2021 North American Heatwave Amplified by Climate-Change-Driven Nonlinear Interactions

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Abstract

Heat conditions in North America in summer 2021 exceeded prior heatwaves by margins many would have considered impossible under current climate conditions. Associated severe impacts highlight the need for understanding its physical drivers and relations to climate change, to improve the projection and prediction of future extreme heat risks. Here, we find that slow- and fast-moving components of the atmospheric circulation interacted, along with regional soil moisture deficiency, to trigger a 5-sigma heat event. Its severity was amplified ~40% by nonlinear interactions between its drivers, likely driven by land–atmosphere feedbacks catalyzed by long-term regional warming and soil drying. Since the 1950s, global warming has transformed the event's peak daily regional temperature anomaly from virtually impossible to a presently-estimated ~200-year occurrence. Its likelihood is projected to increase rapidly with unmitigated global warming, possibly becoming a 10-yearly occurrence in a climate 2°C warmer than preindustrial, which may be reached by 2050.

Main

Unprecedented heat conditions in the North American Pacific Northwest (PNW) in late June and early July 2021 affected millions, likely led to deaths in the thousands, and promoted wildfires affecting air quality throughout the continent. CDC records suggest hundreds of excess deaths in both Washington and Oregon during the heatwave, with hundreds more in British Columbia officially attributed to heat, likely undercounting the true toll[1,2,3]. Heat-related emergency room visits spiked, totaling nearly 3,000 over June 25–30 in the US PNW[4]. The affected region's high vulnerability to extreme heat amplified its dangers: air conditioning access in the Seattle and Portland metropolitan areas is among the lowest in the country[5], while many PNW counties have among the largest outdoor agricultural worker populations and highest social vulnerability in the country[6]. Exacerbated by drought conditions (covering 95% of the US PNW by June 22[7]), wildfires sparked during and following the heatwave constituted some of 93 large fires contributing to millions of western US acres burned by August[8]. Wildfire smoke caused particulate matter pollution across the continent, for instance contributing to New York City's worst air quality in 15 years[9].

Even as global warming increases the severity and frequency of heatwaves[10,11], the magnitude of this event exceeded what many may have considered plausible under current climate conditions[12]. While heat records are typically broken by small increments[13,14], this event shattered records by tens of degrees Celsius[15]. Such an unprecedented event raises the pressing question of whether heat extremes' future projections are too conservative or their mechanisms inadequately captured by climate models. It is therefore important to understand the event's physical drivers and assess their connections with climate change. From an attribution perspective, was this anomaly so extreme to be considered virtually impossible regardless of climate change (a "black swan" event[16,17]), or was it plausible and foreseeable, and even made more likely due to baseline warming (a "gray swan"[18])? Further, were its drivers mechanistically altered by climate trends, beyond their occurrence in a warming background—perhaps indicating exacerbated future risk?

Whether any change in atmospheric dynamics or land–atmosphere interaction is implicated in amplifying current and future heat extremes is a persistent question: common heatwave mechanisms may be modified by climate change beyond a shift in background conditions. Mid-latitude heat extremes, typically triggered by anticyclonic circulation anomalies, have often been associated with persistently-amplified planetary-scale atmospheric waves[19–23]. Conditions favorable for wave amplification may become more frequent, possibly connected to weakening of the north-south temperature gradient[24–26]. Additionally, thermodynamic land–atmosphere feedbacks can strongly amplify heatwave temperatures, often involving nonlinear processes[27–31]. Land areas typically occupy two distinct regimes of soil–atmosphere interaction: areas where soil moisture is too high or too low for its variability to affect evapotranspiration, versus areas with "transitional" climates (between wet and dry), where soil moisture variability affects evapotranspiration and therefore temperature[32]. The central US is a noted transitional-climate hotspot of strong soil moisture–temperature coupling[32,33], but although the presently-wet PNW is projected to dry due to warming[34–36], and aridification of other wet regions has been implicated in amplifying summer temperature variability (e.g. central Europe[37]), the PNW has not garnered similar focus on land–atmosphere contributions to its temperature variability and their potential changes.

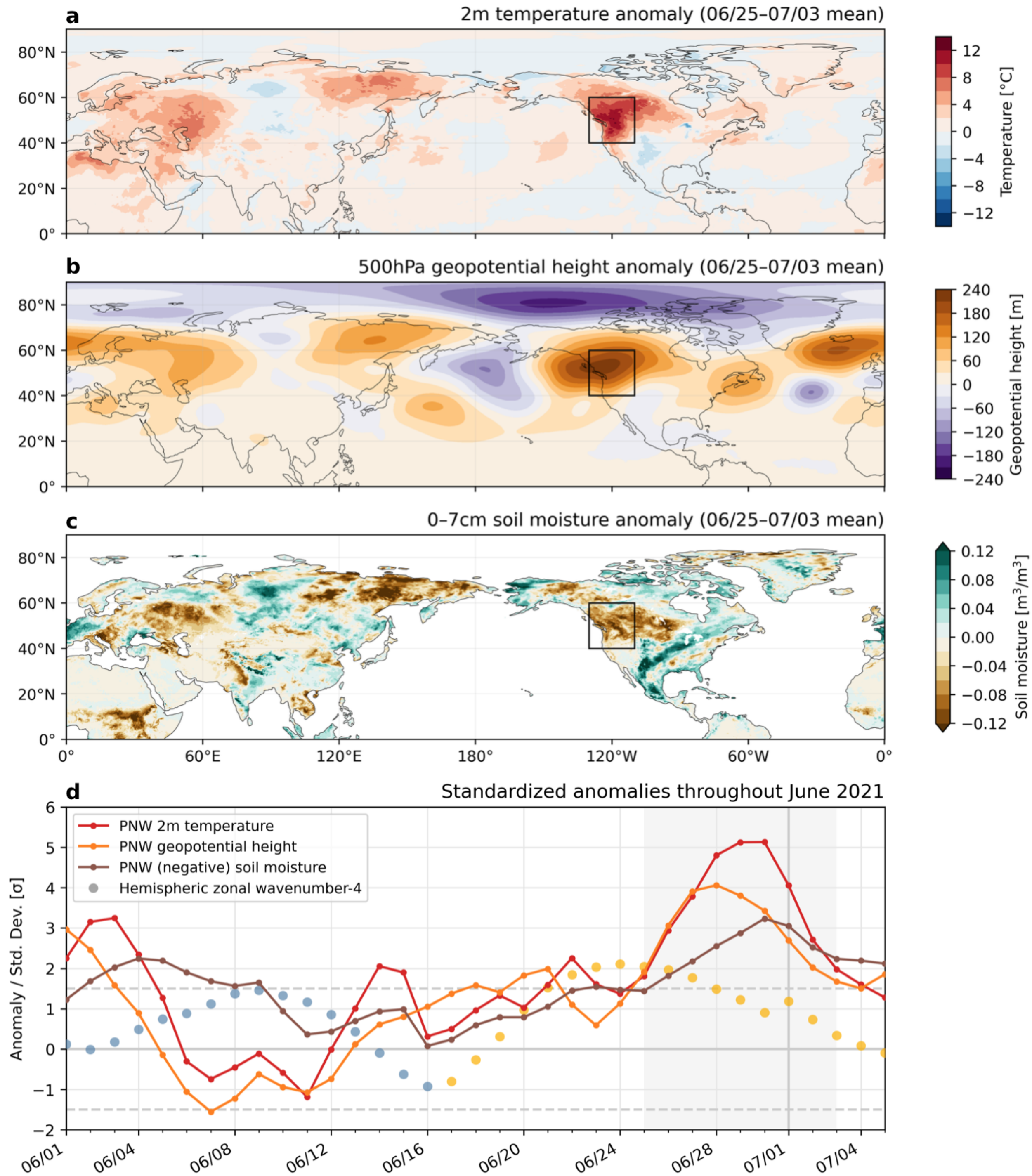

Fig. 1: Timing and location of the PNW heatwave and its associated atmospheric dynamical and land-surface conditions. Northern Hemisphere a) *Temperature,* ***b)*** *geopotential height, and* ***c)*** *soil moisture anomalies during the 2021 PNW heatwave (June 25–July 3), and* ***d)*** *their evolution throughout June averaged over the PNW (black box in* ***a-c)****; 40–60°N, 110–130°W; land temperature only). During the heatwave, much of the PNW experienced extreme anomalies in temperature, geopotential height, and soil moisture exceeding 5, 4, and 3 standard deviations from their 1981–2010 means.* ***d)*** *also shows the amplitude of a zonal-wavenumber-4 disturbance*

in the midlatitude upper-atmospheric circulation, colored blue when in negative phase and yellow in positive phase (see Methods). This wave corresponds to 4 regions of positive (alternating with 4 negative) geopotential height anomalies encircling the hemisphere, visible in ***a–c)*** *with associated temperature and soil moisture anomalies affecting the PNW, central Eurasia, and Northeastern Siberia. See Fig. S2 for a detailed perspective on the evolution of atmosphere dynamical aspects.*

Unprecedented PNW heat conditions and contributing factors

Anomalous near-surface temperatures during the PNW heatwave were accompanied by extremely high geopotential height and exceptionally low soil moisture. The regionally-averaged 2-meter temperature anomaly over land exceeded 5 times its daily standard deviation over 1981–2010 (from ERA5 reanalysis; see Methods), while geopotential height and soil dryness anomalies exceeded 4 and 3 of theirs (Fig. 1d). The PNW experienced at least seven days exceeding the 99th percentile (1981–2010) in each of these variables (Fig. S1). However, this analysis of a large region (40–60°N, 130–110°W), capturing the broad-scale meteorological factors influencing the event rather than focusing on its most severe hotspots, may understate local severity: in some areas, 9-day-averaged (June 25–July 3) temperature exceeded 12°C above normal.

The PNW was not the only anomalously hot region during this period: a hemisphere-wide pattern of anomalies extended from the land surface into the mid-atmosphere (Fig. 1a–c). Central Eurasia and northeastern Siberia both experienced warm anomalies, dry soils and high geopotential heights; the North Atlantic constituted a fourth high-geopotential-height region. With alternating cool, wet, and low-height regions, this pattern comprised a circumglobal wavenumber-4 disturbance (four peaks and troughs in each variable encircling the hemisphere; see Fig. S2 for further details), a pattern historically associated with North American wildfires[38]. A wavenumber-4 upper-atmospheric circulation anomaly (see Methods) was established since June 19 (before the heatwave), and strongly amplified ($>1.5\sigma$) since June 21 (Fig. 1d, Fig. S2). Accordingly, in late June the jet stream assumed a persistent "wavy" configuration with strong meridional wind meanders (Figs. S2, S3)—exhibiting a zonal-mean wind and temperature fingerprint for amplified planetary-scale waves that some evidence suggests may become more frequent with warming[24,25,39]. Further, convection in the western subtropical Pacific may have helped excite a late-June Rossby wavetrain extending towards North America that locked phase with the existing hemispheric wave, amplifying the PNW's geopotential height and temperature anomalies and perhaps also strengthening the hemispheric wave (Fig. S2), suggesting an important role for atmospheric dynamics in this event.

However, during the heatwave the PNW experienced markedly stronger temperature and height anomalies than other nodes of the hemispheric wave, despite similar soil moisture anomalies (compare Fig. 1b and 1c). Additionally, regional temperature continued rising during the event after geopotential height had peaked, mirroring the direction of soil moisture anomalies (Fig. 1d, Fig. S1). These observations suggest a potential role for both shorter-term atmospheric dynamics and two-way land–atmosphere feedbacks in amplifying and prolonging the PNW heatwave.

