

Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021

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Abstract. Towards the end of June 2021, temperature records were broken by several degrees Celsius in several cities in the Pacific northwest areas of the U.S. and Canada, leading to spikes in sudden deaths, and sharp increases in [emergency calls and hospital visits for heat-related illnesses](#) and [emergency calls](#). Here we present a multi-model, multi-method attribution analysis to investigate to what extent human-induced climate change has influenced the probability and intensity of extreme heatwaves in this region. Based on observations ~~and modeling~~, [modeling and a classical statistical approach](#) the occurrence of a heatwave ~~with defined as the~~ maximum daily temperatures (TXx) ~~as~~ observed in the area 45 °N–52 °N, 119 °W–123 °W, was found

to be virtually impossible without human-caused climate change. The observed temperatures were so extreme that they lie far outside the range of ~~historically-observed temperatures~~ historical temperature observations. This makes it hard to quantify with confidence how rare the event was. ~~In the most realistic statistical analysis, which uses the assumption that the heatwave was a very low probability event that was not caused~~ Using a statistical analysis that assumes that the heatwave is part of the same distribution as previous heatwaves, i.e. it can be included in the statistical fit and it was not intensified by new nonlinearities, ~~the event is estimated to be about a 1 in 1000 year event in today's climate.~~ With years under current climate conditions. Using this assumption and in combining the results from the analysis of climate models and weather observations, an event, defined as daily maximum temperatures (TXx) in the heatwave region, as rare as 1 in a 1000 years would have been we find that such a heat event would be at least 150 times rarer less common without human-induced climate change. Also, this heatwave was about 2°C hotter than a 1 in 1000-year heatwave ~~that would have been~~ at the beginning of the industrial revolution would have been (when global mean temperatures were 1.2°C cooler than today). Looking into the future, in a world with 2°C of global warming (0.8°C warmer than today), a 1000-year event would be another degree hotter. ~~It would occur roughly every 5 to 10 years in such global warming conditions.~~

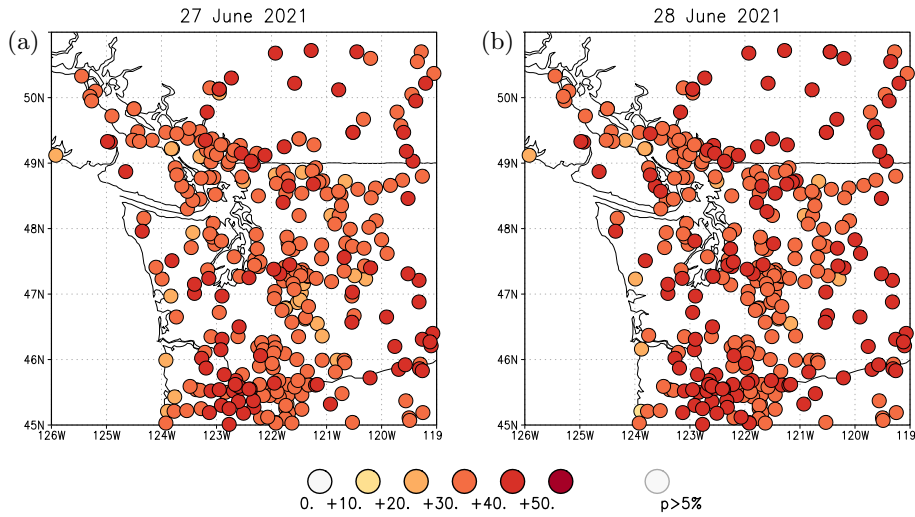
20 Our results provide a strong warning: our rapidly warming climate is bringing us into uncharted territory with significant consequences for health, well-being, and livelihoods. Adaptation and mitigation are urgently needed to prepare societies for a very different future.

1 Introduction

During the last days of June 2021, Pacific northwest areas of the U.S. and Canada experienced temperatures never previously observed, with temperature records broken in multiple cities by several degrees Celsius. Temperatures far above 40 °C (104 °F) occurred on Sunday 27 to Tuesday 29 June (Figs 1a,b for Monday) in the Pacific northwest areas of the U.S. and western Provinces of Canada, with the maximum warmth moving from the western to the eastern part of the domain from Monday to Tuesday. The anomalies relative to ~~normal maximum temperatures~~ the maximum temperature climatology for the time of year reached 16°C to 20 °C (Figs 1c,d). It is noteworthy that these record temperatures occurred one whole month before the climatologically warmest part of the year (end of July, early August), making them particularly exceptional. Even compared to the maximum temperatures in other years independent of the considered month, the recent event exceeds those temperatures by about 5 °C (Figure 2). Records were shattered in a very large area, including setting a new all-time Canadian temperature record in the village of Lytton, at which a temperature of 49.6 °C was measured on June 29 and where wildfires spread on the following day.

35 Given that the observed temperatures were so far outside historical experiences and occurred in a region with only about 50% household air conditioning penetration, ~~we expect large impacts on health.~~ ~~The excess deaths numbers will be finalized in the coming months.~~ ~~There were 815 deaths in~~ were expected. In British Columbia, Canada, ~~of which about 70% were there~~

Maximum temperature



Maximum temperature anomaly

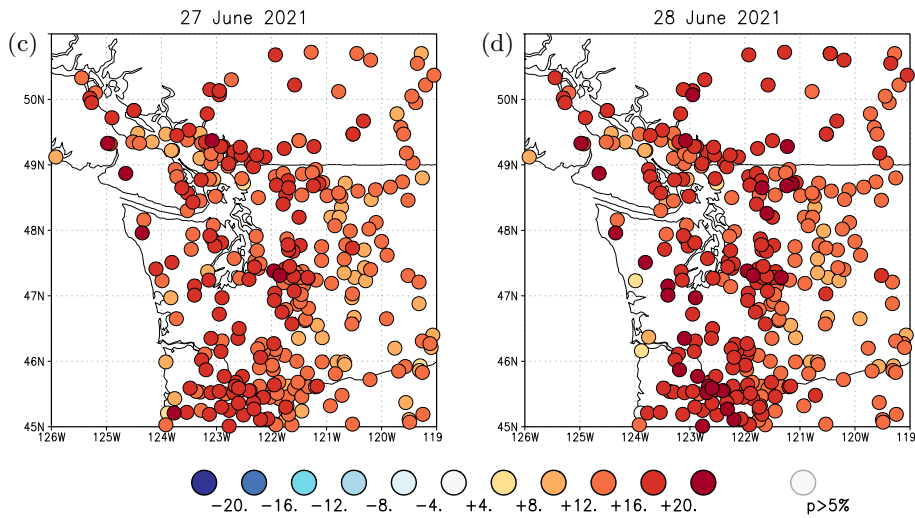


Figure 1. a) observed temperatures on 27 June 2021, b) 28 June 2021, c,d) same for anomalies relative to the whole station records. Source: GHCN-D

were an estimated 740 heat-related excess deaths¹ putting the event among the deadliest weather related events in Canada (Henderson et al., 2021). There were nearly 450 extra deaths in Washington and nearly 160 in Oregon.¹

40 ~~The present report aims to~~ Below we investigate the role of human-induced climate change in contributing to the likelihood and intensity of this extreme heatwave, following an established approach to multi-model multi-method extreme event attribu-

¹ <https://www.cbc.ca/news/canada/british-columbia/bc-heat-dome-sudden-deaths-570-1.6122316>

¹ <https://www.nytimes.com/interactive/2021/08/11/climate/deaths-pacific-northwest-heat-wave.html>

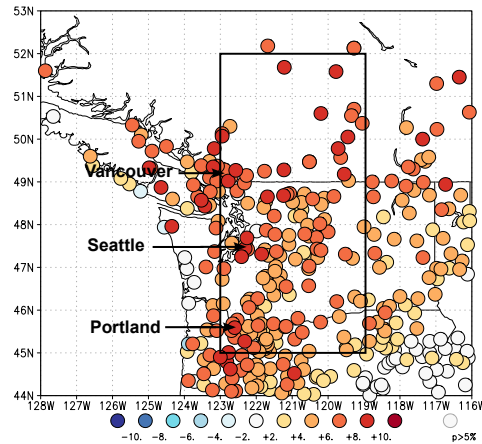


Figure 2. Anomalies of 2021 highest daily maximum temperature (TXx) relative to the whole time series of each station. The black box indicates the study region. Source: GHCN-D

tion (Philip et al., 2020; van Oldenborgh et al., 2021). We focus the analysis on the maximum temperatures in the region where most people were affected by the heat (45 °N–52 °N, 119 °W–123 °W) including the cities of Seattle, Portland, and Vancouver. While the extreme heat was an important driver of the observed impacts, it is important to note that these impacts strongly depend on exposure, vulnerability, and other climatological variables beyond temperature. In addition to the attribution of the extreme temperatures we qualitatively assess whether meteorological drivers and antecedent conditions played an important role in the observed extreme temperatures in Section 7-6.

