-heat interactions include (a) surface energy partitioning effects, in which drought leads to enhanced sensible heat flux relative to latent heat flux, convectively warming the planetary boundary layer, (b) surface net radiation effects, in which drought alters incoming solar radiation or surface albedo; thus, changing the amount of energy that needs to be dissipated from the surface, (c) precipitation-mediated feedbacks related to planetary boundary layer processes or convective dynamics, and (d) broader impacts on atmospheric circulations (Seneviratne et al., 2010). Determining whether any of these processes were active in the record-setting events of June 2021 has implications on how we interpret projections of future climate extremes by global climate models (GCMs) that may or may not include such cascading dynamics.

Given the growing evidence for cascading dry-hot hazard dynamics in theory and global analysis, the Southwest United States drought and heat extreme of 2021 offers an important opportunity to probe for the presence of hypothesized feedbacks. We do this through controlled numerical experiments with the Weather Research and Forecasting (WRF) model (Skamarock et al., 2021) applied at convection resolving scales, allowing us to consider how dynamics often described in GCMs and global scale analysis played out at local to regional scale during a sentinel event.

2. Materials and Methods

We examine the 13–19 June 2021 Southwest United States heat extreme (Liberto, 2021), which coincided with the development of an intense heat dome over the western United States Select surface conditions and fluxes for the period of the event are analyzed using satellite-derived observations of leaf area index (LAI; MODIS product MCD43A1 v006 [Schaaf & Wang, 2015]), white sky broadband albedo (MODIS product MCD15A2H v006 [Myneni et al., 2015]), soil moisture (SMAP L4 Global 3-hourly 9 km EASE-Grid Surface and Root Zone Soil Moisture Analysis Update, Version 6 [Reichle et al., 2022]), and evapotranspiration (SSEBop; [Senay & Kagone, 2019; Senay et al., 2013]). Conditions in June 2021 are compared to those in June 2019, a year that was classified as nearly drought-free in the study region (Figure S1 in Supporting Information S1).

To test the hypotheses that drought preconditioned the region for extreme heat and that mutually reinforcing feedbacks amplified both extremes, we configure the WRF regional climate model for a domain extending from 25° to 51°N and from 88° to 128°W (Figure S2 in Supporting Information S1). Initial and boundary conditions are drawn from the North American Mesoscale (NAM) Forecast System data set provided from the National Centers for Environmental Prediction (NCEP) at 6 hr intervals (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 2015). WRF experiments use the recommended CONUS