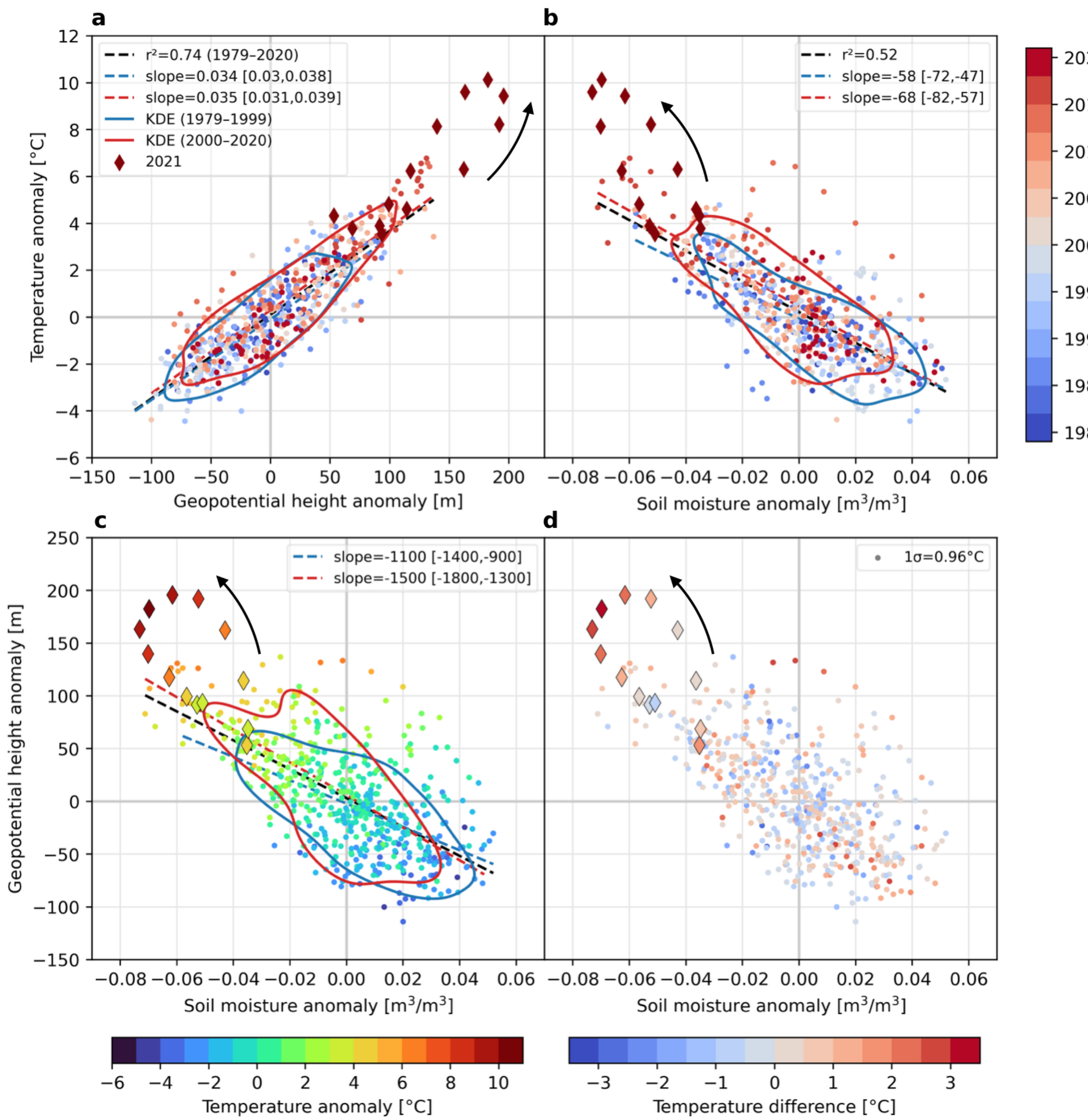

***Fig. 2: Nonlinear interactions of common drivers and their long-term trends. a)**: 3-day running means of PNW-mean 2m temperature versus 500hPa geopotential height anomalies, centered on each day from June 23–July 5 (maximizing on June 30), colored by year (1979–2020). Dark red diamonds show 2021 values; the arrow indicates their temporal evolution and the historical linear regression between the variables in black. Red and blue dashed lines show regressions over 1979–1999 and 2000–2020 with 95% confidence intervals provided in legends. Red and blue curves illustrate the 0.5 contour of a KDE of the variables' 2-dimensional distribution for each of the periods. **b–c)**: same as **a)** for soil moisture versus temperature anomalies and versus geopotential height anomalies; markers in **c)** colored by temperature anomaly. **d)**: same as **c)** but dots colored by the difference between the observed (colors in **c)**) and predicted temperature for each soil moisture and geopotential height value pair (by multiple*

linear regression; see Fig. S4), indicating that the event's highest temperatures involved nonlinear contributions of ~3°C out of a total ~10°C anomaly.

<u>Nonlinear heat contributions from land–atmosphere interactions</u>

Interactions in the land–atmosphere system likely intensified the heatwave, contributing to a ~3°C nonlinear component (of the total ~10°C peak regional-mean heat anomaly) above the heat accounted for by linear processes (Fig. 2). The heatwave's proximate causes were extreme anomalies in common heatwave drivers—high geopotential height (resulting from wave-wave interaction; Fig. S2), and dry soil, which both exceeded their historical (1979–2020) ranges yet largely followed expected bivariate distribution relationships (Fig. 2a–c), as in simulated record-shattering heatwaves in similar regions[15]. However, the heatwave's peak temperatures markedly exceeded temperature's linear regressions against geopotential height or soil moisture (by 4–5°C), which are otherwise strongly predictive (Fig. 2a–b). A multiple regression, incorporating their simultaneous anomalies, confirms nonlinear temperature amplification maximizing during the event's peak at ~3°C (i.e., increasing ~7°C by ~40%), a ~3σ amplification (Fig. 2c–d). Two-way soil moisture–temperature interactions likely drove these nonlinearities, since the amplification term increased as soils continued to dry, despite geopotential height stagnating and declining (Fig. 2d, Fig. 1d). That the amplification term behaved out-of-phase with geopotential height but in-phase with soil moisture is clearer in daily-mean data (Fig. S5), revealing that the day with strongest nonlinear amplification coincided with the driest soil moisture anomaly (and highest temperature anomaly), but occurred three days after the geopotential height anomaly peaked.

From a spatial perspective, dryness across much of the region from a beginning-June heatwave persisted throughout June, even during cool periods, establishing potential preconditions for land-atmosphere feedbacks (Fig. S6; Fig. 1d). Low evaporative fraction anomalies collocated with many of the event's highest temperature anomalies (primarily non-mountainous interior areas with semi-arid and Mediterranean climates; Fig. S7), further suggesting feedbacks' importance—meanwhile, many such areas have experienced multidecadal summer drying, warming, and temperature variability increases (Figs. S7, S8; see Conclusions). Additionally, since upwind drought can enhance heatwaves via advection[40], dry anomalies east of the PNW (Fig. 1c) may have also provided amplification via strong easterlies (Fig. 1d; Fig. S9). An investigation of the 850hPa-level temperature budget during this event substantiates that land-atmosphere processes likely amplified the heating, especially where and when it was strongest (Fig. S9), though further analysis is needed to link 850hPa-level behavior directly to surface processes.

Furthermore, ongoing regional trends favor the nonlinear behavior amplifying the heatwave—thus while 2021's extreme heat was unprecedented, it was nevertheless mechanistically linked to local climate change. First, the driver variables' distributions have individually shifted towards 2021's conditions: late-June–early-July temperature, geopotential height, and soil dryness increased over 1979–2020, with trends accelerating over 1991–2020 (Fig. S10, 11). Consequently, these variables' largest historical extremes tend to occupy more recent years (Fig. 2a–b). Second, bivariate distributions combining these variables have shifted towards high temperature and geopotential height and dry soils occurring simultaneously (Fig. 2a–b, visually comparing KDE contours). Notably, historical extreme temperatures approaching 2021 conditions have also tended to be displaced above the linear driver regressions (Fig. 2a–b). Indeed, while bivariate distribution shifts have primarily followed their underlying regressions, the slopes describing the temperature and geopotential height relationships with soil moisture have strengthened (with probability 71% and 98%, respectively, via bootstrapping), indicating magnified temperature and geopotential height anomalies relative to soil moisture anomalies (Fig. 2b–c). Temperature–height density contours also potentially suggest a changing relationship in the distribution's positive extremes, despite the unchanging linear relation (Fig. 2a), suggesting a change specific to heatwave mechanisms. While these conclusions hold over all of June-July (Fig. S5), we note that late-June–early-July has exhibited especially pronounced trends in these variables and their variabilities (Fig. S11), perhaps reflecting advancing summer onset[41].

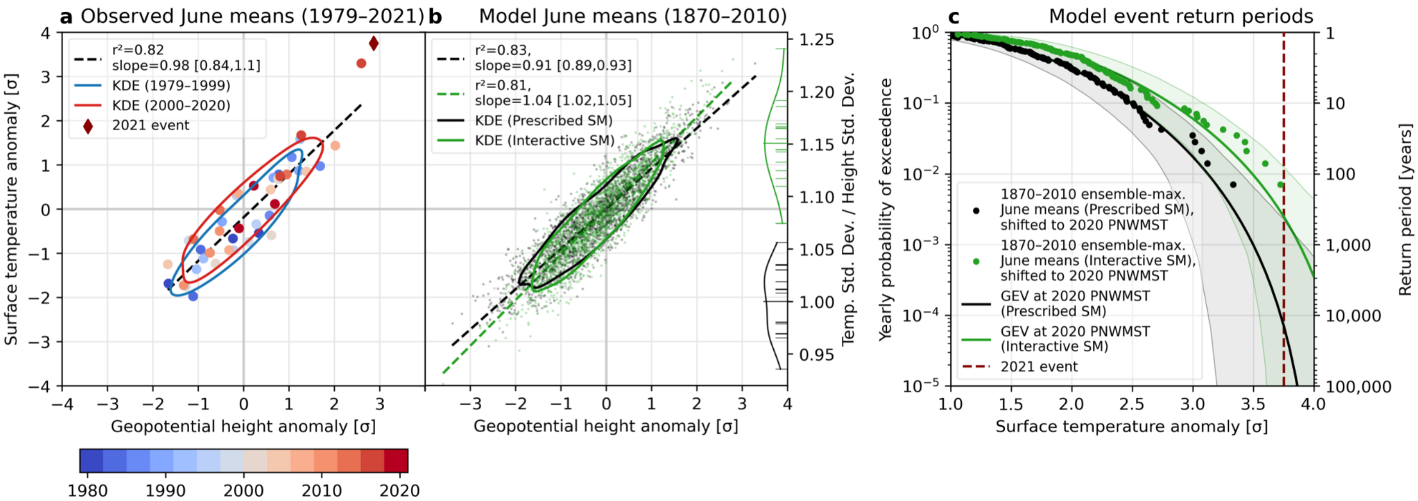

Fig. 3: Modeled PNW monthly temperature variability and extreme event return periods, with versus without soil moisture interaction. *June-mean PNW-mean surface temperature versus 500hPa geopotential height anomalies (standardized), from* ***a)*** *reanalysis (1979–2021) and* ***b)*** *the CAM5–GOGA model experiment (1870–2010), comparing Prescribed (black) versus Interactive (green) soil moisture ensembles. Regressions and KDE contours (with 1.25x smoothing in* ***a)*** *and showing the 0.3 contour in* ***b)****) are as in Fig. 3.* ***b)*** *also compares (right y-axis) the ratio of each member's geopotential height standard deviation to the Prescribed ensemble-total temperature standard deviation. Longer lines show ensemble-total ratios; curves show KDEs.* ***c)*** *shows exceedance probability and return period as a function of standardized temperature anomaly for GEV distributions (curves) fit to 1870–2010 ensemble-maximum June means and empirical return periods (dots). The June 2021 temperature anomaly (~3.75σ) is ~35-fold more likely (~400-yr vs. ~14,000-yr return period) with interactive soil moisture.*

<u>Role of soil moisture in amplifying PNW temperature extremes</u>

Using a model experiment tailored to evaluate the role of soil moisture in climate, we determine that in the PNW, soil moisture–atmosphere interactions likely make monthly-scale temperature extremes of June 2021's magnitude many times more probable. We force a climate model with historical (1870–2010) sea surface temperatures, both with and without soil moisture interactivity (hereafter, Interactive and Prescribed ensembles), and we compare June-mean surface temperature model output with observations (2-meter temperature was not available). We first confirm that the observed June-mean 2021 surface temperature was extreme (Fig. 4a), with monthly temperature reaching ~3.75σ and exceeding its regression against geopotential height. In the model (standardized for comparison with observations; see Methods), we find that soil moisture interaction significantly increases the ratio of monthly temperature variability versus geopotential height variability between ensembles in total (by 15%), and across all members individually (Fig. 4b, right axis). Consistent with previous research[42], temperature variability increases modestly in Interactive members, accompanying strongly increased mean temperature (Fig. S12). Accordingly, the height–temperature regression slope across all member-months is significantly steeper in Interactive (by 14%), while both lie within the confidence interval of the observed slope (Fig. 4b, left axis). However, this linear slope increase may underestimate changes toward the distributions' tails, i.e. during extremes (Fig. 4b, KDE contours).

Consequently, the likelihood of June 2021's standardized temperature anomaly significantly increases when soil moisture interacts with the atmosphere. Generalized Extreme Value (GEV) distributions are fit to each ensemble's yearly ensemble-maximum June-mean temperature anomaly (see Methods), and their location parameters are nonstationary in 5-year-smoothed annual PNW-mean surface temperature (PNWMST). We use PNWMST as a covariate to account for differing PNW mean climate responses to global temperature between model configurations. Estimated empirical return periods are overlaid on the model curves, with each observation shifted by the GEVs' location parameter dependence on PNWMST. Fits and observations for each ensemble can thus be compared at a consistent baseline: at 2020's PNWMST the GEV models estimate a ~35-fold increase (95% CI: 0.07–700,000) in the likelihood of 2021's observed monthly anomaly between Prescribed and Interactive SM ensembles, transforming from an extremely unlikely ~15,000-year (440–∞) event to a ~410-year (80–∞) event. Overlaid empirical return periods suggest that GEV-derived return periods may conservatively estimate particularly severe events. Qualitatively similar results are found if two- or three-year GEV block sizes are used, or if all JJA months are used instead of just June (not shown).