1.1 Event definition

~~Daily maximum temperatures~~ For the attribution analysis, a definition of the event is required. As there are several options to define an event, this step requires some expert judgment. Within this study, we will analyse the daily maximum temperatures, which characterised the event and were the headline figure in the large number of media reports describing the heatwave and the impacts associated with the event. Furthermore, daily maximum temperature was the primary extreme characteristic of the event. ~~it's associated impacts.~~ We therefore define the event based on the annual maximum of daily maximum temperature, TXx. ~~There is some evidence that longer time scales,~~ Here, we first average over the region and then take the annual maximum. Other options for variables that could be selected for analysis include e.g. 3-day average, averaged temperatures, as there is some evidence that longer time scales better describe the health impacts (e.g., D'Ippoliti et al., 2010) or high minimum temperatures which also have strong impacts on human health. However, TXx is a standard heat impact index and thus the results can easily be compared to other studies. ~~High minimum temperatures also have strong impacts on human health. However, here we~~ We intentionally focus on one event definition to keep this analysis succinct and its results easy to communicate, choosing TXx, which not only characterises the extreme character of the event but is also readily available

in climate models allowing us to use a large range of different models. Recognising that the WMO standard definition of a heatwave is a multi-day measure associated with persistent heat, we additionally considered the annual maxima of 5-day and 10-day averages of daily maximum temperatures, TX5x and TX10x, for observations. Trends in these time series, as seen by the intensity change, turn out to be very similar to the results for TXx presented in Sect. 3. As the spatial scale of the event we consider the area 45°N–52°N, 119°W–123°W. This covers the more populated region around Portland, Seattle and Vancouver that were impacted heavily by the heat (with a total population of over 9.4 million in their combined metropolitan areas), but excludes the rainforest to the west and arid areas to the east. Note that this spatial event definition is based on the expected and reported human impacts rather than on the meteorological extremity. Besides ~~this main definition~~ the analysis for this region we also analysed ~~the observations for~~ long and homogeneous observational records of three stations in Portland, Seattle and Vancouver ~~with long homogeneous time series.~~

1.2 Previous trends in heatwaves

Figure 3 shows the observed trends in TXx in the GHCN-D dataset over 1900–2019. The stations were selected on the basis of a long time series, at least 50 years of data, and being at least 2° apart. The trend is defined as the regression on the global mean temperature, so the numbers represent how much slower or faster ~~than the global mean~~ the temperature has changed ~~compared to the global mean~~ the. Individual stations with different trends than nearby stations usually have inhomogeneities in the observational method or local environment. The negative trends in eastern North America and parts of California are well-understood to be the result of land use changes, irrigation and changes in agricultural practice (Donat et al., 2016, 2017; Thiery et al., 2017; Cowan et al., 2020). The large trends in heatwaves in Europe are not yet fully understood or adequately represented in climate models (Vautard et al., 2020). The Pacific Northwest showed trends ~~of about two times~~ twice as large as the global temperature trend up to 2019.

2 Data and methods

2.1 Observational data

The dataset used to represent the heatwave is the ERA5 reanalysis (Hersbach et al., 2019) from ~~the~~ ECMWF at 0.25° resolution. A very rapid analysis performed directly after the heatwave and published on <https://www.worldweatherattribution.org/western-north-american-extreme-heat-virtually-impossible-without-human-caused-climate-change/> used ERA5 extended by the ECMWF operational analysis and the ECMWF forecast. ~~There is only a very minor~~ The difference in the heatwave amplitude between the ~~two analyses and this makes no difference to the rounded~~ rapid analysis and the updated analysis presented here are minor and do not affect the estimated return period used in this study ~~and~~ Therefore, the analysis results ~~are therefore not affected~~ do not require to be updated following the availability of the ERA5 data for the event's timeframe.

Temperature observations were ~~collected to directly assess the~~ used to assess probability ratios and return periods associated with the event for ~~the~~ three major cities in the study area: i.e. Portland, Seattle, and Vancouver. Observing sites were chosen

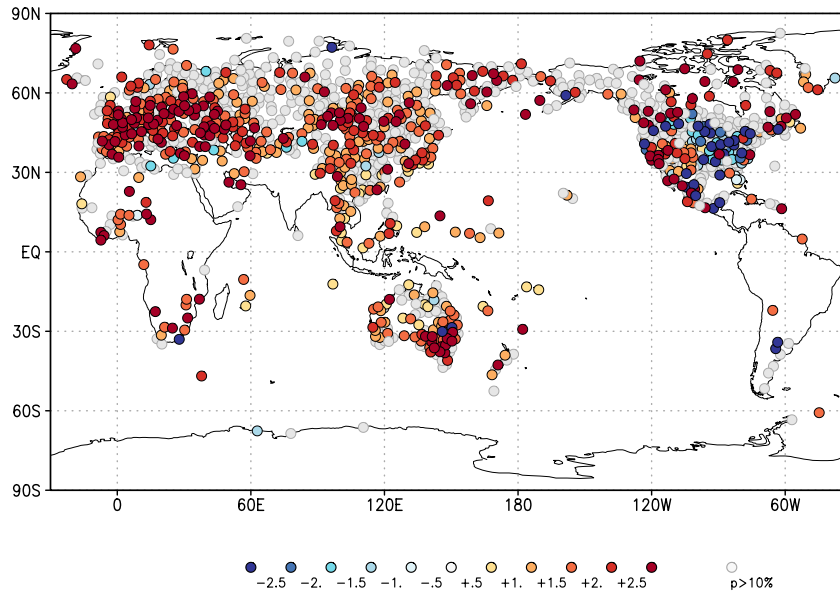


Figure 3. Trends in the highest daily maximum temperature of the year in the GHCN-D station data. Stations are selected to have at least 50 years of data and to be at least 2° apart. The local trends are defined by their regression on the global mean temperature, and shown in units of multiples of the global mean temperature rise. Source: GHCN-D

~~that had based on (i) the availability of~~ long homogenized historical records ~~and were representative of,~~ ~~(ii) their ability to represent~~ the severity of the event by avoiding ~~exposure to nearby sites within the proximity to~~ large water bodies. ~~Sites were also chosen to be representative of the,~~ ~~and (iii) their representativeness for~~ populous areas of each city to better illuminate impact on inhabitants.