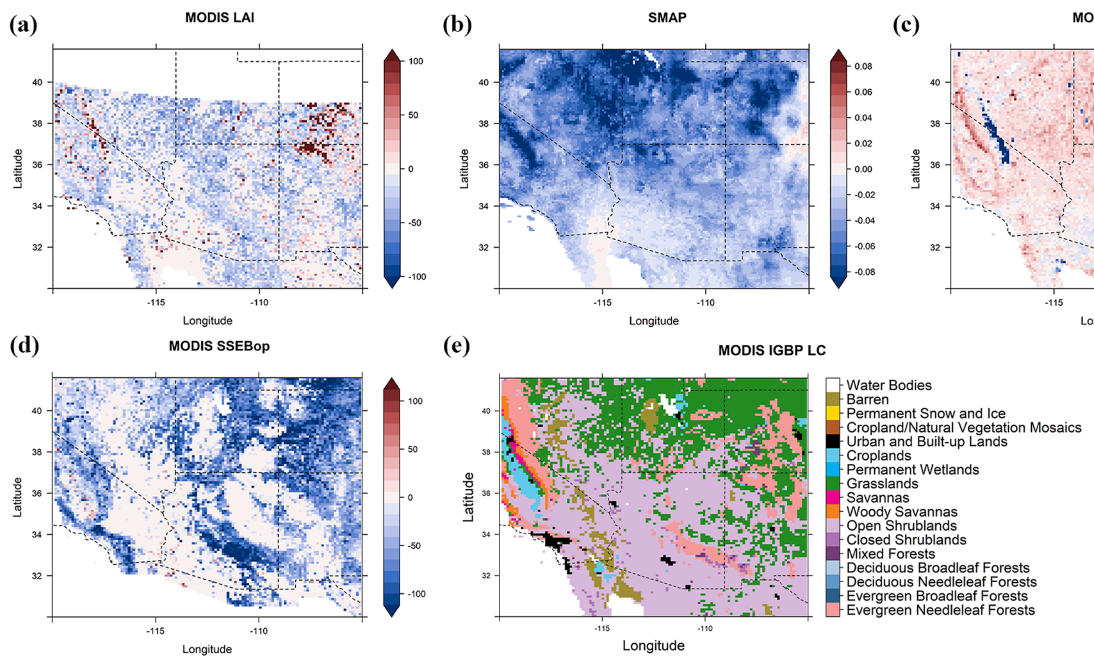

Figure 2. The observed difference between 2021 and 2019 time averaged for the period from June 13 to June 19 over the region of interest for: (a) MODIS LAI (%), (b) SMAP root zone soil moisture (m/m), (c) MODIS surface albedo, (d) MODIS SSEBop evapotranspiration (W/m^2), and (e) MODIS IGBP land cover classification.

physics suite (https://www2.mmm.ucar.edu/wrf/users/physics/ncar_convection_suite.php) and are performed at 4 km horizontal resolution and with 27 vertical levels up to 150 hPa. The Noah-MP Land Surface Model is used with dynamic phenology enabled, such that the model predicts the evolution of vegetation conditions over the course of the simulation.

Two sets of ensemble experiments are performed. The first set is designed to simulate the 2021 heatwave using initial conditions from observations of the same year, drawn from the NAM (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 2015). For the second set of simulations, we replace all initial soil moisture, soil temperature, canopy water, snow, surface albedo, and vegetation fields with values drawn from the same date in 2019. Each set represents an ensemble of four experiments initialized at different times (every 18 hr from 00:00 UTC 20 May).

Our study focused on the drought core during the observed heatwave, which lies between 105°–120°W and 31°–40°N (Figure 1) as detected by USDM for the week of 15 June 2021. The area is dominated by semiarid to arid grassland, shrubland, and desert, with some forested areas associated with higher topography (Figure 2e).

3. Results

First, we consider whether observed land surface states in June 2021 were consistent with hypothesized mechanisms of drought-heat interaction. When compared to the nearly drought-free conditions seen in June 2019, satellite observations of conditions in mid-June 2021 show a widespread negative anomaly in leaf area index (LAI) in the drought affected region (Figure 2a). This anomaly is modest in magnitude but it represents a substantial reduction for this generally arid and semiarid region (Figure S1 in Supporting Information S1). As one might expect in a climatologically dry region (Zaitchik et al., 2007), this reduction in vegetation and generally low soil moisture conditions (Figure 2b) are associated with an increase in albedo (Figure 2c). Elevated albedo reduces the amount of solar radiation absorbed at the surface and is associated with a negative forcing on near-surface air temperatures (Zaitchik et al., 2007). At the same time, satellite-derived estimates show reduced rates of evapotranspiration over a substantial fraction of the drought-affected area (Figure 2d), including in forested areas of Arizona in the core of the dry-hot extreme (Figure 2e), which is typically associated with a shift from latent to sensible heat flux, exerting a positive forcing on air temperature. These elevated albedo and reduced

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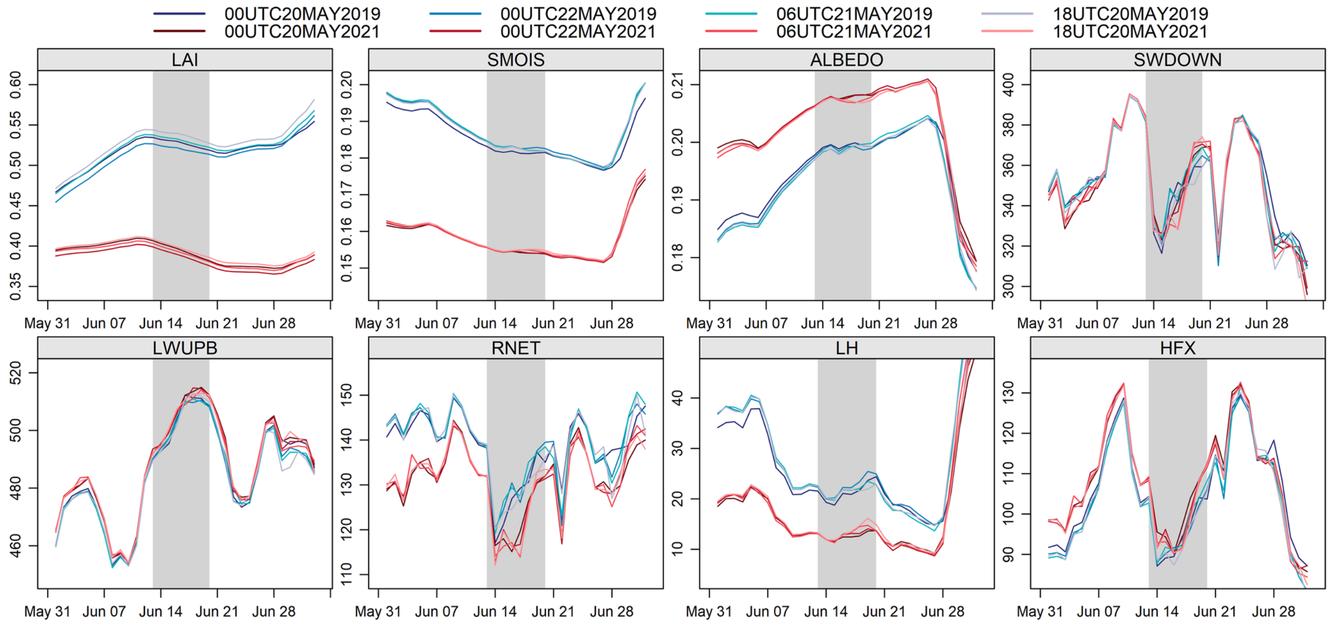