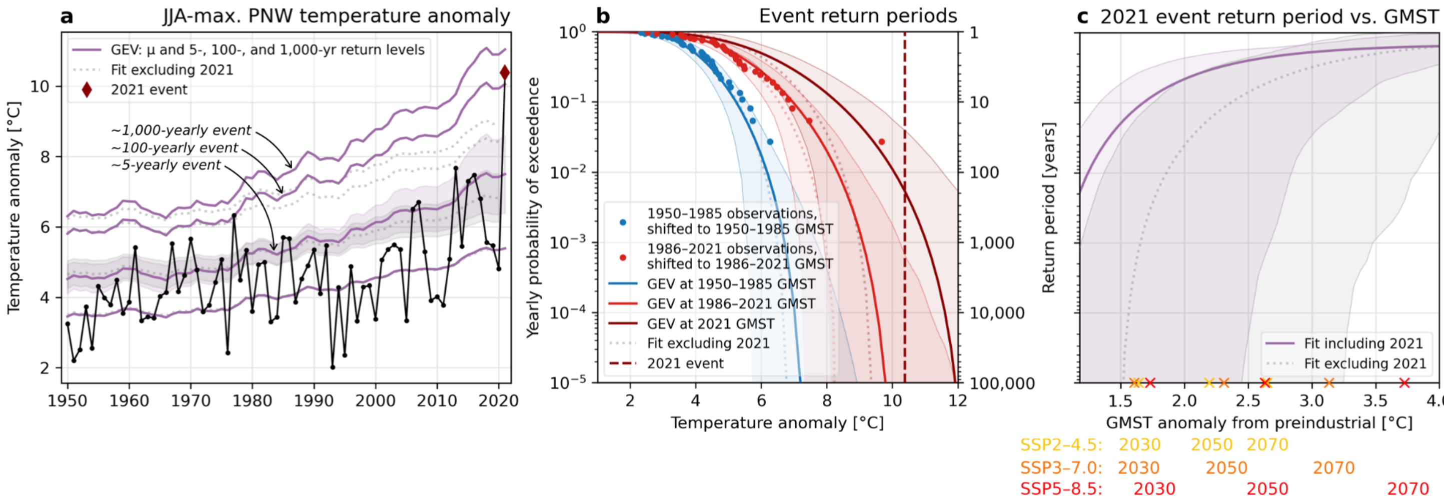

Fig. 4: 2021 heatwave likelihood estimates over recent decades and under future emissions pathways. a)*: A GEV distribution fit to yearly June–August (JJA)-maximum daily-mean PNW-mean 2m temperature overlaid on observations, both including (purple) and excluding (gray dotted) 2021's event, plotting the location parameter (μ) and 5-, 100-, and 1000-year return period temperature levels (5-year return level bootstrapped 95% confidence interval shaded).* ***b)****: return periods of temperature anomalies for historical periods 1950–1985 and 1986–2021 (fits are evaluated at and observations are shifted to the period-mean GMSTs), and estimating a ~200-yr return period by 2021.* ***c)****: GEV fits evaluated as a function of GMST, providing likelihood estimates for a future analogous event under different emission pathways (CMIP6 multimodel-mean warming trajectories are displayed for reference). Future probabilities far exceed those estimated until today: the event may become a 10-year event before 2050 in even an intermediate emissions scenario (SSP2-4.5).*

Increasing event likelihood driven by climate change

Recent climate change has rapidly increased the likelihood of the 2021 heatwave: over the past 70 years, such an event has multiplied in probability from virtually impossible to a multi-hundred-year event (Fig. 5). As above, we apply GEV analysis, a targeted approach for estimating extreme value statistics and an established method for attributing climate extremes to anthropogenic warming[43–45]. We note, however, that assessing the probability of this event in temperature alone—despite its multivariate extreme characteristics—likely conservatively estimates its increasing likelihood as a compound event, given simultaneous trends in other variables such as soil moisture.

First, we find that the PNW has experienced not only shifting mean temperatures but also changing variability since 1979: daily-mean June–July temperature anomalies have displayed positive and increasing skewness both regionally-averaged (Fig. S14) and across many within-region areas (Fig. S8). While station-based daily-maximum and -minimum temperatures during July–August have shown small skewness in the PNW and not displayed strong historical increases[46], here we highlight an earlier summer period and daily-mean temperatures. We further note that research has projected future modeled temperature skewness increases under CO_2 forcing in the PNW, likely linked to soil moisture interaction[47].

We apply GEV analysis to yearly-maximum June–August (JJA) daily temperatures extending back to 1950, to maximize sample size and robustness, with both location and scale parameters nonstationary in 5-year-smoothed global mean surface temperature (GMST; see Methods; stationary scale parameter results are shown in Fig. S15). Results reveal drastic historical changes in heatwave probabilities: a hypothetical daily 8°C regional temperature anomaly is estimated to have been virtually impossible in the 1950–1985 climate, but has become a ~50-year event in the climate since 1986 (Fig. 5b). Similarly, the 2021 heatwave (a ~10.4°C peak anomaly, far exceeding the historical range) was virtually impossible even at the average global temperature over 1986–2021 (return period 95% CI: 1,500–∞), but by 2021 has become a ~200-year event (25–∞)—thereby experiencing an infinite increase in probability (at least ~13-fold). Its probability increase since 1950–1985 is likewise infinite (at least ~500,000-fold). Furthermore, the probability of an event exceeding 2021's magnitude will increase rapidly under further-increasing GMST—projected to recur ~10-yearly before 2050 even at the warming of SSP2-4.5, a 'moderate' emissions scenario (before 2070 if excluding 2021 from the fit; Fig. 5c).

Fig. 5 shows GEV fits both including 2021's heatwave as well as excluding it. In including 2021, we follow Van Oldenborgh et al.[44] and Philip et al.[45,48], assuming 2021's observation is drawn from the same distribution as historical observations, since the study region was not selected solely to maximize local extremity but rather for a large-scale regional perspective, reducing (but not eliminating) selection bias. The excluding-2021 fit estimates a finite maximum possible temperature well below the 2021 observation even under current warming (Fig. 5b), questioning its validity. We note that the including-2021 fit is not rejected by a Kolmogorov-Smirnov test (Fig. S13) despite its poor fit in similar analyses[48], which maintained a fixed scale parameter and analyzed a smaller region more concentrated on the extreme. Ultimately, both fits underscore dramatic increases in heat extreme probabilities resulting from gradual warming: in both, a ~1,000-year event in the 1950s would currently resemble a ~5-year event, and has been surpassed multiple times (Fig. 5a). Furthermore, comparing future projections of a 2021-magnitude event, the fits roughly converge, both projecting <10-yearly recurrences by 2.5°C GMST above preindustrial. This threshold only increases to 2.75°C GMST in a fit with stationary instead of nonstationary scale parameter (Fig. S15).

Conclusions

Given the 2021 heatwave's extreme magnitude, an important question is whether it represents a black swan event[16,17], effectively unforeseeable no matter the climate conditions; a gray swan event[18], made plausible by linking to common drivers and even more likely by background warming; or further, an event whose drivers do not act stationarily with respect to a moving background climate but are instead mechanistically altered by climate trends—with event likelihood thereby increasing beyond that induced by a background shift. We first find that, although 2021's event was unprecedented by large margins, it was traceable to common drivers, exhibiting extreme anomalies[15]. Interacting circulation features provided highly anomalous atmospheric dynamical forcing (4σ geopotential height exceedance), and land–atmosphere feedbacks likely amplified the event's severity, contributing to a ~40% nonlinear amplification. Further, however, we also find that the interactions amplifying this heatwave are mechanistically linked to ongoing regional trends in temperature, soil moisture, and geopotential height increasing their likelihood, possibly suggesting a shift in feedback behavior underway in the region compounding background warming.

In contrast to first assessments[48] who concluded that the atmosphere dynamical patterns during this extreme were likely not exceptional, we provide evidence that the interaction of a persistent anomalous wavenumber-4 Rossby wave in the polar front jet and an atmospheric wave emanating from the Pacific likely played a key role in this extraordinary temperature anomaly (Fig. 1, Fig. S2). Further research is required to assess if the conditions for such waves are becoming more likely, e.g. by strengthened waveguidability[49] of the polar front jet due to amplified land warming at high latitudes[50,51] or increased convective activity in the tropical Pacific.

Warming-forced midlatitude land drying[34,35] could shift wet regions, such as much of the PNW, towards a transitional climate between wet and dry, possibly strengthening land-atmosphere feedbacks and temperature variability[32]. However, the PNW has received little examination of shifting soil moisture–temperature coupling, despite that some PNW areas already occupy transitional regimes during summer[52,53] and dry soil–heatwave linkages in the region are recognized[54]. Our findings suggest that rapid soil drying (particularly in early July, drying ~7% regionally between 1979–1999 and 2000–2020; Fig. S11) may already be altering extreme heat mechanisms: many of the 2021 heatwave's anomalously hottest temperatures occurred in areas experiencing long-term decreasing evaporative fraction and increasing temperature variability (Fig. S7, 8). Additionally, we find increasing trends in four metrics of the terrestrial component of land–atmosphere coupling in many of the same areas since 1979 (Fig. S8). Notably, land-atmosphere coupling and temperature variability increases are strongest where soil moisture is climatologically moderate instead of the driest areas—thus in the PNW, drying may increase temperature variability more than in already-arid regions like the southwestern US[32]. In accordance with recent research demonstrating the emergence of heat-amplifying land–atmosphere feedbacks in regions not historically experiencing them[31] and, moreover, projections of widespread midcentury soil moisture regime shifts including the PNW[36], we suggest that the 2021 heatwave may represent an alarming manifestation of a shifting regime across much of the PNW from wet to transitional climate, making such events more likely through strengthened soil moisture–temperature coupling—however, further research is required to substantiate this.

Our results underscore that even gradual warming over recent decades dramatically transformed the character of this event. Since 1950, an anomaly of this magnitude has been refigured from virtually impossible to plausible and somewhat expected, with a hundreds-of-years return period. Continued warming will cause the probability of an equal or stronger event to rapidly increase, potentially becoming a ~10-year occurrence with 2°C warming above preindustrial, potentially reached by 2050 in even a ‘moderate’ emissions scenario.

Methods

Reanalysis data

All reanalysis data are provided by ECMWF's ERA5[55], obtained at ~0.25° and 6-hourly resolution; all analyses involve daily or longer means.

Model data

The model experiment we present in Fig. 3b–c is referred to as CAM5–GOGA[56,57]. The atmospheric model is CAM5 (National Center for Atmospheric Research [NCAR] Community Atmosphere Model, version 5.3), which is the atmospheric component of the Community Earth System Model, version 1.2[58], at T42 spectral (~2.75°) resolution. The GOGA (Global Ocean Global Atmosphere) experiment involves forcing 16 members of CAM5 with historical monthly sea surface temperatures (HadISSTv2[59]) over the period 1856–2014. Greenhouse gasses (GHGs) and radiative forcing are fixed (GHGs at 2000 levels), and sea ice concentration follows HadISSTv2. One 16-member ensemble allows soil moisture to interact with the atmospheric model, while the other prescribes soil moisture as the monthly climatology over 1950–2015 at each location derived from all members. We begin analysis in 1870 to avoid model spin-up effects, and discard two full members and all years after 2010 due to data discrepancies, resulting in a 14-member by two-ensemble by 141-year dataset. For comparison with reanalysis, we standardize all anomalies, based on the whole period for all grouped Prescribed members, for model data, and based on the 1981–2010 climatology for reanalysis data. We note a caveat that in this experimental design, water is not strictly conserved in the Prescribed SM case, as noted for GLACE-CMIP5 models[42,60,61]—however, an analysis of the resulting water balance perturbation in the CESM model[60] shows the perturbation is small in the PNW relative to other global regions.

Future GMST trajectories in Fig. 4c are based on decadal-mean CMIP6 multimodel mean anomalies from the preindustrial period (1850–1900), using all models available (42 for SSP2-4.5, 35 for SSP3-7.0, and 44 for SSP5-8.5[62].

Planetary wave analysis

We apply a Fourier transform to 15-day running means of 300hPa meridional wind averaged over 37.5–52.5°N, obtaining amplitudes and phase positions of the circulation components of zonal wavenumbers *k*=1–9. Amplitudes are compared with a monthly climatology over 1981–2010 to calculate standardized anomalies.

Extreme value analysis

Our estimates of likelihoods and return periods of extreme temperatures are derived by fitting Generalized Extreme Value (GEV) distributions to both observational (ERA5) and model data, following widely-used procedures designed for investigating extreme events rather than the body of distributions[43–45,48,63]. For all GEV analysis we use the Python package *climextRemes*[64].

For observations, we first calculate the maximum daily-mean PNW-mean temperature anomaly over June–August (JJA) each year since 1950 using the ERA5 back extension[65]. We fit a GEV function with nonstationary location and scale parameters to both datasets 1950–2020 and 1950–2021. Both nonstationary parameters use 5-year smoothed annual-mean GMST as a covariate, provided by NASA's GISTEMP[66]. For both datasets, the addition of nonstationarity in the scale parameter improves the model fit over a stationary-scale fit, based on a Likelihood Ratio Test (significant at the $p<0.025$ level for the 1950–2021 dataset, and with $p=0.267$ for 1950–2020; Table S1), and on comparing Kolmogorov-Smirnov test statistics (Fig. S13, 15). A comparison of the GEV fits against empirical temperature return periods in 1950–1985 vs. 1986–2021 visually supports a potential widening (Fig. 4b, Fig. S13). Moreover, as such nonstationarity would reflect a variability change rather than a mean shift, it may be physically justified by observed increases in regional temperature skewness since 1979, particularly in June (Fig. S8, 13). The shape parameter, however, is kept stationary: it corresponds to the shape of the GEV's upper tail, and a negative value (as found) indicates a fixed upper bound determining the highest temperature anomaly possible at a given global temperature, which is likely to be true based on energetic constraints.

For model data, we calculate the maximum June mean among all 14 ensemble members for each year. We fit a GEV to these ensemble-maximum June means over 1870–2010, with nonstationary location parameter using 5-year smoothed annual PNWMST as a covariate. Nonstationarity in GMST does not significantly improve the fits over total stationarity, while nonstationarity in PNWMST does ($p<0.1$ and $p<0.001$ for Prescribed and Interactive SM ensembles, respectively). Fits are presented in Fig. 3 evaluated at 2020's annual PNWMST (calculated from ERA5) to provide present-day estimates of the 2021 event return periods without including its information in the PNWMST itself. We repeat the analysis with block size of 28 and 36 member-years (maxima over 2 and 3 years of data, respectively) and find fairly consistent results but with drastically increased uncertainty as the total block number decreases.

For all GEV results, 95% confidence intervals surrounding return period curves are shown based on a bootstrapping method, as a non-parametric alternative to a parametric method using asymptotic standard errors. Bootstrapping is done with a block size of one year, and is obtained by resampling (drawing n out of a given n datapoints with replacement, for 5,000 iterations for model data and 1,000 iterations for observational data) and calculating the desired output (i.e., return periods as a function of return level) for each iteration. The displayed 95% confidence interval bounds are taken as the 2.5th and 97.5th percentiles of the resulting return period curves. (Bootstrapping in Fig. 2 is also done with a one-year block size and 5,000 iterations.)

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Data Availability

All ERA5 output used in this study is available from ECMWF at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels. All CAM5_GOGA output used in this study is available at https://doi.org/10.5281/zenodo.5800726. CMIP6 multimodel mean warming levels are available at https://doi.org/10.5281/zenodo.4600695.