For Portland, the Portland International Airport National Weather Service station was used, which has continuous observations over 1938–2021. The airport is located close to the city centre, adjacent to the Columbia River. The river’s influence is thought to be small ~~and the water temperature is warm by June~~. For Seattle, Seattle-Tacoma International Airport was chosen, which has almost continuous observations ~~between~~ 1948–2021, among the longest records in the Seattle area. This location is further inland and ~~lacks thus avoids~~ the influence of Lake Washington that ~~downtown Seattle has~~ affects downtown Seattle. Two long records exist adjacent to downtown Vancouver, but they are both very exposed to the Georgia Strait that influenced observations due to local onshore flow during the peak of the event. ~~A record was chosen~~ ~~Thus the time series from a site further inland at New Westminster~~ ~~.-The observations start was selected, which starts~~ in 1875 but ~~here are data gaps~~ contains data gaps in 1882–1893, 1928, 1980–1993.

The data for Portland International Airport and Seattle-Tacoma International Airport were gathered from the Global Historical Climatology Network Daily (GHCND; Menne et al., 2012) while data for New Westminster were gathered from the Adjusted Homogenized Canadian Climate Dataset (AHCCD) for daily temperature (Vincent et al., 2020). This station’s record

is a composite of data from three locations in two nearby cities ~~with location changes as location changes took place~~ in 1966 and 1980. From 1874 to 1966, the station operated at an elevation of 118 m above sea level near the centre of New Westminster.

110 In 1966, the station was moved ~~roughly about~~ 2 km ~~to the~~ east and to an elevation of 18 m. The portion of the homogenized record from 1980 onward is from Pitt Meadows, BC ~~located roughly~~, located about 14 km east of the previous location ~~and~~ at an elevation of 5 m. Using a composite station is non-ideal given the potential influence of local ~~micro-climate effects and micro-climatic effects and particularly~~ the increasing distance from ~~the cooling effects of The theThe~~ Strait of Georgia ~~. Those effects which exhibits a cooling effect to sites in its vicinity. Use of data from this composite site~~ may increase the uncertainty

115 of our analysis, but given the magnitude of the signal and the consistency of results among the datasets presented here (and analysis of other temperature ~~records in datasets from~~ BC, not shown here), we accept these issues. The AHCCD dataset is updated annually and ends in 2020. Data for 2021 were appended from unhomogenized recent records from Environment and Climate Change Canada. Overlapping data for 2020 were compared between the two sources and found to be identical except for several duplicate/missing observations ~~which~~. Such duplicate or missing data would not cause error in the present analysis

120 because the records are complete for June ~~,~~ 2021.

As a measure of anthropogenic climate change we use the global mean surface temperature (GMST), where GMST is taken from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Science (GISS) surface temperature analysis (Hansen et al., 2010; Lenssen et al., 2019, GISTEMP.). We apply a 4-yr running mean low-pass filter to suppress the influence of ENSO and winter variability at high northern latitudes as these are unforced variations.

125 2.2 Model and experiment descriptions

In this study a variety of climate model simulations are analysed and will be described in the following.

Model simulations from the 6th Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016) are assessed ~~. We combine after combining~~ the historical simulations (1850 to 2015) with the Shared Socioeconomic Pathway (SSP) projections (O'Neill et al., 2016) for the years 2016 to 2100. Here, we only use data from SSP5-8.5, ~~although the pathways noting that SSPs~~

130 are very similar ~~to each other~~ over the period 2015–2021. Models are excluded if they do not provide the relevant variables, do not run from 1850 to 2100, ~~or and if they either~~ include duplicate time steps or ~~missing miss~~ time steps. All available ensemble members are used. A total of 18 models (88 ensemble members), which fulfill these criteria and passed the validation tests (Section ~~4~~ 4), are used.

In addition ~~to the CMIP6 simulations, the an~~ ensemble of extended historical simulations from the IPSL-CM6A-LR model

135 is used (see Boucher et al., 2020, for a description of the model), which follows the CMIP6 protocol (Eyring et al., 2016). It is composed of 32 members, ~~following the CMIP6 protocol (Eyring et al., 2016) and the simulations cover~~ over the historical period (1850-2014) ~~and~~. It is extended until 2029 using all forcings from the SSP2-4.5 scenario, except for the ozone concentration which has been kept constant at its 2014 climatology (~~, as it was not available at the time of performing the extensions~~). This ensemble is used to explore the influence of internal variability.

140 The GFDL-CM2.5/FLOR (Vecchi et al., 2014) is a fully coupled climate model developed at the Geophysical Fluid Dynamics Laboratory (GFDL). While the ocean and ice components have a horizontal resolution of only 1°, the resolution of ~~the~~

atmosphere and land is about 50 km and might therefore provide a better simulation [that coarser model simulations](#) of certain extreme weather events (Baldwin et al., 2019). The data used in this study cover the period from 1860 to 2100, and ~~include both the combine~~ historical and RCP4.5 experiments driven by transient radiative forcings from CMIP5 (Taylor et al., 2011).

145 We also examine five ensemble members of the AMIP experiment (1871-2019) from the GFDL-AM2.5C360 (Yang et al., 2021; Chan et al., 2021), which consists of the atmosphere and land components of the FLOR model but with ~~horizontal resolution doubled to~~ [finer horizontal resolution of](#) 25 km for a potentially better representation of extreme events.

~~The project~~ [Further, we use simulations of the Climate of the 20th Century Plus Project \(C20C+\) project which](#) was designed specifically for event attribution studies (Stone et al., 2019). ~~The experimental design uses C20C+ simulations are based on~~ models of the atmosphere and land with prescribed sea surface temperatures and sea ice concentrations, similar to the ~~AMIP experiment~~ [design of AMIP experiments](#). To quantify the impact, if any, on extreme events, participating models were run following the AMIP protocol. The ~~distributions~~ [distribution](#) of TXx in the study area ~~were examined in~~ [was examined for](#) three C20C+ models, [i.e. CAM5.1, MIROC5 and HadGEM3-A-N216](#) and compared to that of the ERA5 reanalysis. Only the Community Atmospheric Model (CAM5.1, [Neale et al. \(2010\)](#)), run at ~~the default~~ $\sim 1^\circ$ resolution, satisfied the requirements of this study in the statistical description of heat extremes. ~~The model is described in Neale et al. (2010)~~. The actual world ensemble consists of 99 simulations of mixed duration all ending in 2018, resulting in a sample size of 4090 years. A counterfactual world ensemble of similar size consists of 89 simulations resulting in a sample size of 3823 years.

2.3 Statistical methods

A full description of the statistical methods is given in (Philip et al., 2020; van Oldenborgh et al., 2021). Here we give a
160 summary.

As discussed in ~~section 1.2~~ [Section 1.1](#), we analyse the annual maximum of daily maximum temperatures (TXx) averaged over 45°N - 52°N , 119°W - 123°W . Initially, we analyse reanalysis data and station data from sites with long [data](#) records. Next, we analyse climate model output ~~for the same metric of~~ TXx. We follow the steps outlined in the ~~WWA~~ [World Weather Attribution \(WWA\)](#) protocol for event attribution. ~~The analysis steps which~~ include: (i) trend calculation from observations;
165 (ii) model validation; (iii) multi-method multi-model attribution and (iv) synthesis of the attribution statement.

For the event under investigation we calculate the return periods, probability ratio (PR) and change in intensity as a function of GMST, [where PR is defined as \$PR = p_1/p_0\$, with \$p_1\$ the probability of an event as strong as or stronger than the extreme event in the current climate and \$p_0\$ the probability of such an event in a counterfactual climate without anthropogenic emissions](#). The two climates we compared are defined as the GMST of the event year 2021 and a GMST value representative of the climate of the late nineteenth century, -1.2°C relative to 2021 (1850-1900, based on the Global Warming Index <https://www.globalwarmingindex.org>). To statistically model the selected event, we use a GEV distribution that shifts with GMST, i.e., the location parameter has a term proportional to GMST and the scale and shape parameters are assumed constant. ~~Next, results~~ [The PRs are calculated](#) from observations and from ~~the models~~ [different models and results](#) are synthesized into a consistent attribution statement. For models (except for IPSL-CM6A-LR and CAM5.1), we additionally analyse the PR between [the current climate and](#) a future climate at $+2^\circ\text{C}$ above the 1850-1900 reference, which is equivalent to $+0.8^\circ\text{C}$ above
175

the current climate of 2021. For this analysis of future change we use model data up to about 2050 or when the model GMST reaches +0.8 °C compared to now.