Figure 3. Time series of selected variables for the 2021 and 2019 initialization experiments spatially averaged over the region of interest during the month of June.

evapotranspiration conditions suggest that drought had the potential either to moderate or elevate near-surface air temperatures during the emerging heat extreme.

WRF simulations captured the direction of these surface conditions, albeit with some differences from observation in snow-affected and forested areas (Figure 3). General similarity between WRF and observations largely inherits from initial conditions: lower LAI, higher albedo, and lower soil moisture conditions at the initialization of simulations are preserved through the peak of the heatwave (Figures 4a–4c; Table 1). The combination of elevated surface albedo, small and mixed signals in surface downwelling solar radiation, and increased surface upwelling longwave radiation due to higher surface temperatures results in a negative drought impact on net radiation at the surface (Figures 4d–4f; Table 1). At the same time, drought is associated with a substantial reduction in latent heat flux (Figure 4g; Table 1), consistent with satellite-derived observation (compare Figures 2d and Figure 3d; Figure 2d shows a larger magnitude difference but only a portion of this difference would be expected to be a result of surface conditions). This change in energy partitioning, when taken together with the reduction in net radiation, results in a systematic but modest increase in sensible heat flux (Figure 4h; Table 1).

The combination of this modest increase in sensible heating and the increase in upwelling longwave radiation from the surface points to a small positive forcing of drought on air temperature. Indeed, simulated 2 m air temperature in the core region of the drought and heatwave was on average 0.28°C higher in the simulations that accounted for drought. Notably, over the more vegetated forest areas (where latent heat flux is generally higher compared to sensible heat flux) within the core region the simulated energy partitioning effect dominated the simulated net radiation effect, resulting in simulated 2 m air temperature differences on the order of 2°C averaged over the peak of the heatwave (Figures 2d and 4i). Temperature differences are generally small in more arid, low vegetation areas, falling slightly above or below zero. Our simulations do not show strong evidence of drought impacts on heat via changes in cloud cover or in the intensification of the heat dome and associated circulations. The height of the planetary boundary layer is deeper in simulations that account for drought conditions but incoming solar radiation is not systematically different (Table 1). Differences in surface pressure and 500 hPa geopotential height are both small—on the order of 0.5 hPa for surface pressure and 3 m for 500 hPa geopotential height—and would not be expected to have a meaningful influence on the evolution of the heatwave.

Our simulations are not designed to simulate the full impact that the heat anomaly had on drought, but they can be used to examine simulated drought feedbacks on drought, including any cascading drought-heat-drought feedbacks. For example, drought has been hypothesized to lead to reduced precipitation either by reducing net radiation and associated surface energy input to the planetary boundary layer (Eltahir, 1998) or by increasing