Code Availability

All figures were produced using Python v.3.6 (https://www.python.org/downloads/release/python-360/). All code needed to reproduce the main figures is available at https://github.com/sambartusek/pnw_hw_2021.

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Supplementary Information

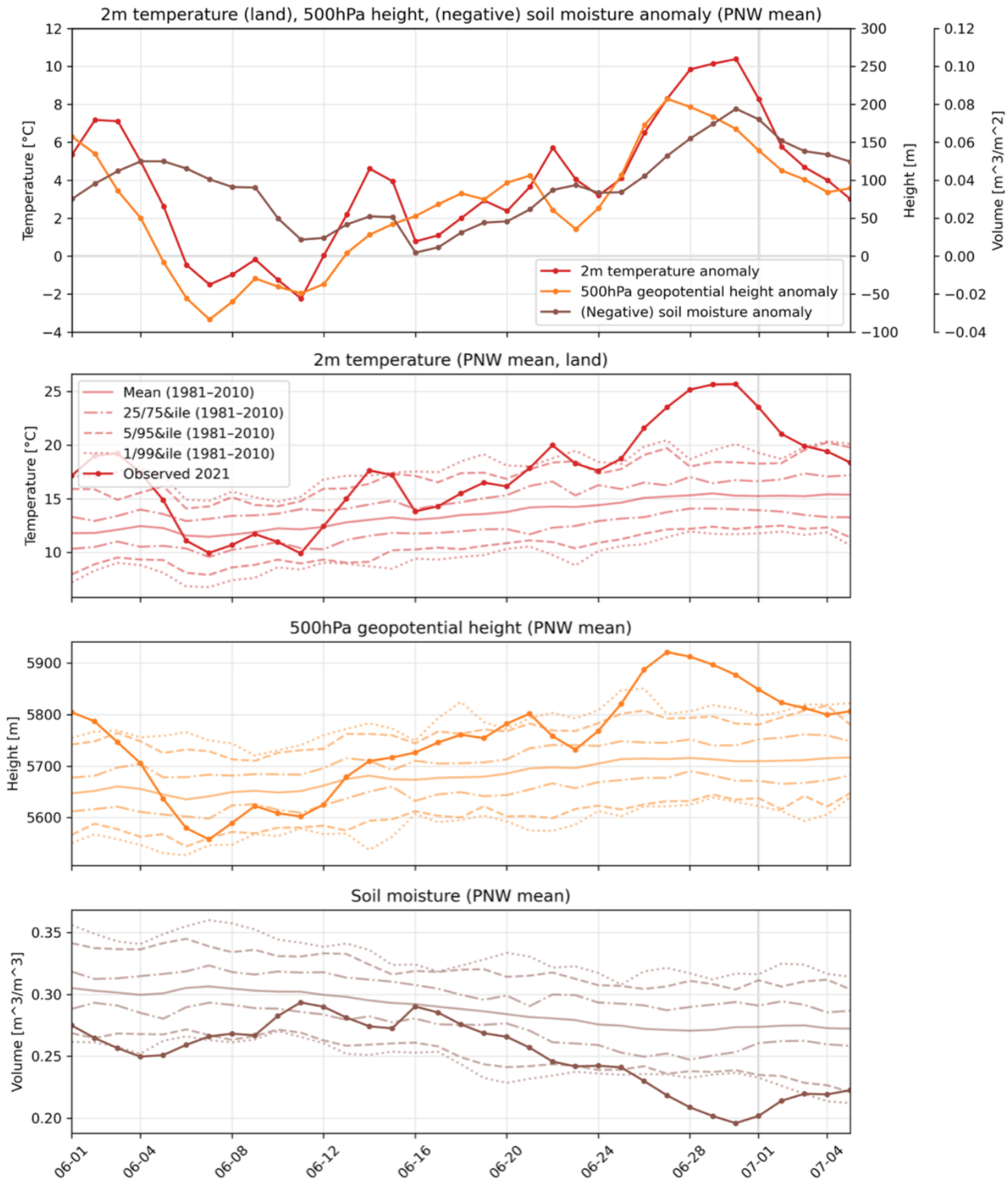

Fig. S1: PNW anomalies and actual values compared with historical distributions. Top: As in Figure 1d, but anomalies are not standardized. **Bottom three:** PNW-mean actual variable values during June 2021 compared with their historical distributions (over 1981–2010).

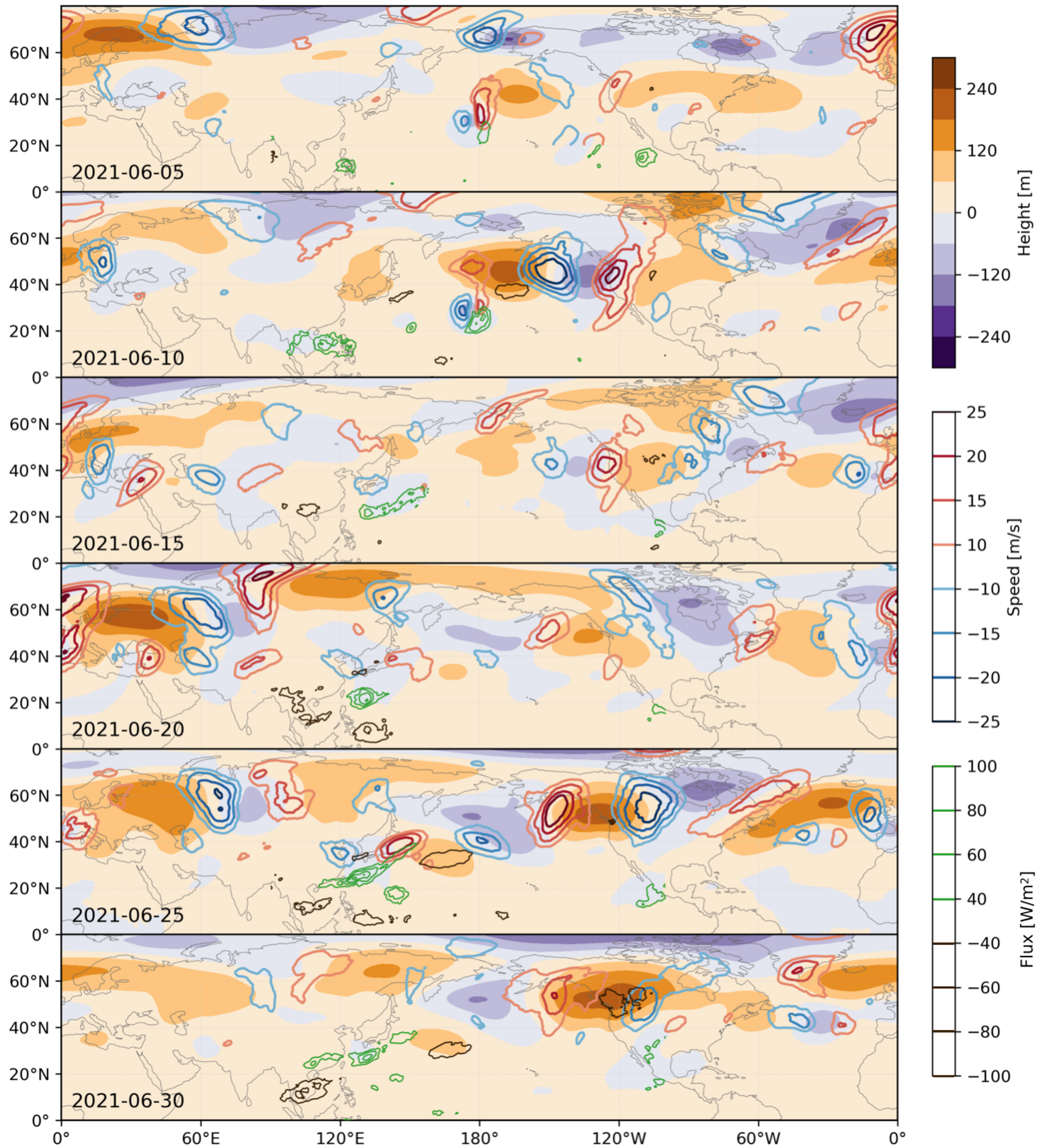

Fig. S2: Atmospheric dynamics during June 2021 leading to the anomalous geopotential heights associated with the PNW heatwave. a-f): 500hPa Geopotential height (filled contours), 300hPa meridional wind speed (red and blue contours), and outgoing longwave radiation (OLR; green and dark brown contours) anomalies averaged over 9-day periods centered on the annotated date. For clarity, the meridional wind field is only shown poleward of 20°N and the OLR field is only shown within 90°E–100°W (roughly the Pacific Ocean). **a)** shows the 9-day mean surrounding 06/05, when geopotential heights were high in the PNW accompanying a heatwave, with centers of low and high geopotential height extending westward over the Pacific and forming a tripole. By 06/10 (**b)**) the tripole had expanded longitudinally, placing negative geopotential height over the PNW, and begun to constitute part of a wavenumber-4 pattern in meridional wind and geopotential height encircling the midlatitudes. Over 06/10–06/20 (**c–e)**) this wavenumber-4 pattern moved slightly northward and shifted phase longitudinally, eventually placing high geopotential height over the PNW. Throughout the last two weeks of June (**d–f)**) the wavenumber-4 pattern persisted and amplified, causing extreme temperatures and dry soils in central Europe, Siberia, and the PNW, and was reinforced by a Rossby wavetrain emanating from the subtropical western Pacific.

Anomalous geopotential heights fueled by the interaction of two distinct Rossby waves

Mutually-reinforcing slow- and fast-moving circulation features provided atmospheric dynamical forcing for the heatwave, each carrying potential climate linkages that may result in increased risk of concurrency and associated extreme impacts. First, the planetary wavenumber-4 circulation anomaly persisted during much of June, producing synchronized climate extremes throughout the hemisphere, and dramatically amplified in late June boosting temperatures and drying soils in the PNW. Accordingly, in late June the jet assumed a persistent anomalous "wavy" configuration with strong meridional wind meanders (Fig. 2, Fig. S3). Its northern excursions, encircling anticyclonic anomalies, formed an anomalous polar jet that together with the subtropical jet created a midlatitude waveguide, and zonal-mean temperature anomalies then peaked where zonal wind gradients were strongest (~60°N; Fig. S3). These conditions represent a fingerprint for planetary wave amplification that some evidence suggests may become more frequent with warming, and may be connected to a weakening meridional temperature gradient[24,25,39]. Secondly, convection in the western subtropical Pacific (south of Japan) generated negative outgoing longwave radiation (OLR) anomalies, exciting a late-June Rossby wavetrain extending towards North America. This synoptic wavetrain locked phase with the existing hemispheric wave, amplifying the PNW's geopotential height and temperature anomalies and perhaps also strengthening the hemispheric wave (Fig. S2). Recent findings show that typhoons undergoing extratropical transition south of Japan can heighten PNW wildfire risk by inducing downslope easterly winds across the Cascade Range that adiabatically warm and dry[67,68], as demonstrated during 2021[48]. A projected northward shift in typhoon tracks in this region under global warming[69–71] could increase the risk of such events.

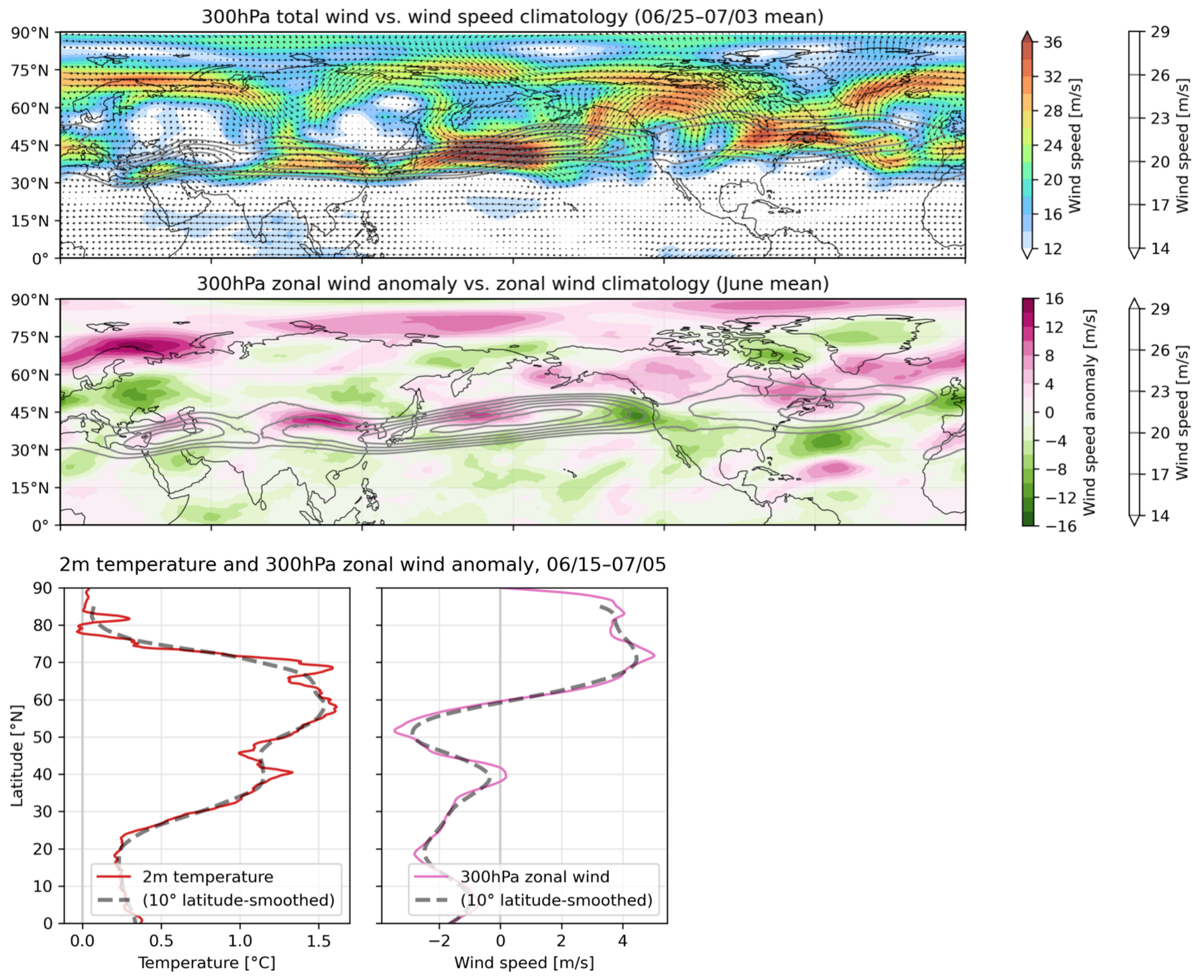

Fig. S3: Total wind, zonal wind, and temperature anomalies in summer 2021. Top: anomalous total wind over 06/25–07/03, with direction in vectors and magnitude in vectors and color, compared with climatological total wind speed in gray contours. **Middle:** June-mean anomalous zonal wind in color compared with climatological zonal wind in gray contours. **Bottom:** 06/15–07/15-mean 2m temperature and zonal wind anomalies and their 10-degree smoothings.