The CMIP6 data are analysed using the same statistical models as the main method. However, for practical reasons, the parameter uncertainty is estimated in a Bayesian setting using a Markov Chain Monte Carlo (MCMC) sampler instead of a
180 bootstrapping approach (see Ciavarella et al., 2021, for details).

3 Observational analysis: return time and trend

Time series of various aspects of the main index are shown in Figure 4: a) the daily ~~Tmax~~ maximum temperature (Tmax) evolution from ERA5 (from 1 May to 31 Aug); and b) annual ~~max of the~~ maximum of the time series. The value for 2021, 39.7 °C, is 5.7 °C above the previous record of 34.0 °C, ~~which is an~~. This extremely large increase ~~that gives rise~~ leads to
185 difficulties in the statistical analysis described ~~in Section 3.1~~ below. There are two possible sources of this extreme jump in peak temperatures. The first is that ~~a~~ an event with very low probability ~~event~~ occurred — the statistical equivalent of "really bad luck". ~~It~~ An event with very low probability could have also occurred in pre-industrial climate but its amplitude would have been aggravated by climate change in the current climate which already includes about 1.2°C of global warming. The second option is that strong nonlinear interactions and feedbacks took place in this event with yet unseen temperatures, relative
190 to previous heatwaves, amplifying the intensity of the extreme, a sign that climate change could exacerbate extreme heatwaves beyond expected temperatures. In this case, the event would not belong to the "same population" as the other ones and we would not expect the method applied here to be successful. This second possibility ~~needs further research to be confirmed.~~ requires further investigation. While we keep this possibility in mind, we assume the first option within this study.

In Figure 5a we show the seasonal cycle of the daily maximum temperature averaged over the index region and in Figure 5b
195 the spatial pattern of ~~the annual maximum of the daily maximum temperature~~ TXx averaged over several years individually at each grid point. These two metrics are also used in the model validation procedure, see Section 4.

3.1 Analysis of station and gridded data

Figure ~~6a shows our~~ 6 shows the standard extreme value ~~analysis and the challenge of applying it to this event~~ evaluation
200 applied for attribution studies within WWA, which in general excludes data of the analysed extreme event from the statistical fit when the study area has been chosen based on the location of the extreme event, to avoid selection bias. Figure 6a shows the observed TXx as a function of smoothed GMST and shows that the value observed in 2021 is far outside the range of any values observed to date. The distribution of ~~our index~~ TXx including data up to 2020 is described very well by a GEV distribution that has linearly warmed at a rate about twice as fast as the GMST. ~~This~~, see Figure 6b. The warming rate is consistent with the ~~general characteristic of global warming that summers over continents warm~~ expectation as summer temperatures over
205 continents increase faster than the global mean. The GEV fit has a negative shape parameter ξ , which implies a finite tail, and hence an upper bound. ~~In this case it is~~, here at 35.5 ± 1.3 °C (2σ uncertainty). However, the ~~observed value~~ value observed in

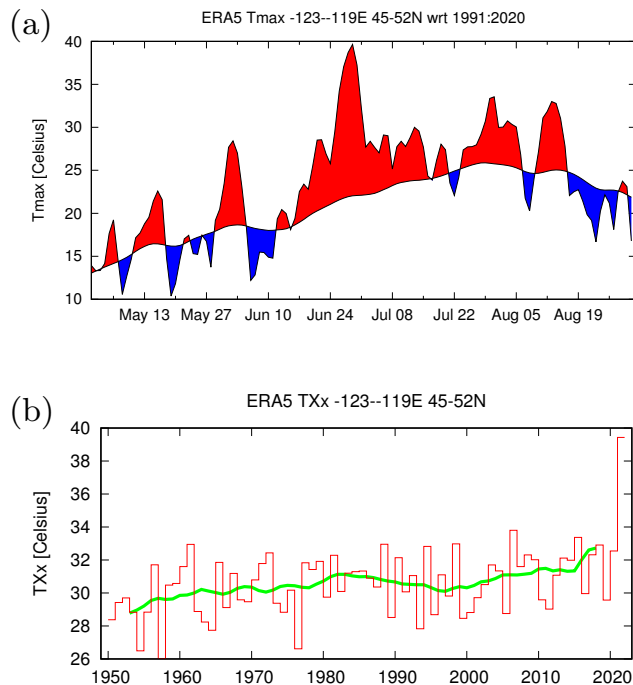


Figure 4. a) Time series for May-Aug 2021 of the maximum daily temperature averaged over the study area based on ERA5, with positive and negative departures from the 1991–2020 climatological mean of daily maximum temperature shaded red and blue, respectively. b) Annual maximum of the index series with a 10-yr running mean (green line). Source: ERA5.

2021, 39.7 °C, is far above this upper bound. Therefore, this GEV fit with constant shape and scale parameters that excludes all information about 2021 is not does not provide a valid description of ~~the~~ heatwaves in the area.

An alternative to the standard approach of not using any for which no information of the event under study is used (to avoid a selection bias), is to use some of the information from the June 2021 heatwave, namely the information that it actually happened. Specifically, in the next fit we still, yet without including the value observed in 2021 in the fit. Specifically, we again assume that the data up to 2020 can be described by a GEV distribution with constant scale and shape parameters, but we reject all GEV models in which the upper bound is below the value observed in 2021. In other words, we enforce fitting to that the fit parameters are within a subset of parameters that are compatible with the 2021 event. The result is shown in Figure 7.

215 While the distribution now includes the 2021 event, the fit to the data up to and including the year 2020 is noticeably worse than when not taking 2021 into account. The return time for the 2021 event under these assumptions still has a lower bound of 10,000 years in the current climate. The fit differs from the previous one mainly in the shape parameter, which is now much less negative (about -0.2 instead of -0.4). This shifts the upper bound to higher values. The fit also gives a somewhat higher trend parameter.

220 The third possibility is to fit the GEV distribution over all available data, including observations from 2021. This yields a return time of 1,000 years (95% CI > 100 yr). ~~This~~ approach implicitly assumes that the 2021 event is drawn from the same

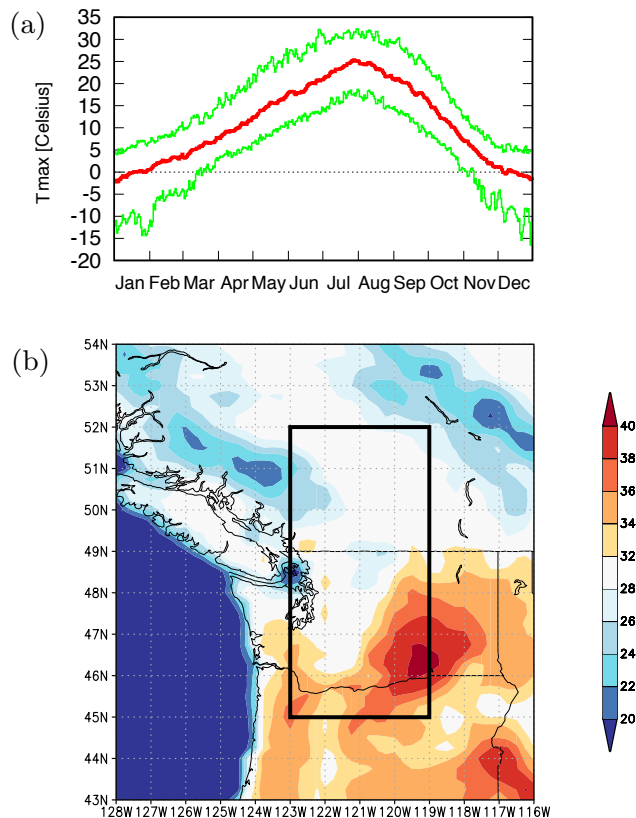


Figure 5. a) Seasonal cycle of Tmax averaged over the land points of 45 °N–52 °N, 119 °N–123 °N, showing the 1950–2021 mean (red) and 2.5% and 97.5% percentiles of the distribution (green). b) Spatial pattern of the 1950–2021 mean of the annual maximum of Tmax (multi-year mean TXx) at each grid point. Source: ERA5 data.