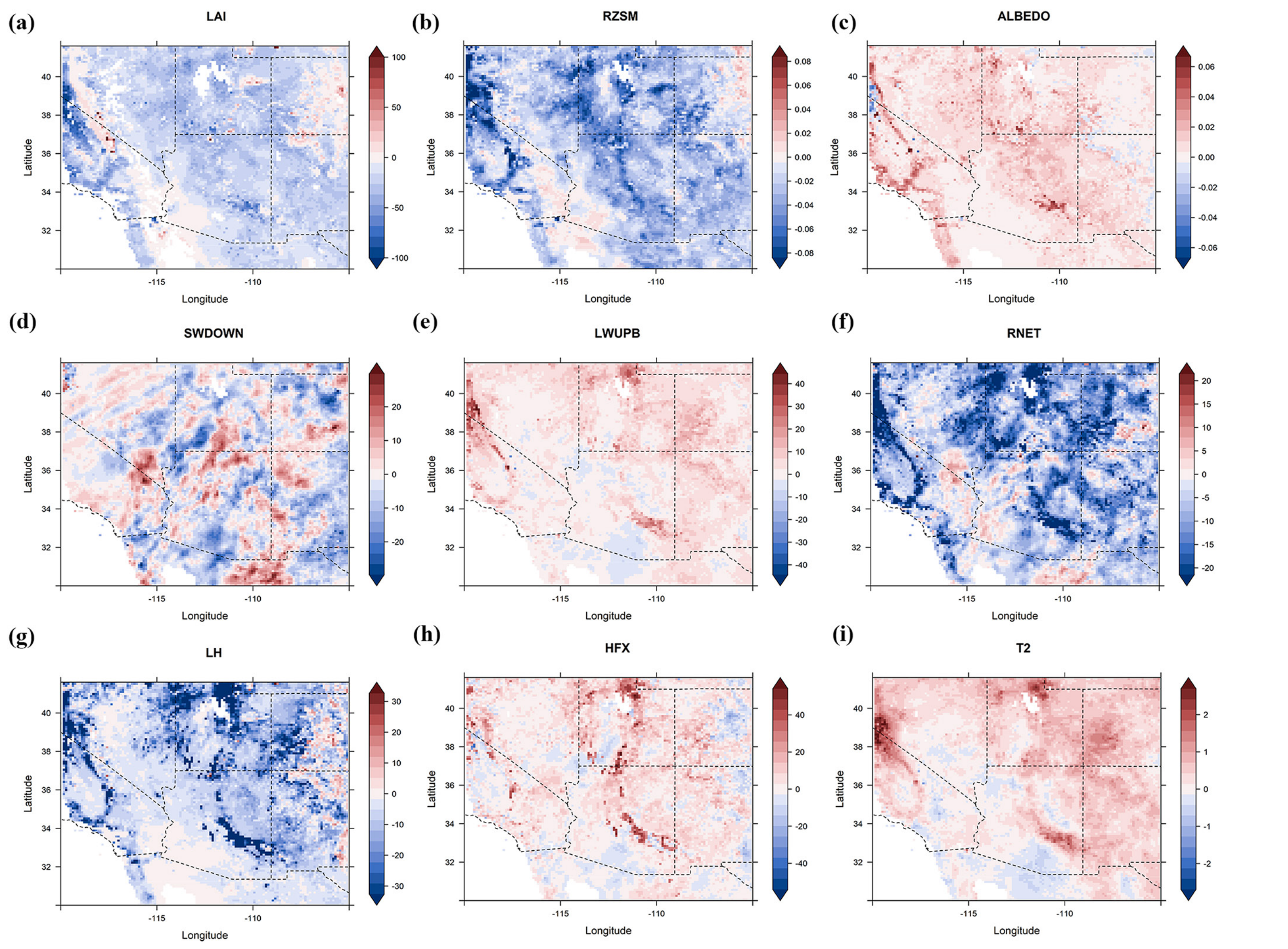

Figure 4. The simulated difference between the 2021 and 2019 initialization experiments, time averaged and ensemble averaged for the period from June 13th to June 19th over the region of interest for: (a) Leaf Area Index (%), (b) Root zone soil moisture (m/m), (c) Surface albedo, (d) Surface downwelling solar radiation (W/m^2), (e) surface upwelling longwave radiation (W/m^2), (f) Net radiation (W/m^2), (g) latent heat flux (W/m^2), and (h) Sensible heat flux (W/m^2).