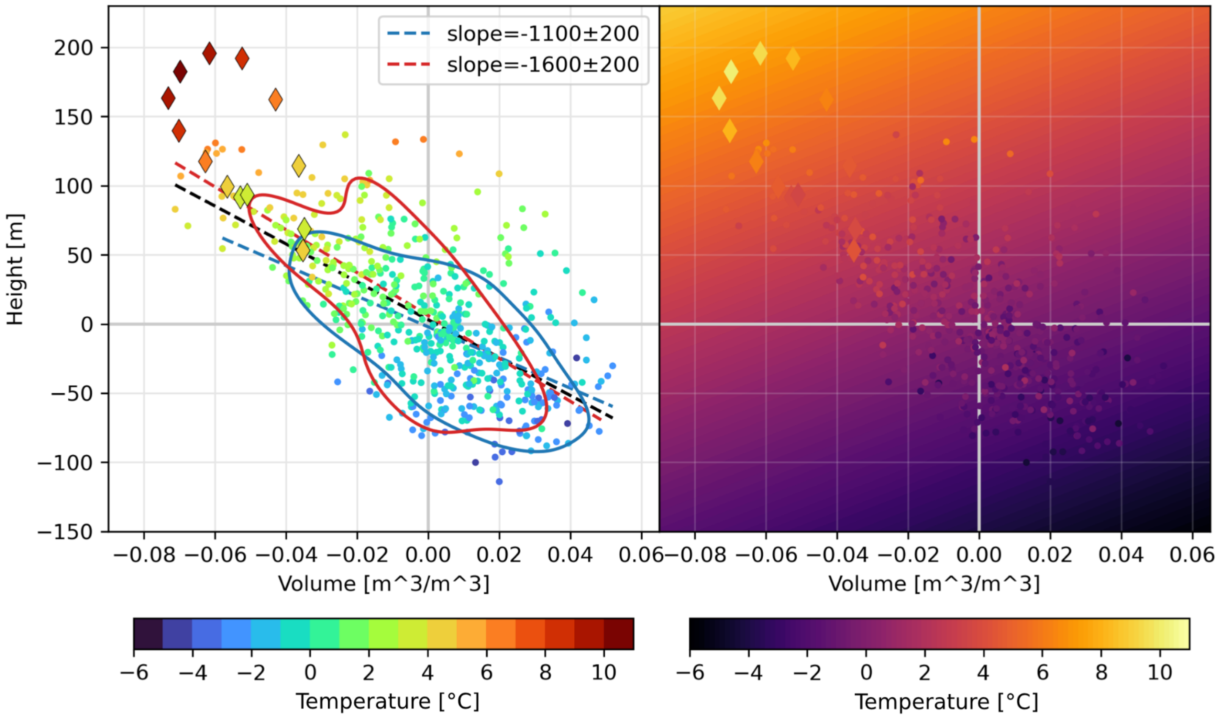

Fig. S4: Comparison of observed temperature versus multiple linear regression prediction. Left panel: copied from Figure 3 for ease of interpretation. **Right panel:** in the background gradient, the temperature modeled by a multiple linear regression based on both soil moisture and geopotential height anomalies, with the regressions calculated from the 3-day mean data over 06/23–07/05 from 1979–2020. The point data show observed temperatures (i.e., the same values as shown in the left panel, but according to a different colormap), with dots for 1979–2020 and diamonds for 2021. The difference between the observed temperature (scattered point data) and the predicted temperature (the background gradient value underlying each scattered point) is what is shown in Figure 2d.

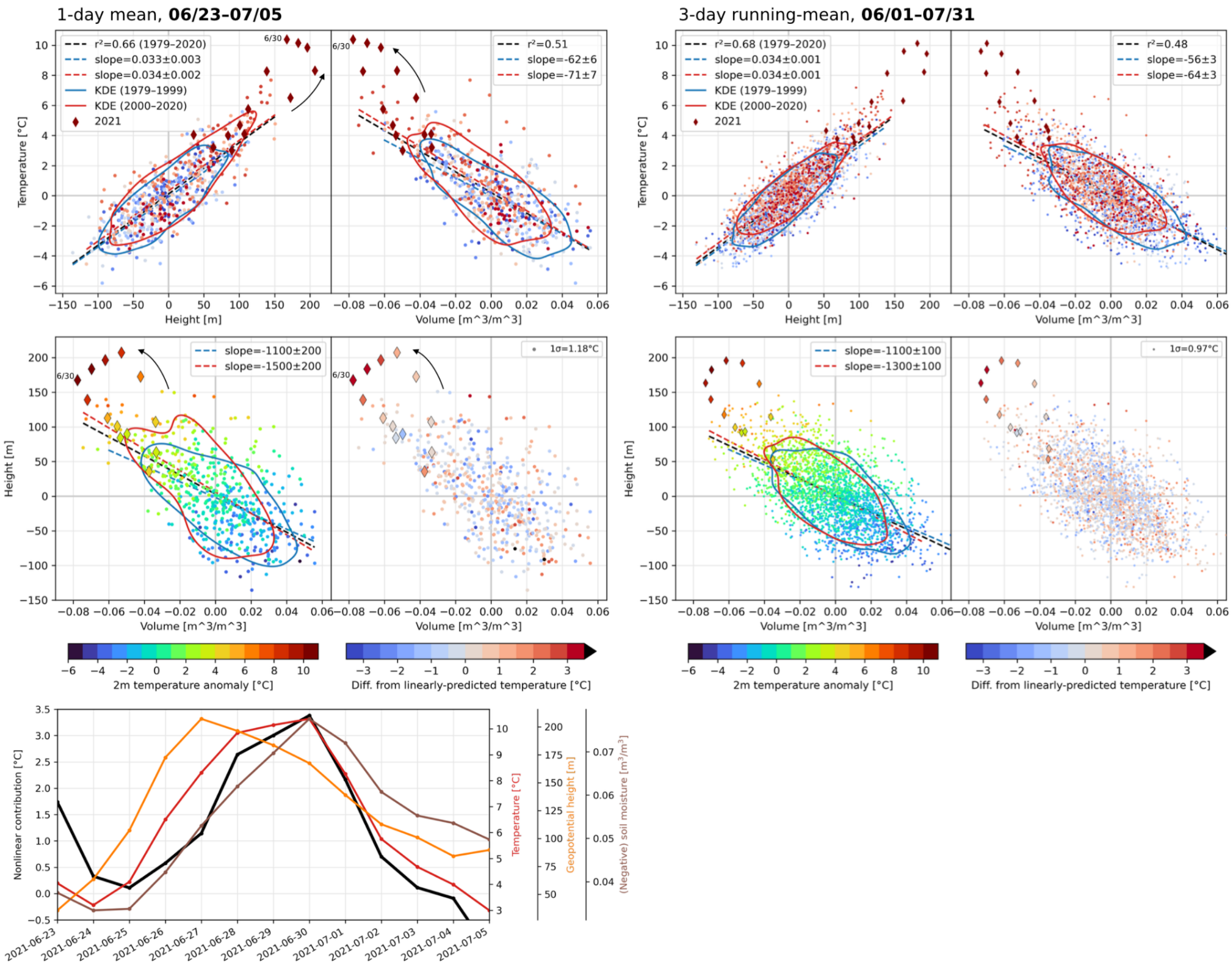

Fig. S5: Top: As in Figure 2a–d but for daily mean data over 06/23–07/05 (left) and 3-day running mean data over 06/01–07/31 (right). **Bottom:** daily mean time series of the nonlinear contribution term, temperature, geopotential height, and soil moisture anomalies throughout the heatwave.

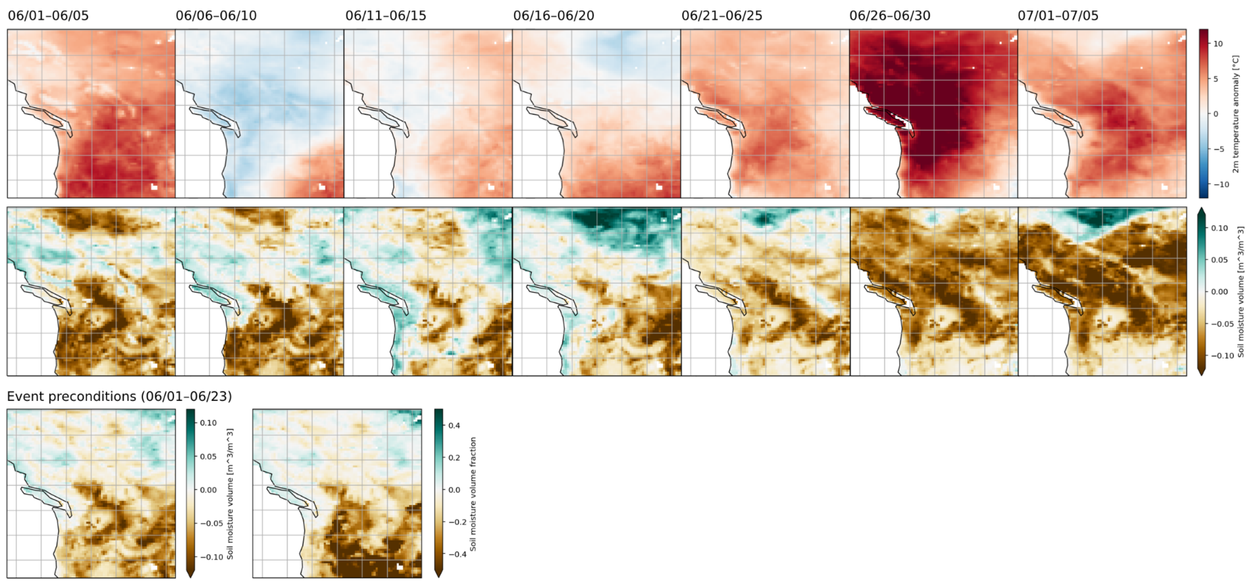

Fig. S6: June evolution of temperature and soil moisture anomalies and soil preconditions for the late-June heatwave. Top row: 5-day means of (land) temperature anomalies over the PNW from 06/01 to 07/05. **Second row:** as in top row but for soil moisture anomalies. **Bottom row:** 06/01–06/23 mean soil moisture anomalies over the PNW (left) and the same data expressed as fraction of climatology (right), emphasizing large fractional anomalies where soil moisture is climatologically low and therefore non-fractional anomalies are limited in magnitude compared to wetter areas. (I.e., soil moisture anomalies in Figure 1c show comparatively small dry anomalies in the southwest US despite its deep long-term drought, versus the PNW.)