population. We could typically do not make this assumption if we had in cases where we intentionally selected a specific region in order to maximise the extremity (i.e. return period) of the event —known as to avoid a selection bias. In intentionally choosing the time-series-region with the largest (rarest) return period for the 2021 event, we would in fact be selecting it in
 225 preference to others from a larger population of time-series and we could not assume the 2021 event to be a representative member of the population for that point alone. This the extreme value is drawn from a different distribution and cannot be included. However, this is only partly the case here as we did choose the general region because the heat was exceptional there. However, we also based our exact choice We based the choice of a subregion for the analysis on population density and type of terrain, parameters that are more-independent of the heatwave. However, this approach uses all information available and
 230 assumes this was just a chance event The benefit of this approach is that it uses all available information. With this approach we still assume this was an event happening by chance. We use this third approach thus as the best estimate, although follow-up
Given the extremity of the event and the relatively low number of data, a robust GEV fit is hard to obtain, and the appropriateness of the method is difficult to assess. However, the application of this classical method in this case is interesting

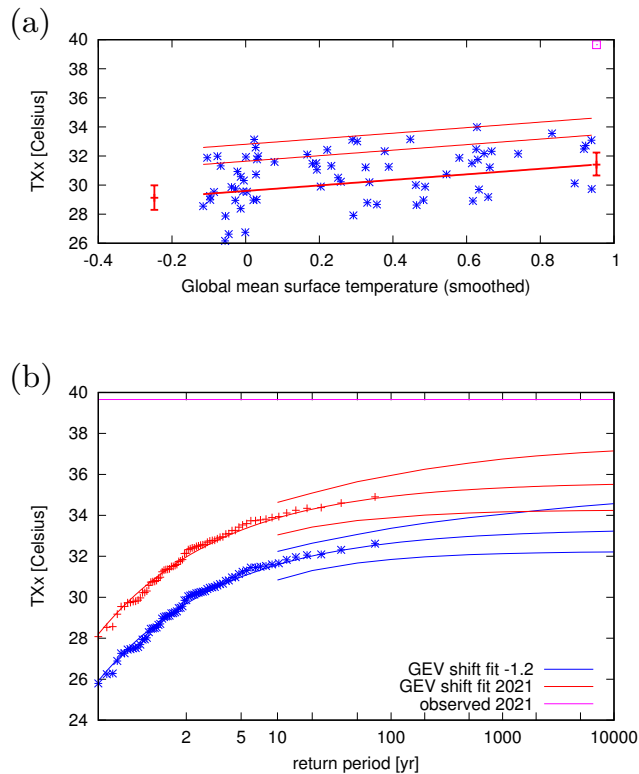


Figure 6. GEV fit with constant scale and shape parameters, and location parameter shifting proportional to GMST of the index series. No information from 2021 is included in the fit. (a): the observed TXx as a function of the smoothed GMST. The thick red line denotes the location parameter, the thin red lines the 6-yr and 40-yr return times. The June 2021 observation is highlighted with the magenta square and is not included in this fit. (b): Return time plots for the climate of 2021 (red) and a climate with GMST 1.2 °C cooler (blue). The red and blue lines indicate the best fit and the 95% confidence intervals, the magenta line shows the observed value. The past observations are shown twice: once shifted up to the current climate and once shifted down to the climate of the late nineteenth century. Source: ERA5, fit: KNMI Climate Explorer.

235 provided we keep in mind the assumptions we make. While we acknowledge that none of the three possibilities to fit a GEV
distribution is fully satisfying, we decided on using this third approach to estimate the return period leading to an estimate of
1,000 years (95% CI >100 yr). Follow-up research will be necessary to investigate the potential reasons ~~of~~ for this outstand-
ing event and the consequences on assumptions for these fits (see also the discussion in ~~Section 7~~ Sections 6 and 8). Also,
further research is needed into the limitations of standard GEV analysis on annual maxima with short records and seemingly
non-stationary behavior. Climate model large ensembles offer a future test bed to investigate the robustness of the method in
240 light of current limitations.

This fit gives a 95% CI of 1.4 K to 1.9 K for the scale parameter σ and -0.5 to 0.0 for the shape parameter ξ . These values are used for the model validation in Section ~~4~~ 4.

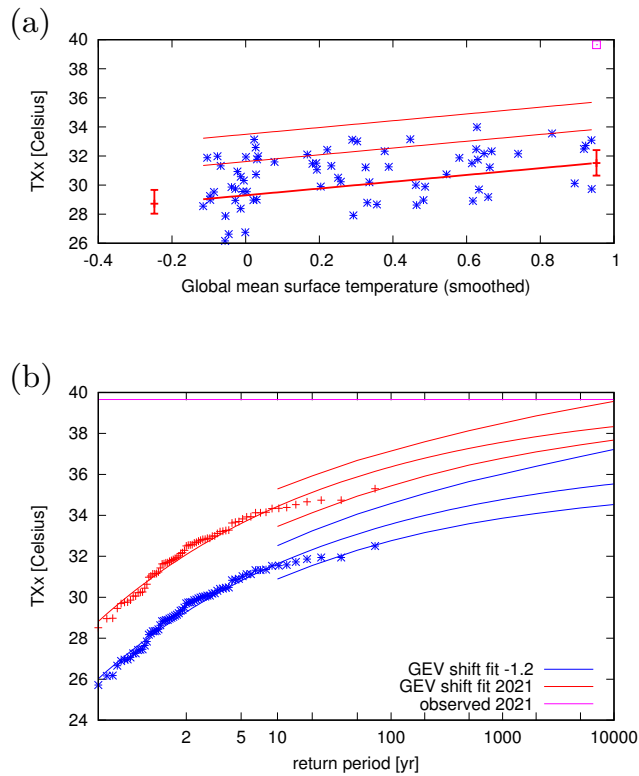


Figure 7. As Figure 6 but demanding the 2021 event is possible in the fitted GEV function, i.e., the upper bound is higher than the value observed in 2021.

The detection results, i.e., the comparison of the fit for 2021 and for a pre-industrial climate, show an increase in intensity of TXx of $\Delta T = 3.1 \text{ }^\circ\text{C}$ (95% CI: 1.2 to $4.8 \text{ }^\circ\text{C}$) and a probability ratio PR of 390 (3.2 to ∞).

245 3.2 Analysis of temperature in Portland, Seattle and Vancouver

For Portland we chose the International Airport station, which is located on the northern edge of the city and has been collecting data since April 1938; the data are in the GHCN-D v2 database. Figure 9 (top panel) shows the annual maxima of the Portland station time series, assuming there will be no higher value during the rest of the year. The record before this year was $41.7 \text{ }^\circ\text{C}$ in 1965 and 1981, and TXx reached $46.7 \text{ }^\circ\text{C}$ this year, so the previous record was broken by $5.0 \text{ }^\circ\text{C}$.

250 We fit a GEV distribution to this data, including 2021 (Figure 9, lower panels). It gives a return time of 700 yr for the 2021 event with a lower bound of 70 yr. For the PR we can only give a lower bound of 6, since the best estimate is infinite. This corresponds to an increase in temperature of $3.4 \text{ }^\circ\text{C}$ with a large uncertainty of 0.3 to $5.3 \text{ }^\circ\text{C}$. The large uncertainties are due to the somewhat shorter time series and large variability at this station.