sensible heating of the planetary boundary layer, leading to a deeper, drier planetary boundary layer with enhanced entrainment of low energy air from the free troposphere (Betts & Ball, 1998). Our simulations do indicate that accounting for the drought results in a small but systematic reduction in precipitation during the period of the heatwave maximum (Table 1), with strongest impacts in the downwind and less arid eastern portion of the study area (Figure 5a), a pattern that is consistent with the concept of downwind self-propagation of droughts in drylands (Schumacher et al., 2022). Both reduced net radiation and increased sensible heat flux and planetary boundary layer depths might contribute to this effect (Table 1). Those drought-drought feedbacks, however, do not explicitly depend on temperature mediation. A specific drought-heat-drought cascade can occur when drought leads to elevated temperatures that increase evaporative demand, further drying out soils and vegetation. We see an increase in vapor pressure deficit (VPD) over the whole region of interest (Figure 5b), which is consistent with temperature-driven soil desiccation. But overall, we find that soil moisture conditions converge rather than diverge in the period leading up to and through the heat maximum (Table 1)—perhaps because the drought had already driven moisture conditions so low—such that there is no clear indication that this increase in evaporative demand triggered a cascading drought-heat-drought feedback. We note that this result might not hold when severe heatwaves hit more humid regions or when there is not already a severe drought; indeed, some types of rapid-onset "flash droughts" are understood to be triggered by elevated air temperatures (Osman et al., 2022).

Table 1
June 13–19, 2021 Ensemble Mean Values of Selected Variables of Interest, Spatially Averaged Across the Area of USDM Exceptional Drought (D4; Figure 1) Within the Focus Study Region

		INIT 2021	INIT 2019	Diff (2021–2019)
LAI	(m^2/m^2)	0.59	0.74	−0.16
SMOIS	(m/m)	0.17	0.20	−0.03
ALBEDO	(–)	0.20	0.19	0.01
SWDOWN	(W/m^2)	350.6	351.7	−1.2
LWUPB	(W/m^2)	495.0	492.2	2.8
RNET	(W/m^2)	129.42	137.5	−8.2
LH	(W/m^2)	17.0	26.61	−9.6
HFX	(W/m^2)	101.7	97.9	3.8
T2	(°K)	301.8	301.5	0.3
PBLH	(m)	1,635	1,535	100
PSFC	(hPa)	840.2	840.6	−0.4
GHT500	(m)	5,878	5,878	0
PRCP	(mm)	9.98	14.93	−5.38
VPD	(hPa)	34.7	33.4	1.3
ΔSMOIS	(m/m)	−3.39E-03	−4.74E-03	1.35E-03

Note. INIT 2021 = initialization with 2021 surface conditions and INIT 2019 = initialization with 2019 surface conditions.

4. Discussion and Conclusions

The dry-hot extreme that struck the Southwest United States in June 2021 was a record-breaking compound climate hazard. Globally, large scale dry-hot extremes are on the rise due to anthropogenic climate warming (Alizadeh et al., 2020), and land-atmospheric feedbacks can play a role in the temporal evolution and spatial propagation of such events (Miralles et al., 2019). The potential or these reinforcing interactions are featured in early descriptions of the June 2021 event (Liberto, 2021), but there has been no evaluation of whether the event was actually a cascading hazard in which one climate extreme triggered or intensified the other.

In controlled simulation experiments we find evidence of a modest positive forcing of drought on heat: In the core dry-hot region, average temperature in the week of the heatwave maximum was 0.28°C higher in ensemble simulations that accounted for the drought relative to those that did not account for drought. This spatially consistent but modest intensification of heat conditions is the product of offsetting land-atmosphere interactions: The drought led to a brighter surface, reduced net radiation, and a decrease in total turbulent heat flux to the atmosphere, but dry conditions also changed the partitioning of energy fluxes, such that sensible heat flux from the surface was higher. There was also evidence of a positive drought feedback, as simulations that accounted for drought had a deeper, drier planetary boundary layer and reduced precipitation during the period of heatwave maximum. Increased vapor pressure deficit due to drought (Figure 5b) is consistent with a positive heat-mediated (drought-heat-drought) feedback, but there was no evidence of enhanced soil drying due to this influence. When considering the entire drought-affected domain, soil moisture fields converged across the simulation experiments over the course of the heat event (Table 1); in more humid forested areas within this area, there is neither convergence nor divergence such that these ecosystems might be closer to a feedback regime but still do not show evidence of feedback in this study. We emphasize that these numerical experiments rely on a single modeling system and quantitative details of results should not be overread. The general sign consistency between simulations and available observations, however, offer some confidence in the proposed role of land-atmosphere interactions during the event.