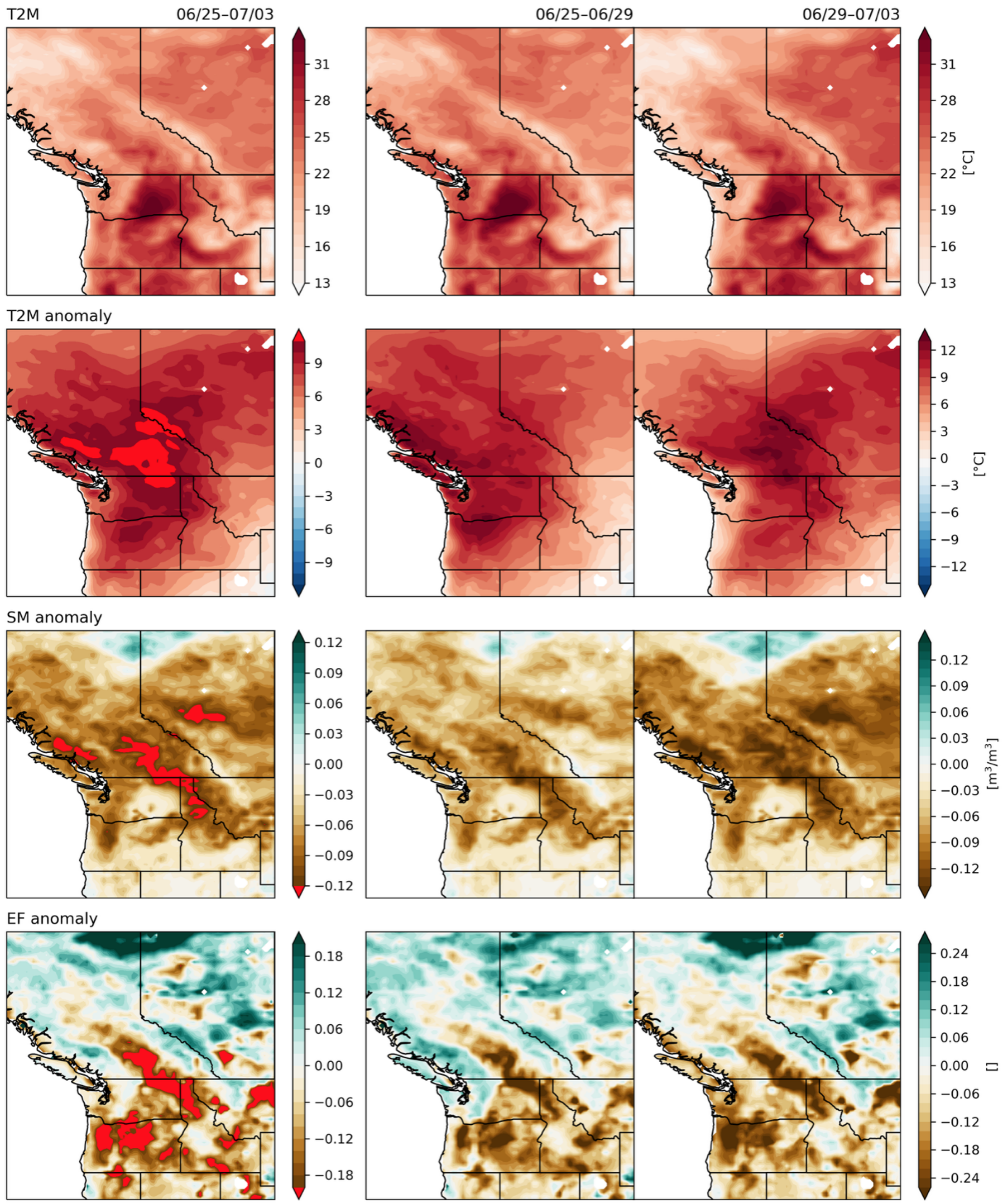

Fig. S7: PNW land-atmosphere anomalies during the 2021 heatwave. Mean conditions over the whole 9-day heatwave period (06/25–07/03; **left column**), its first half (06/25–06/29; **middle column**), and its second half (06/29–07/03; **right column**), for 2m temperature (T2M) (**top row**), T2M anomalies (**second row**), soil moisture (SM) anomalies (**third row**), and evaporative fraction (EF) anomalies (**bottom row**). EF is calculated from daily-mean latent heat flux (LHF) and sensible heat flux (SFH) as LHF/(SHF+LHF). Many of the regions of hottest (absolute) T2M and hottest T2M, driest SM, and lowest EF anomalies during this heatwave overlapped, particularly in the center of the region: across northern Oregon, eastern Washington, northern Idaho, and central southern British Columbia (the Interior Plateau). However, some of the largest T2M anomalies were associated with high EF anomalies instead—mostly in the Coastal and Cascade mountains on the British Columbia coast and the Cariboo and Monashee mountains between British Columbia and Alberta. This pattern is very consistent with climatological daily correlation between EF and T2M anomalies (see Fig. S8): areas where EF and T2M are anti-correlated (both typically and during this event) tend to be warmer, non-mountain areas with relatively low soil moisture and Mediterranean and/or semi-arid climates (i.e., across much of eastern Oregon and Washington (the Columbia Plateau), Idaho, and British Columbia's Interior Plateau. Therefore, overall, throughout the heatwave, the spatial anti-correlation between EF and T2M anomalies was very weak, reflecting the diversity of land types and land-atmosphere coupling regimes across the large region. Overall, the spatial correlation between 9-day-mean (06/25–07/03) EF and T2M during the heatwave was highly significant but very weak, yielding $r=-0.04$ with $p<0.005$. However, where T2M was both anomalously and climatologically high, EF and T2M were more tightly anti-correlated. Masking to retain only land regions under the 850hPa level, the spatial correlation was –0.24, with $p<0.0001$.

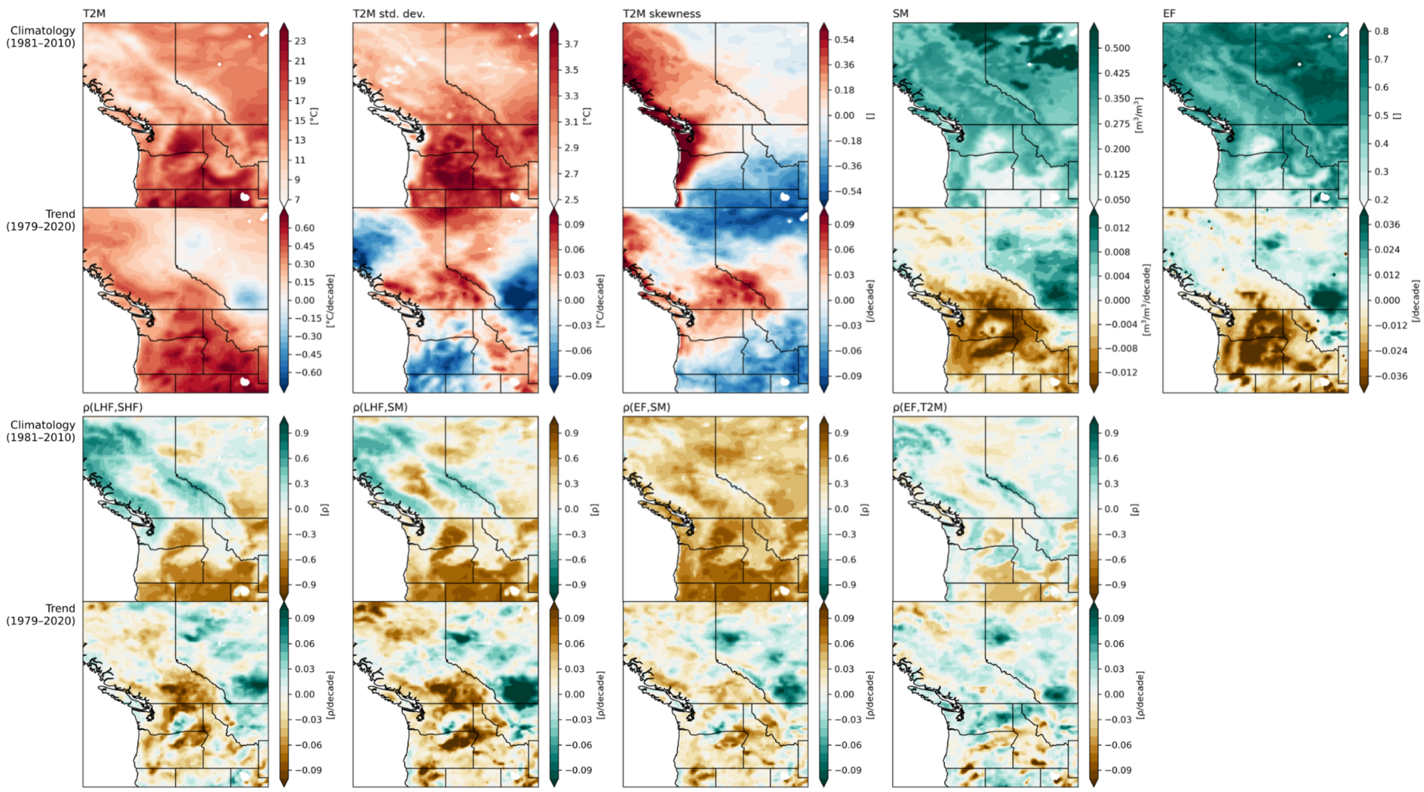

Fig. S8: Climatologies and trends of PNW temperature variability, land surface quantities, and land-atmosphere coupling climatologies and trends. Top row: 1981–2010 June–July climatologies (top panels) and 1979–2020 linear trends (bottom panels) of 2m temperature (T2M), T2M variability, soil moisture (SM), and evaporative fraction (EF). T2M standard deviation and skewness are intra-annual, measuring the within-year variability of daily anomalies (taken from the 1981–2010 daily climatology). EF is calculated from daily latent heat flux (LHF) and sensible heat flux (SHF) as LHF/(LHF+SHF). Climatologies are calculated using only 1981–2010 data. Trends consider 1979–2020 and are presented in per-decade units. **Bottom row:** Climatologies and trends of four metrics of land-atmosphere coupling: correlations between LHF and SHF, LHF and SM, EF and SM, and EF and T2M. At each gridpoint, a correlation climatology is created by taking daily anomalies (from the daily 1981–2010 climatology) for each variable during June–July 1979–2020, removing their 1979–2020 linear trends, and correlating two variables against each other throughout all June–July 1981–2010 days. Correlation trends are determined by calculating correlations within each year (June–July) separately, and finding a linear trend in yearly correlation values over 1979–2020 at each gridpoint. Results are consistent if trends are estimated by subtracting the correlation over 1979–

1999 from that over 2000–2020. The first three correlations represent the terrestrial component of land-atmosphere coupling while ρ(EF,T2M) represents the total feedback pathway. While SM and T2M are nearly everywhere anticorrelated, these correlations show where soil moisture deficit may causally affect T2M. Areas where LHF and SHF are anticorrelated, LHF and SM are correlated, EF and SM are correlated, and EF and T2M are anticorrelated indicate “moisture-limited” regimes with potentially stronger land-atmosphere coupling (as distinct from “energy-limited” regimes where the atmosphere dominantly controls land-surface processes). Such correlation directionalities are typical of “transitional” climate zones between wet and dry: in wet enough areas, soil moisture deficits do not affect evapotranspiration (near-zero ρ(EF,SM)) because a non-limited supply of moisture allows LHF to increase in response to atmospheric heating (positive ρ(LHF,SHF) and negative ρ(LHF,SM))—conversely, if SM is lower, LHF is limited and thus EF (LHF’s proportion of total flux) decreases (positive ρ(EF,SM) and ρ(LHF,SM) and negative ρ(LHF,SHF)). In moisture-limited evapotranspiration areas, decreased EF (i.e., increased SHF partition of total flux) can raise T2M, allowing for positive land-atmosphere feedbacks as raised T2M can further decrease SM, increase SHF, decrease LHF, and decrease EF. Such areas climatologically extend from the drier interior central West, to the Columbia Plateau in eastern Washington, and even into the British Columbia Interior Plateau (bottom row, top panels). Trends over 1979–2020 indicate that much of the PNW is has undergone strengthening in at least the terrestrial component of land-atmosphere coupling—notably, mostly where soil moisture is climatologically moderate as opposed to extremely low (where further drying may instead decrease such correlations), which includes much of BC’s Interior Plateau, much of the Cascade Range region (including Portland and near Seattle) and to the east of the Columbia Plateau. Trends in ρ(EF,T2M) indicate that in some of these areas (mostly in the southern PNW but including some of the BC Interior Plateau), T2M itself has become more coupled to EF, potentially signifying increased feedbacks—but overall, such trends have not conclusively emerged. The spatial pattern of trends toward stronger land-atmosphere coupling correspond relatively well with warming, drying SM, and decreasing EF, and in some places with increasing T2M variability: areas of increasing T2M standard deviation and skewness correspond better to land-atmosphere correlation trends than to SM or EF trends alone. (Increasing skewness is furthermore detectable at the regional level; see Fig. S14.)

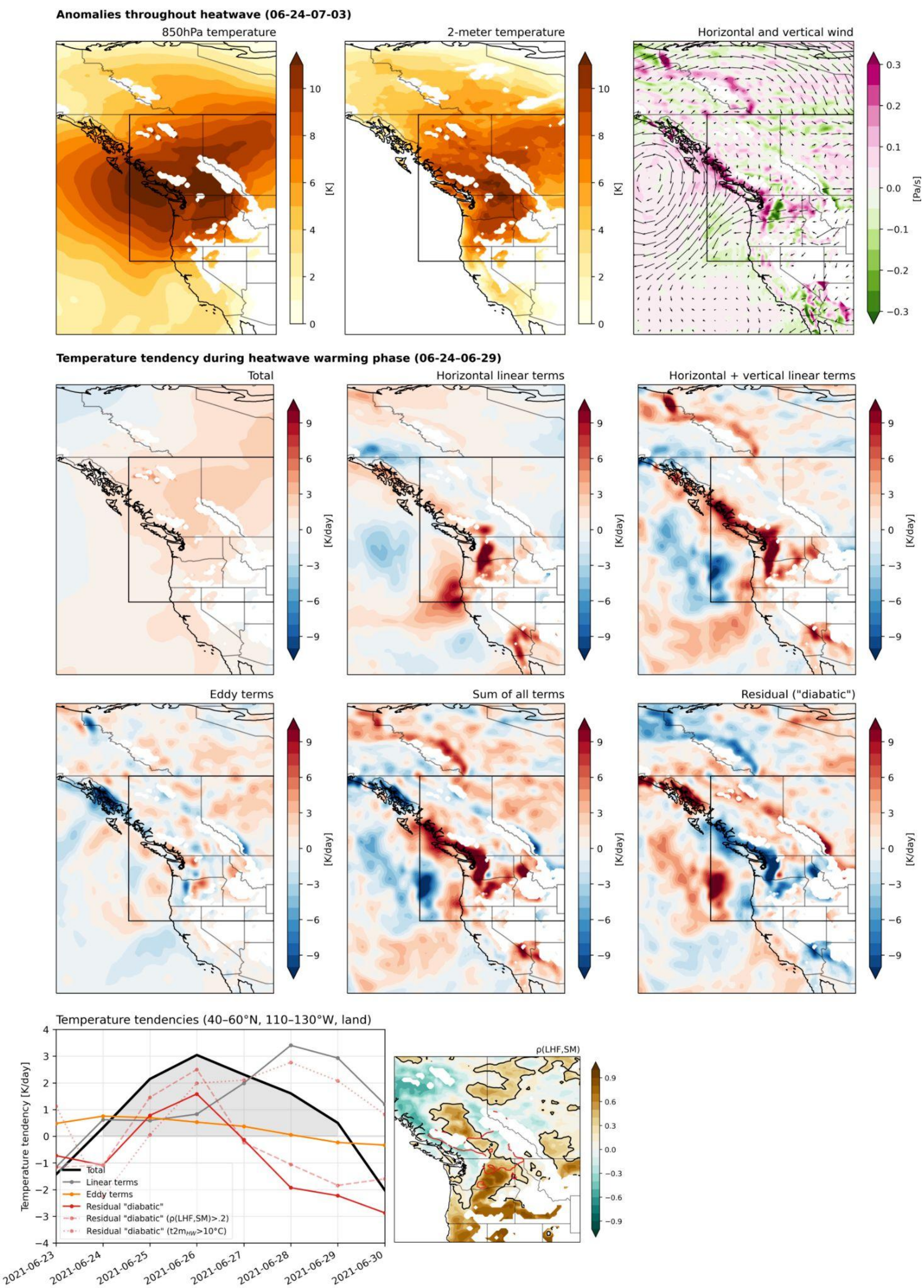

Fig. S9: Temperature tendency budget analysis at 850hPa. Top row: Temperature (at 850hPa and 2 meters) and wind (horizontal and vertical) anomalies averaged during the heatwave