In Seattle, the only station with a sufficiently long time series that includes 2021 is Seattle-Tacoma International Airport. It
 255 is located ~ 15 km south of the city but has similar terrain, without the proximity to water of the city itself. The previous record

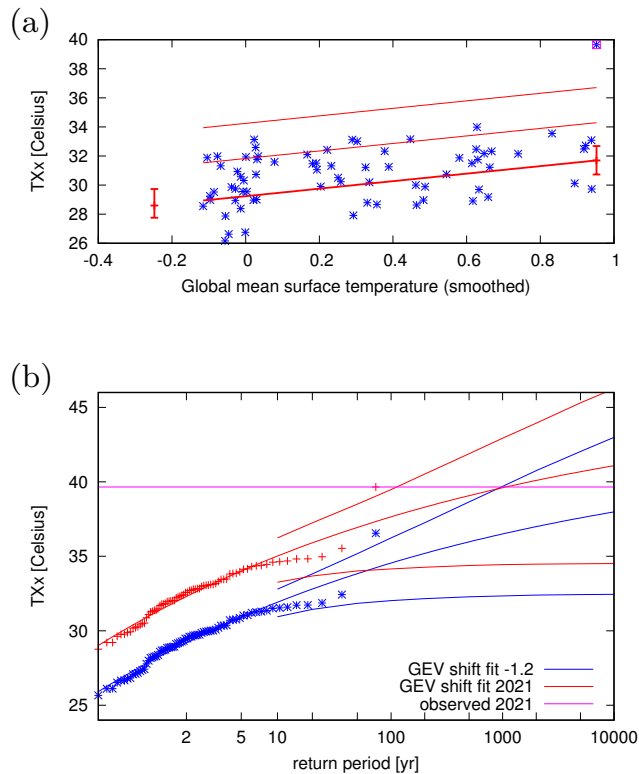


Figure 8. As for Figure 6 but including data from the 2021 heatwave into the fit.

was 39.4 °C in 2009, and this year it reached 42.2 °C. This is still a large increase of 2.8 °C over the previous record. The event was also not quite as improbable, with a return time of 300 yr (lower bound 40 yr) in the current climate (Figure 10). The PR is again infinite with a lower bound of 7, and the increase in temperature from a late nineteenth century climate is 3.8 °C (0.7 °C to 5.7 °C).

260 In the Vancouver area the most representative station with the least missing data is New Westminster. It has data from 1875 to 2021 with a few gaps. The previous record was 37.6 °C in 2009, and in 2021 a temperature of 41.4 °C was observed, 4.0 °C warmer. A GEV fit including 2021 gives a return time of 1000 yr with a lower bound of 70 yr (Figure 11). The PR is infinite with a lower bound of 170, and the temperature increased by 3.4 °C (1.9 °C to 5.5 °C).

4 Model evaluation and analysis

265 In this section we show the results of the model validation. The validation criteria assess the similarity between the modelled and observed seasonal cycle, the spatial pattern of the climatology, and the scale and shape parameters of the GEV distribution. The assessment results in a label "good", "reasonable" or "bad", according to the criteria defined in Ciavarella et al. (2021). In this study, we use models that are labelled "good" or "reasonable". However, if five or more models are classified as "good"

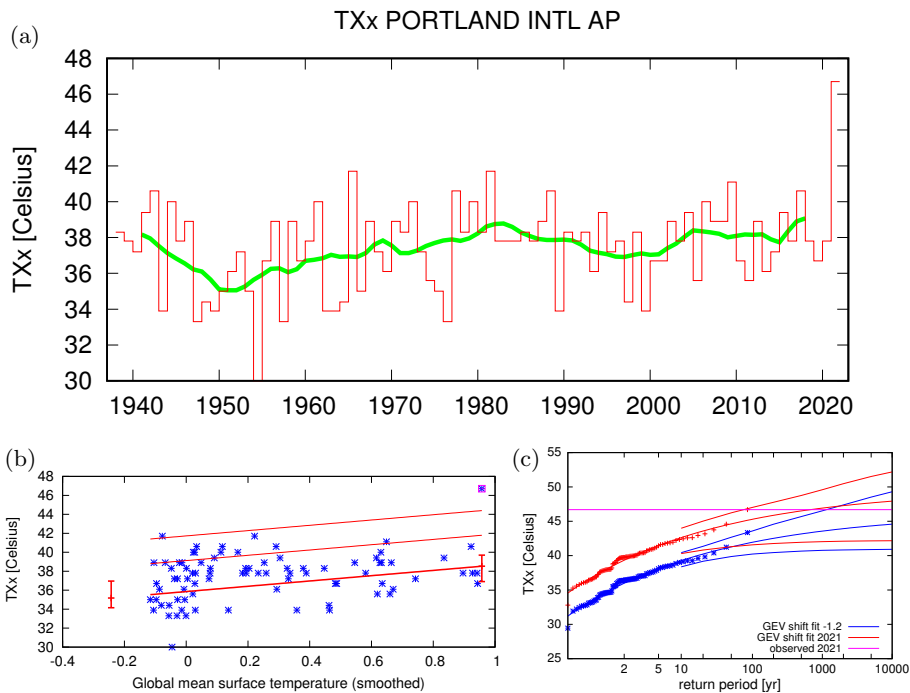


Figure 9. (a) time series of observed highest daily maximum temperature of the year at Portland International Airport. (b,c): as Figure 8 but for the station data at Portland International Airport. Source: data GHCN-D, fit: KNMI Climate Explorer.

within a particular framing such as the CMIP6 models, then we do not include all of the "reasonable" models but only those
 270 that pass the specific test on fit parameters as "good". Table 1 shows the model validation results. The full table including the
 models that did not pass the validation tests is given in Table 3. 21 models and a combined 224 ensemble members passed the
 validation test.

Next, we show probability ratios and change in intensity ΔT for models that pass the validation tests and also includes the
 values calculated from the fits to observations (Table 2). Results are given both for changes in current climate (1.2°C) compared
 275 to the past (pre-industrial conditions) and, when available, for a climate at +2°C of global warming above pre-industrial climate
 compared with current climate. The results are visualized in Section 6-5.

5 Hazard synthesis

~~We calculate~~ In Sections 3 and 4 we calculated the probability ratio as well as the change in magnitude of the event in the
 observations and the models. ~~We synthesise the models with the observations~~ In this section we combine these results to
 280 give an overarching synthesized attribution statement (please see e.g. Kew et al. (2021) for details on the synthesis technique
 including how weighting is calculated for observations and for models). Observations and models are combined into a single
 result in two ways. Firstly, we neglect common model uncertainties beyond the averaged model spread that is depicted by the

Table 1. Validation results for models that pass the validation tests on seasonal cycle, spatial pattern and fitted GEV scale parameter and shape parameter (sigma). Observations in blue, models in black.