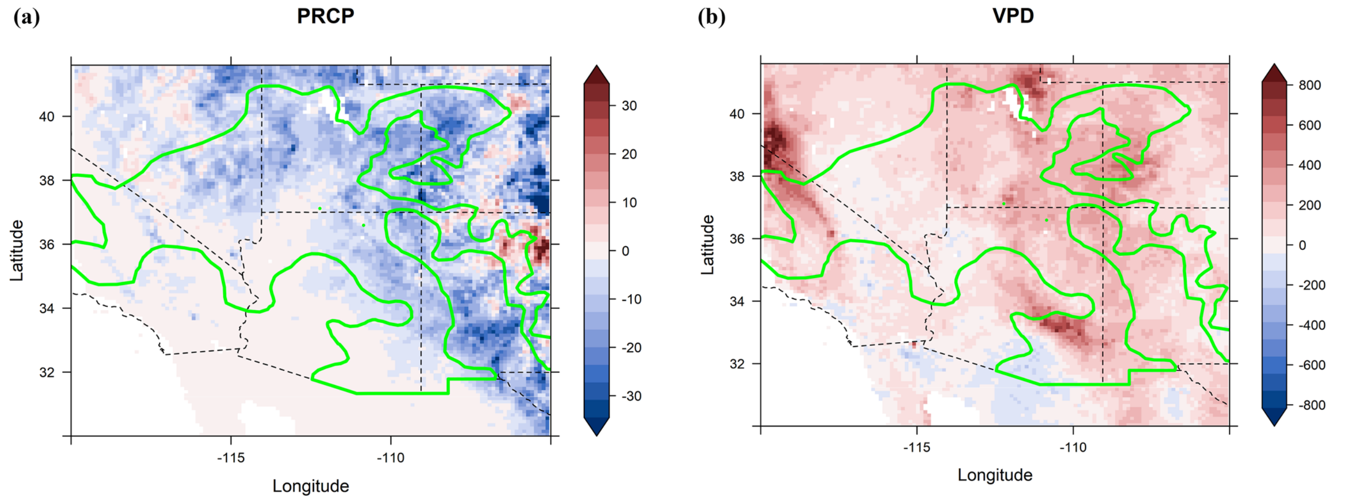

Figure 5. The simulated difference between the 2021 and 2019 initialization experiments time averaged for the period from 13 June to 19 June for: (a) Total precipitation (mm) and (b) Vapor pressure deficit (Pa). The light green outline shows the United States Drought Monitor (USDM) D4 (Exceptional Drought) region as identified in Figure 1a.

The results of this study emphasize the importance of climatic and ecological context when considering the potential for cascading dry-hot climate extremes or to the contribution of heat to drought-associated ecological impacts. The Southwest United States heatwave of June 2021 was concentrated in a semiarid and arid region with low vegetation cover and typically bright, low organic content soils. In this setting, a drought that causes vegetation to die back will expose a high albedo dry soil surface, and the reflection of solar radiation by this bright surface will reduce net radiation at the surface and associated turbulent heat flux to the atmosphere (Eltahir, 1998; Zaitchik et al., 2007). The situation can be quite different in transitional climate zones of strong land-atmosphere coupling where drought can cause dramatic reductions in evapotranspiration (Koster et al., 2004; Seneviratne et al., 2010), while the impact on vegetation does not always lead to a dramatic increase in albedo—either vegetation is dense enough to maintain coverage over soils, or the soils that are revealed by vegetation dieback are high organic matter soils that are relatively dark even when dry. In that setting, the potential for a dry-hot cascading extreme is considerably higher, as the energy partitioning effect dominates over the net radiation effect (Betts & Ball, 1998; Zaitchik et al., 2006). Indeed, we find the strongest energy partitioning effects and positive forcing of drought on heat in the relatively densely vegetated forested areas of the study region.

The risk of cascading dynamics in dry-hot hazard extremes in a warming climate, then, should be considered in climatic and ecological context. Transitional climate zones, in which energy partitioning is highly sensitive to soil moisture, are particularly sensitive. As the Southwest United States heatwave of June 2021 shows, these zones include forests in water-limited environments. The sensitivity of these systems to cascading dry-hot hazards has potential implications for fire risk and forest carbon sinks in a warming world.

Conflict of Interest

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

Data Availability Statement

Processed data sets for this research are available and accessible for all researchers at the open access Zenodo repository: https://doi.org/10.5281/zenodo.6620888. Software used for experiments design is WRF v.4.2.2 available at the URL: https://www2.mmm.ucar.edu/wrf/users/download/get_sources_new.php Software used for data analysis and creation of figures is the free R programming language at the URL: https://www.r-project.org/.

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