(06/24–07/03). The black box shows the region focused on in the manuscript. **Middle rows:** Spatial patterns of temperature tendency contributions from various (grouped) terms in the temperature budget, conducted at the 850hPa level and averages during the heatwave warming phase (06/24–06/29). The residual "diabatic" term is calculated as the total tendency minus the sum of all non-diabatic terms, and indicates processes not accounted for by the non-diabatic terms that may in part be attributed to land-atmosphere processes. **Bottom row:** Temporal evolution of grouped terms in the budget over the course of the heatwave warming period (06/24–06/29), averaged over the black box in the maps above. Solid lines show the total heating, the sum of all linear non-diabatic terms, the sum of all eddy non-diabatic terms, and the residual term. Additionally, we show the residual term averaged over two sub-regions (broken lines). The dashed line shows the term only where the long-term daily correlation between latent heat flux (LHF) and soil moisture (SM) exceeds 0.2 (designated by the black contour in the map). The dotted line shows the term only where the heatwave-averaged (06/25–07/03) 2-meter temperature anomaly exceeded 10°C (red contour on map). The map background is the same as that shown in Fig. S8, with altitudes above the 850hPa level masked.

Temperature Budget Analysis

We first present a comparison of temperature anomalies averaged throughout the heatwave (06/24–07/03) at both 2 meters and 850hPa, showing similar geographical patterns with the most intense anomalies centered over interior British Columbia and eastern Washington. Horizontal and vertical wind anomalies are also shown, notably displaying easterly anomalies over the Cascades in western Washington and Oregon, accompanied by upwind ascent and downwind descent. Given the complex topography in the region, we next perform a temperature budget analysis at the 850hPa level, using the methodology of He and Black (2016, Heat budget analysis of Northern Hemisphere high-latitude spring onset events, J. Geophys. Res. Atmos., 121, 10,113–10,137, doi:10.1002/ 2015JD024681).

Overall, at the 850hPa level, we find heterogeneous patterns and strong canceling between large terms in the temperature budget equation. Throughout the heatwave warming period (06/24–06/29), horizontal advection clearly contributes to heating along the Cascades but is opposed in many areas by vertical terms and eddy terms, and remains overall slightly negative in the interior British Columbia and eastern Washington plateau regions, where temperature anomalies were highest (both at 2 meters and 850hPa). Adiabatic compression and vertical advection strongly oppose each other in many areas, and when added to the horizontal linear terms, heating is strong along the Cascades and the immediate coastal mountains of British Columbia, but still near zero (and even negative in places) in the interior Plateaus of British Columbia and eastern Washington. Eddy terms are noisy (even at the smoothed spatial scale presented here, with a 4-grid-cell or ~1° smoother) and contribute both heating and cooling. Altogether, a time-averaged "diabatic" term (estimated as a residual of all non-diabatic budget terms from the total temperature tendency) indicates that unaccounted-for diabatic processes may have been important to the total heating, notably in the interior British Columbia and Columbia Plateaus, where we have argued that EF and T anomaly correspondence indicates potential feedback activity and where temperature anomalies were highest. We finally note that because this budget analysis was undertaken at the 850hPa level, it may potentially underestimate land-surface processes.

A temporal view of some aggregated terms of the heat budget shows that on the days of maximum heating, the residual term played a large warming role, providing above 50% of the heating on the maximum day (06/27). It later became negative as the linear terms strengthened, and heating overall weakened (but as the actual temperature anomalies increased). Subsetting for areas where historical latent heat flux and soil moisture anti-correlation indicates that land-atmosphere feedbacks may be typical (black contour on map; $\rho(LHF,SM)>0.2$)), the residual term strengthens, indicating that these areas may be especially responsible for the residual effects. Furthermore, subsetting by where t2m anomalies throughout the heatwave (06/24–07/03) reached over 10°C, the residual term is greatly strengthened specifically in the later days of heating (06/27–06/29). This helps corroborate that the residual term is especially active in the regions experiencing the most extreme heat, where feedbacks may have been strongest. Both subsets help narrow down what specific processes may be responsible for this residual term.

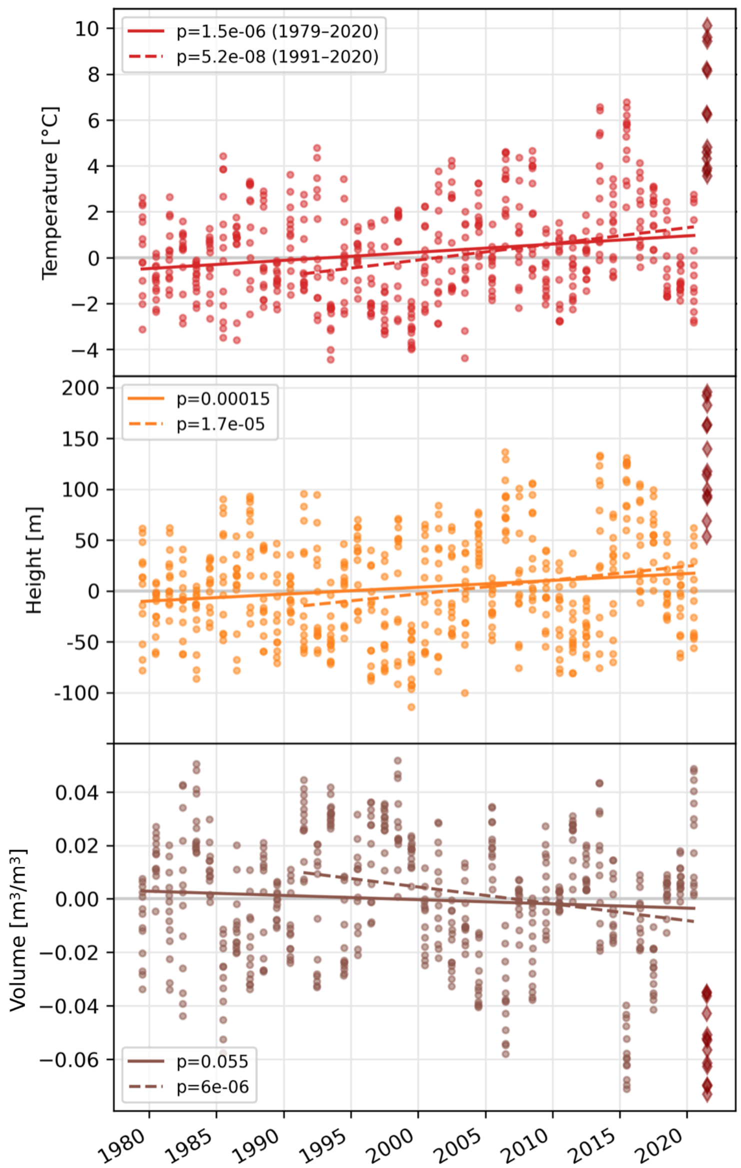

Fig. S10: The same data as in Fig. 2 plotted against year, shown individually for temperature (**top)**), geopotential height (**middle)**), and soil moisture (**bottom)**), and linear trends over 1979–2020 and 1991–2020 (with p-values in legends).

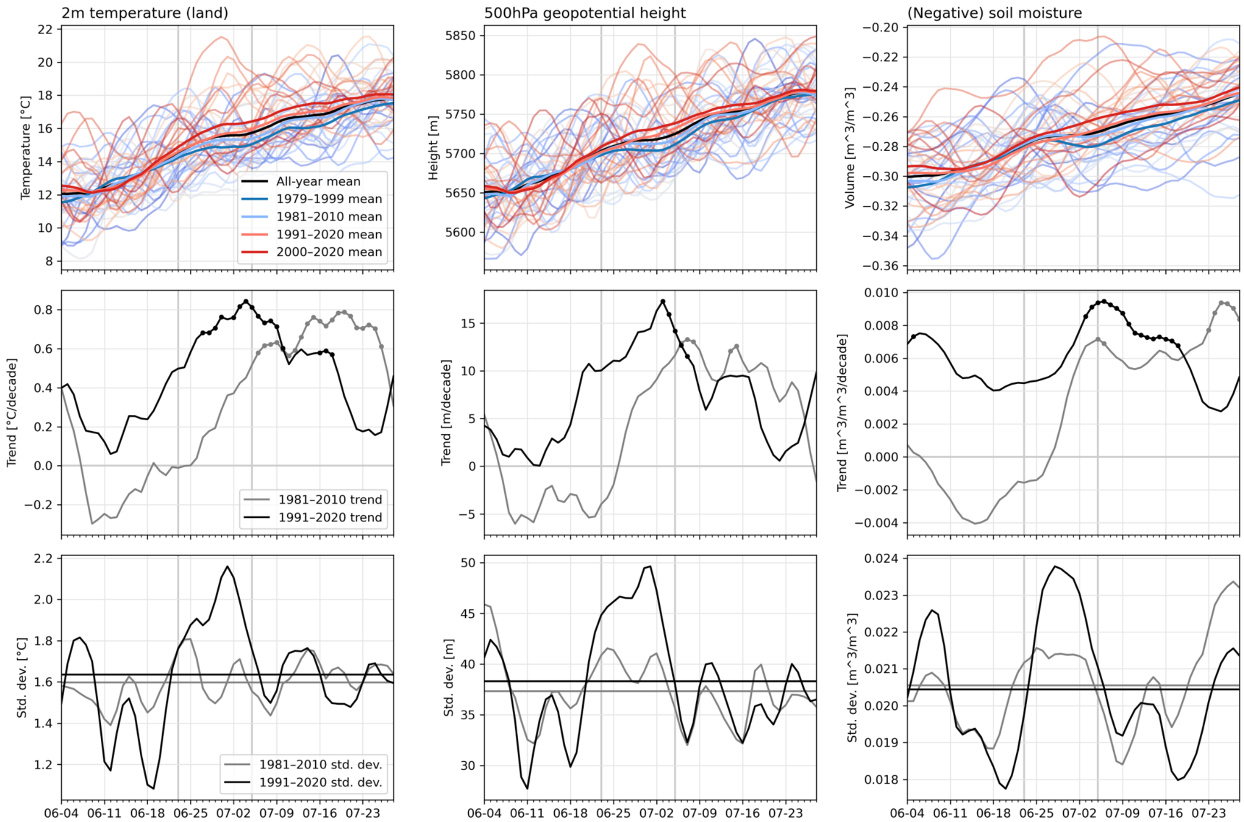

Fig. S11: Historical changes in temperature, geopotential height, and soil moisture and their interannual variability. PNW-mean raw (i.e., non-anomalous) temperature, geopotential height, and soil moisture data from ERA5 over the entire period of analysis except 2021 (1979–2020, throughout June and July). All data are 7-day running means. Gray vertical bars mark 06/23 and 07/05. **Top row:** color-coded data for each year (blue in 1979 to red in 2020), with means throughout the various analysis periods overlaid according to the legend. Second row: linear trends in data over 1981–2010 and 1991–2020, marked with dots where significant at 90% level. **Bottom row:** interannual standard deviations across 1981–2010 and 1991–2020, with horizontal lines demarcating the June-July mean for each period. The bottom row shows that in the PNW, standard deviation is increasing for temperature and geopotential height over June and July as a whole, and especially for late-June–early-July (when soil moisture standard deviation is also increasing sharply)—which is likely associated with warming trends shifting earlier in the year in accordance with an advancing summer onset (as illustrated in the left panel of the middle row).