Model / Observations (number of members)	Seasonal cycle	Spatial pattern	Sigma	Shape parameter	Conclusion
ERA5			1.70 (1.40 ... 1.90)	-0.200 (-0.500 ... 0.00)	
GFDL-CM2.5/FLOR historical-rcp45 (5)	good	good	2.01 (1.84 ... 2.17)	-0.201 (-0.272 ... -0.144)	reasonable, include as different experiment than most other models
ACCESS-CM2 historical-ssp585 (2)	good	good	1.86 (1.71 ... 2.02)	-0.200 (-0.260 ... -0.120)	good
AWI-CM-1-1-MR historical-ssp585 (1)	good	good	1.50 (1.35 ... 1.69)	-0.200 (-0.280 ... -0.110)	good
CNRM-CM6-1 historical-ssp585 (1)	good	good	1.54 (1.39 ... 1.72)	-0.210 (-0.290 ... -0.100)	good
CNRM-CM6-1-HR historical-ssp585 (1)	good	good	1.48 (1.33 ... 1.66)	-0.190 (-0.270 ... -0.100)	good
CNRM-ESM2-1 historical-ssp585 (1)	good	good	1.71 (1.54 ... 1.92)	-0.180 (-0.250 ... -0.0900)	good
CanESM5 historical-ssp585 (50)	good	reasonable	1.79 (1.76 ... 1.82)	-0.180 (-0.190 ... -0.170)	reasonable, include because statistical parameters good
EC-Earth3 historical-ssp585 (3)	good	good	1.87 (1.76 ... 2.00)	-0.220 (-0.270 ... -0.170)	good
FGOALS-g3 historical-ssp585 (3)	good	reasonable	1.80 (1.69 ... 1.92)	-0.180 (-0.210 ... -0.140)	reasonable, include because statistical parameters good
GFDL-CM4 historical-ssp585 (1)	good	good	1.43 (1.29 ... 1.62)	-0.210 (-0.300 ... -0.110)	good
INM-CM4-8 historical-ssp585 (1)	good	good	1.63 (1.46 ... 1.83)	-0.210 (-0.300 ... -0.110)	good
INM-CM5-0 historical-ssp585 (1)	good	good	1.80 (1.63 ... 2.03)	-0.240 (-0.310 ... -0.140)	good
IPSL-CM6A-LR historical-ssp585 (6)	good	reasonable	1.79 (1.71 ... 1.88)	-0.220 (-0.250 ... -0.180)	reasonable, include because statistical parameters good
MIROC-ES2L historical-ssp585 (1)	reasonable, peaks early	reasonable	1.46 (1.31 ... 1.65)	-0.190 (-0.300 ... -0.0900)	reasonable, include because statistical parameters good
MPI-ESM1-2-HR historical-ssp585 (2)	good	good	1.49 (1.39 ... 1.62)	-0.250 (-0.310 ... -0.190)	good
MPI-ESM1-2-LR historical-ssp585 (10)	good	good	1.63 (1.58 ... 1.69)	-0.260 (-0.280 ... -0.230)	good
MRI-ESM2-0 historical-ssp585 (2)	reasonable, peak too flat	good	1.41 (1.30 ... 1.53)	-0.280 (-0.340 ... -0.220)	reasonable, include because statistical parameters good
NESM3 historical-ssp585 (1)	good	good	1.48 (1.34 ... 1.67)	-0.290 (-0.370 ... -0.200)	good
NorESM2-MM historical-ssp585 (1)	good	good	1.90 (1.70 ... 2.12)	-0.250 (-0.350 ... -0.140)	in between reasonable and good, include
IPSL-CM6A-LR historical-ssp245 (32)	good, from CMIP6	reasonable, from CMIP6	1.69 (1.64 ... 1.75)	-0.220 (-0.250 ... -0.200)	reasonable, observed GMST used, include
CAM5-1-1degree C20C historical (99)	NA	NA	1.70 (1.68 ... 1.72)	-0.176 (-0.172 ... -0.180)	good, values used with warming level 1.7

Table 2. Analysis results showing the model threshold for a 1-in-1000 year event in the current climate, and the probability ratios and intensity changes for the present climate with respect to the past (labelled "past") and for the +2°C GMST future climate with respect to the present (labelled "future").

Model / Observations (number of members)	Threshold	Probability ratio PR - past [-]	Change in intensity ΔT - past [°C]	Probability ratio PR - future [-]	Change in intensity ΔT - future [°C]
ERA5	39.7 °C	3.5e+2 (3.2 ... ∞)	3.1 (1.1 ... 4.7)		
GFDL-CM2.5/FLOR historical-rcp45 (5)	34 °C	6.5e+2 (16 ... ∞)	1.6 (1.2 ... 2.1)	4.6 (3.4 ... 12)	1.2 (1.0 ... 1.3)
ACCESS-CM2 historical-ssp585 (2)	35 °C	25 (2.3 ... ∞)	1.1 (0.41 ... 1.9)	45 (4.5 ... ∞)	1.2 (0.96 ... 1.4)
AWI-CM-1-1-MR historical-ssp585 (1)	36 °C	1.1e+4 (6.6 ... ∞)	1.6 (0.84 ... 2.3)	2.8e+2 (5.5 ... ∞)	1.3 (1.1 ... 1.6)
CNRM-CM6-1 historical-ssp585 (1)	34 °C	1.9 (0.0 ... ∞)	0.22 (-0.51 ... 0.95)	69 (3.4 ... ∞)	1.1 (0.76 ... 1.3)
CNRM-CM6-1-HR historical-ssp585 (1)	35 °C	5.2e+2 (5.4 ... ∞)	1.5 (0.73 ... 2.2)	56 (4.1 ... ∞)	1.3 (1.0 ... 1.5)
CNRM-ESM2-1 historical-ssp585 (1)	38 °C	1.5e+2 (3.6 ... ∞)	1.6 (0.68 ... 2.6)	15 (2.8 ... ∞)	0.97 (0.64 ... 1.3)
CanESM5 historical-ssp585 (50)	38 °C	1.6e+3 (2.6e+2 ... 6.7e+4)	2.0 (1.9 ... 2.1)	62 (32 ... 1.5e+2)	1.5 (1.4 ... 1.5)
EC-Earth3 historical-ssp585 (3)	38 °C	3.2e+2 (8.2 ... ∞)	1.3 (0.88 ... 1.7)	20 (5.2 ... 5.8e+2)	1.2 (1.1 ... 1.4)
FGOALS-g3 historical-ssp585 (3)	41 °C	71 (8.5 ... 2.1e+8)	1.5 (1.0 ... 2.0)	17 (5.2 ... 2.2e+2)	1.1 (0.87 ... 1.3)
GFDL-CM4 historical-ssp585 (1)	31 °C	∞ (14 ... ∞)	2.1 (1.3 ... 3.0)	∞ (16 ... ∞)	1.7 (1.4 ... 1.9)
INM-CM4-8 historical-ssp585 (1)	42 °C	∞ (28 ... ∞)	2.6 (1.7 ... 3.6)	2.7e+3 (6.5 ... ∞)	1.7 (1.4 ... 2.0)
INM-CM5-0 historical-ssp585 (1)	41 °C	∞ (14 ... ∞)	2.2 (0.95 ... 3.3)	∞ (12 ... ∞)	1.6 (1.3 ... 2.0)
IPSL-CM6A-LR historical-ssp585 (6)	34 °C	1.5e+5 (50 ... ∞)	1.7 (1.4 ... 2.0)	2.4e+2 (16 ... ∞)	1.3 (1.1 ... 1.4)
MIROC-ES2L historical-ssp585 (1)	33 °C	75 (1.3 ... ∞)	1.2 (0.040 ... 2.3)	12 (2.2 ... ∞)	0.71 (0.41 ... 1.0)
MPI-ESM1-2-HR historical-ssp585 (2)	34 °C	∞ (27 ... ∞)	1.4 (0.82 ... 1.9)	4.8e+4 (12 ... ∞)	1.2 (0.96 ... 1.4)
MPI-ESM1-2-LR historical-ssp585 (10)	32 °C	∞ (1.1e+11 ... ∞)	1.6 (1.4 ... 1.9)	∞ (1.8e+3 ... ∞)	1.3 (1.2 ... 1.4)
MRI-ESM2-0 historical-ssp585 (2)	32 °C	∞ (1.3e+2 ... ∞)	1.4 (0.86 ... 1.9)	13 (4.9 ... 54)	1.0 (0.84 ... 1.2)
NESM3 historical-ssp585 (1)	30 °C	∞ (1.1e+5 ... ∞)	2.5 (1.9 ... 3.2)	∞ (66 ... ∞)	1.5 (1.3 ... 1.7)
NorESM2-MM historical-ssp585 (1)	41 °C	∞ (11 ... ∞)	2.6 (1.3 ... 3.9)	4.3e+7 (7.0 ... ∞)	1.7 (1.3 ... 2.1)
IPSL-CM6A-LR historical-ssp585 (32)	34 °C	∞ (∞ ... ∞)	2.6 (2.4 ... 2.9)	-	-
CAM5-1-1degree C20C historical (99)	43 °C	2.4e+2 (1.5e+2 ... 3.8e+2)	1.6 (1.5 ... 1.8)	-	-