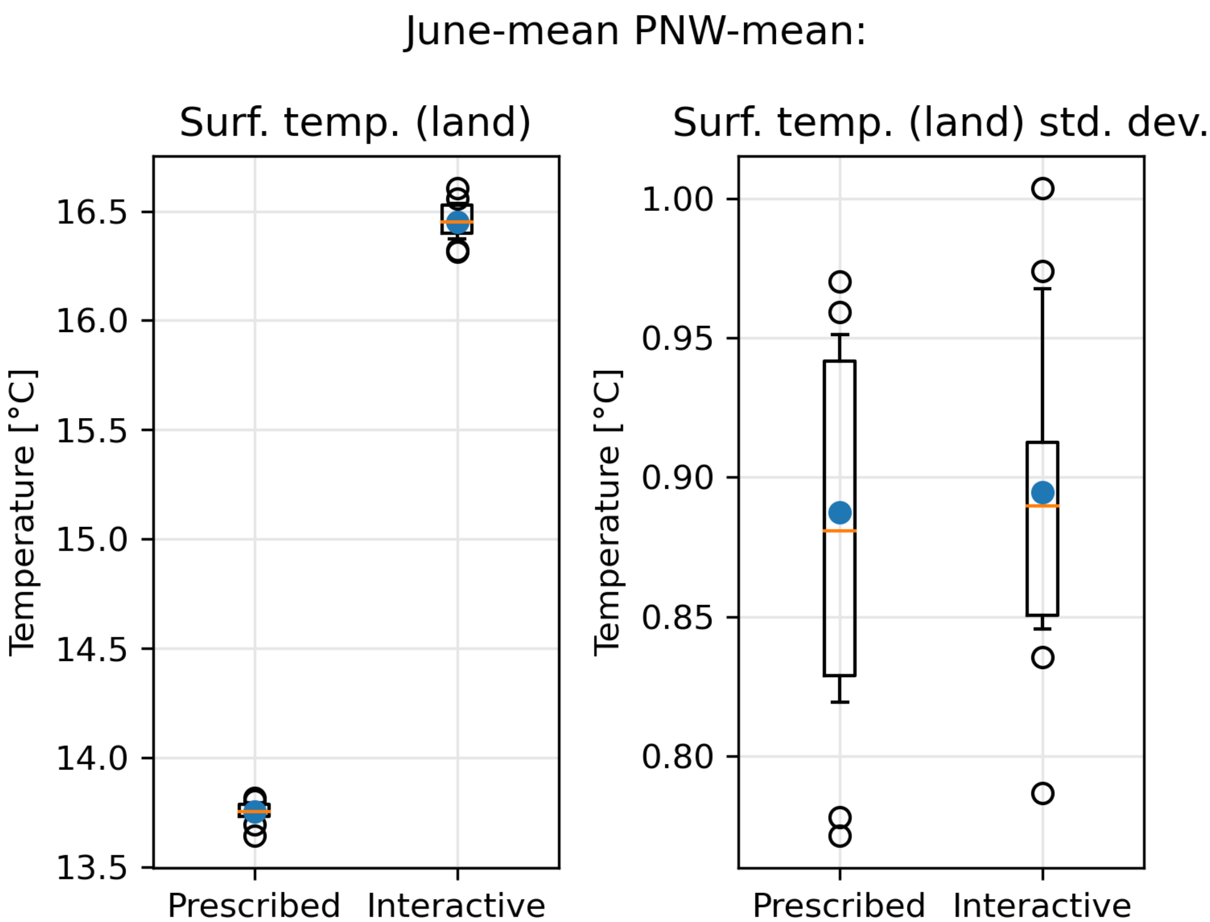

Fig. S12: Shift and variability changes of June-mean PNW-mean temperature in the model experiment. Boxplots show the model member spread, with the two most distant members towards either end of the 14-member distribution shown as individual dots. Blue dots show the ensemble total (all member-months) and orange lines show the ensemble mean. The left plot is the mean surface temperature, and the right plot is the surface temperature standard deviation. All standard deviations are calculated internally for each member, i.e., across each member's entire 1870–2010 run.

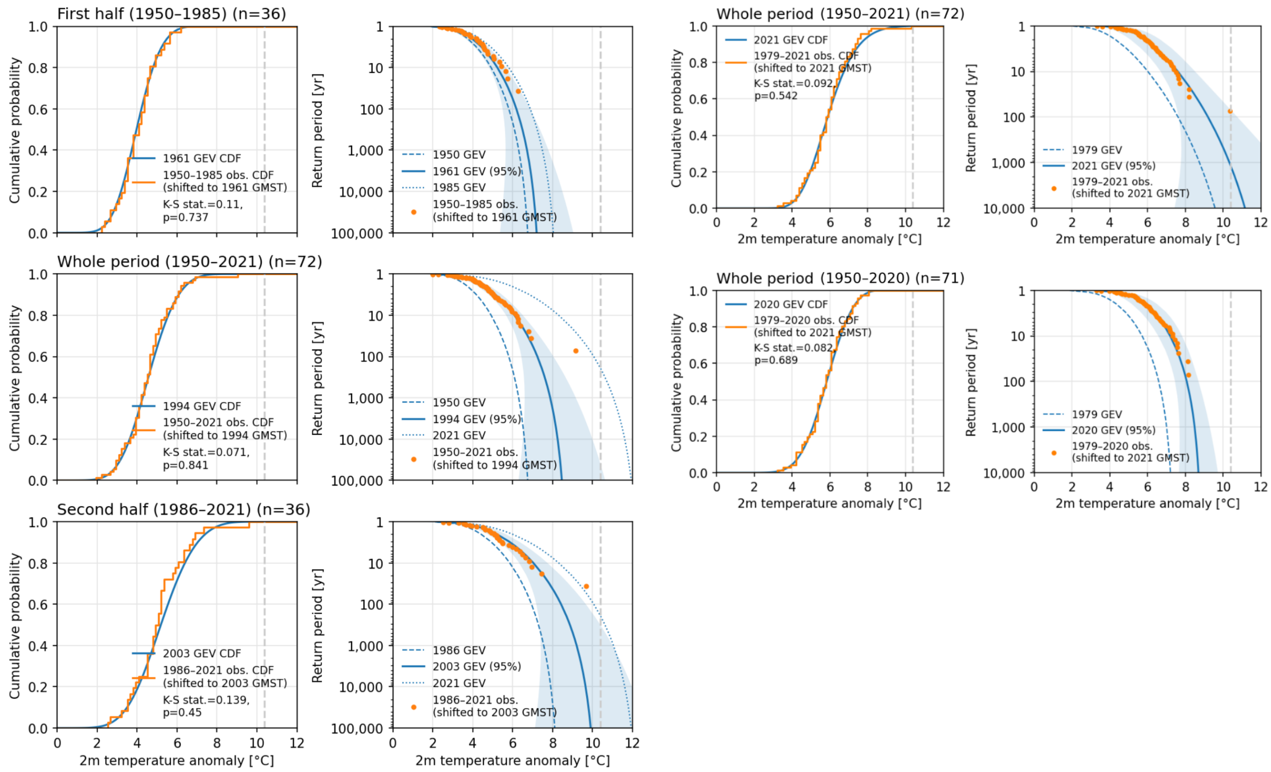

Fig. S13: Validation of nonstationary-scale GEV fits including the 2021 observation (first two columns), and stationary-scale fits (second two columns). First column: For each period, empirical CDFs of observations in that period (orange) are compared with the nonstationary-scale GEV fit CDF (blue) evaluated at the mean GMST of that period. Results of a Kolmogorov-Smirnov test (D statistic and p-value), testing whether the samples can be determined as drawn from different distributions, are indicated in the legends. No p-values are low enough to reject the GEV fits even with the inclusion of 2021**. Second column:** For each period, empirical return periods (orange dots) are compared with GEV-derived return periods (blue curves) evaluated at the mean GMST of the period. Empirical return periods are estimated as $1/(1-i/(n+1))$, with n the number of observations in each period and i their ranking in ascending temperature order. In both columns, the observations' raw temperatures are "shifted", based on the location parameter's dependence on GMST, to each period's mean GMST (for example, the highest temperature observation in the lower right plot, representing the 2021 heatwave, is shifted down from its raw temperature [the dashed gray line], to the median GMST of 1986–2021, seen in 2003; compare with Fig. 4b to see that mean and median are indistinguishable). Shifting observations by GMST in this way still does not account for any variability changes (i.e., only considers location parameter nonstationarity, not scale parameter nonstationarity), so K-S tests may even overestimate the true difference between GEV fits and observations. **Third and fourth columns:** As in first two columns but for the stationary-scale-parameter GEV fit both including (top) and excluding (bottom) 2021 (both covering the whole time period, as observations can simply be shifted based on location parameter while their scale is fixed).

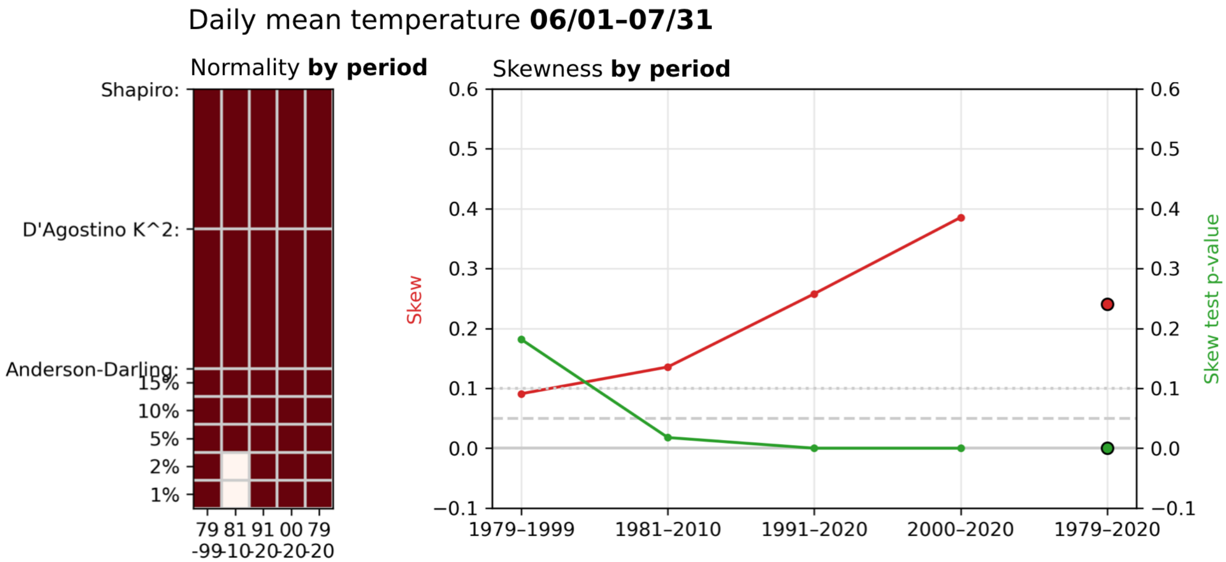

Fig. S14: Skew tests for temperature anomaly distributions over historical periods. **Top row:** for daily mean temperature anomalies over 06/23–07/05, the plots show results from three normality tests determining whether the dataset (individual days over the 1981–2010 period (left) and 1991–2020 period (right)) can be statistically distinguished from normal (red) or not (white). Shapiro and D'Agostino tests report a single output, and the Anderson-Darling test reports at 5 different confidence levels. These results only register interannual variability (one day per year). **Bottom row:** The left plot compares the daily temperature anomalies over all of June and July subset for 5 different periods (1979–1999, 1981–2010, 1991–2020, 2000–2020, and 1979–2020, from left to right). The right plot shows the skewness (red) calculated for temperature data for each of the 5 period subsets, along with the *p*-value of the skew test (.1 and .05 significance levels indicated). These results register both interannual and intra-annual variability (61 days per year over 21- or 30-year periods).

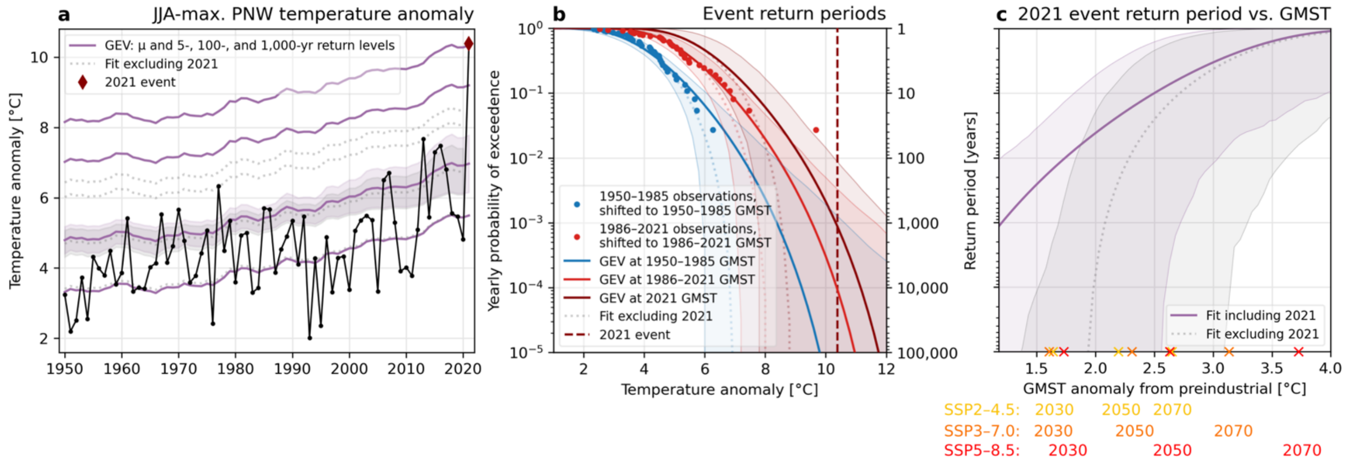

Fig. S15: Nonstationary-location, stationary-scale GEV fit. Same as Fig. 4 but for the GEV fit with fixed scale parameter

ERA5 data

Does allowing nonstationarity in the location and/or scale parameters improve the GEV model fit? Finding the test statistic D > 0 indicates improvement, with significance tested according to the critical values in the bottom table.

	Location	Scale
Fit with 2021	D=18.749 **(p<0.001)**	D=6.593 **(p<0.025)**
Fit without 2021	D=20.837 **(p<0.001)**	D=1.231 (p=0.267)

Model data

Does allowing nonstationarity in the location parameter improve the GEV model fit?

	Covariate: PNWMST	Covariate: GMST
Prescribed SM	D=3.573 **(p<0.1)**	D=0.461 (p>0.1)
Interactive SM	D=13.836 **(p<0.001)**	D=2.400 (p>0.1)

Critical values and significance definitions (from 1-d.o.f. Chi-square distribution):

Critical values of D	D=2.706	D=3.841	D=5.024	D=6.635	D=10.828
Significance if critical value exceeded	p<0.1	p<0.05	p<0.025	p<0.01	p<0.001

Table S1: Likelihood Ratio Test. The Likelihood Ratio Test (from Theorem 2.7 of Coles et al. (2001) tests whether adding nonstationarity in parameters improves the GEV model fit. Tables show test statistics (D) and significance levels for adding nonstationarity in the location and scale parameters for ERA5 data and nonstationarity in the location parameter for model data, with different covariates.