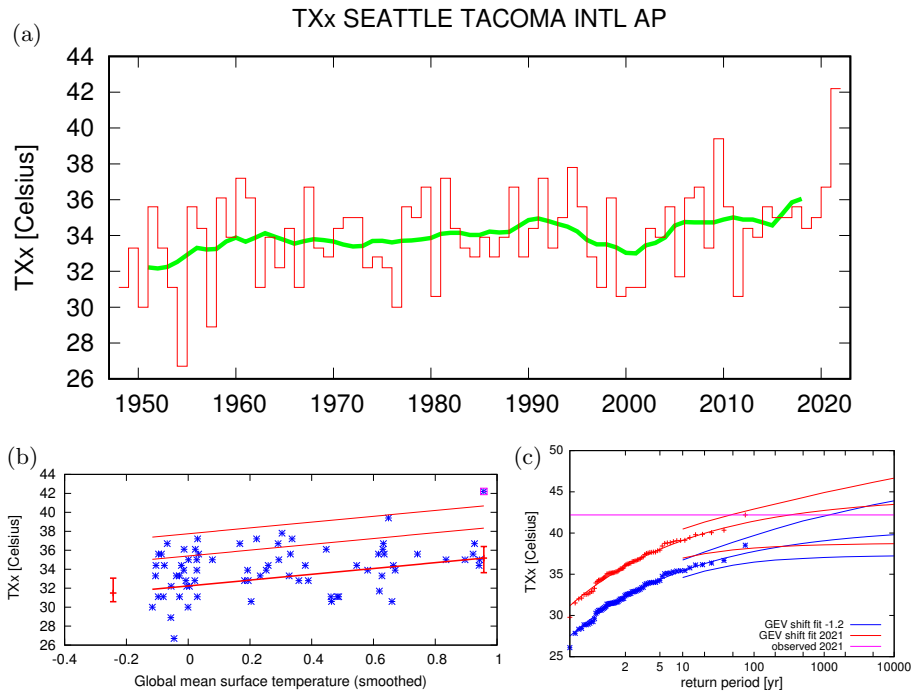


Figure 10. as Figure 9 but for the station data at Seattle-Tacoma International Airport.

bright red bar, and compute the weighted average of models and observations: this is indicated by the magenta bar, see Figure 12. The weighting applied is the inverse square of the uncertainty (the width of the bright bars). As, due to common model
 285 uncertainties, model uncertainty can be larger than the model spread, secondly, we also show the more conservative estimate of an unweighted average of observations and models, indicated by the white box accompanying the magenta bar in the synthesis figures.

Figure 12 shows the synthesis results for the current vs. past climate; the results for the future vs. current climate are presented in Figure 13. Where the results for the probability ratio do not give a finite number we replace them by 10000, to
 290 allow all models to be included in the synthesis analysis. This means that the reported synthesized probability ratio gives a more conservative, lower value. For the intensity change we report the weighted synthesis value. For probability ratio we can only give a lower estimate of the range. Generally, we do not see any consistent departures in the model results that can be traced back to experiment differences, except that models which consist of many ensemble members have smaller uncertainties.

Results for current vs past climate, i.e., for 1.2°C of global warming vs pre-industrial conditions (1850-1900), indicate an
 295 increase in intensity of about 2.0 °C (1.2 °C to 2.8 °C) and a PR of at least 150. Model results for additional future changes if global warming reaches 2°C indicate a further increase in intensity of about 1.3 °C (0.8 °C to 1.7 °C) and a PR of at least 3, with a best estimate of 175. This means that an event like the current one, ~~that is currently estimated to occur only once every analysed here as having a return period in the current climate of~~ 1000 years, would occur ~~roughly every 5 to 10 years in that in the~~ future world with 2°C of global warming roughly every 5 to 10 years according to the best PR estimate, albeit with

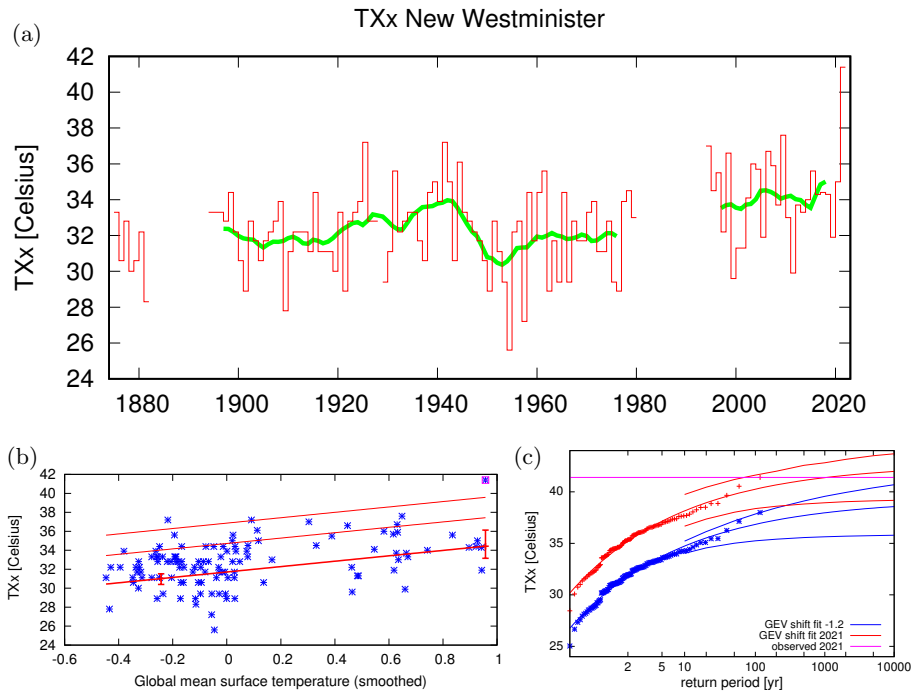


Figure 11. as Figure 9 but for the station data at New Westminster. Source: see text.

300 [large uncertainties around it](#). Such a 2°C climate could, according to the IPCC AR6 SSP2-4.5 which is the scenario closest to current emission levels, be reached as early as the 2040s (Lee et al., 2021).

6 The broader context of the heatwave

305 ~~In this discussion section we discuss the probabilities of extreme heatwaves in a broader perspective and the meteorological conditions and other~~ [the previous section we summarised and synthesised trends in TXx that were detected in observations and attributed to climate change using model data. In this section we provide context to the analysed heat event by evaluating the assumption that this heatwave occurred in this location by chance and by discussing](#) factors that possibly influenced the extremity of this heatwave event, [being the specific meteorological conditions and dynamics, preceding dryness - which can amplify temperature during heatwaves and reduce evaporation, and the ENSO and PDO modes of of natural variability that are relevant for this region.](#)

310 6.1 Probability of a chance event

In [Section 3 we offered two explanations for having such a record breaking heat wave as studied here; it could either occur by chance or nonlinear effects could have made such a heatwave possible. Here we provide some context to the first option by providing an estimate of how many heat waves that are characterised by a return time of 1000 years at their given location we](#)

Heatwaves today compared to the pre-industrial climate

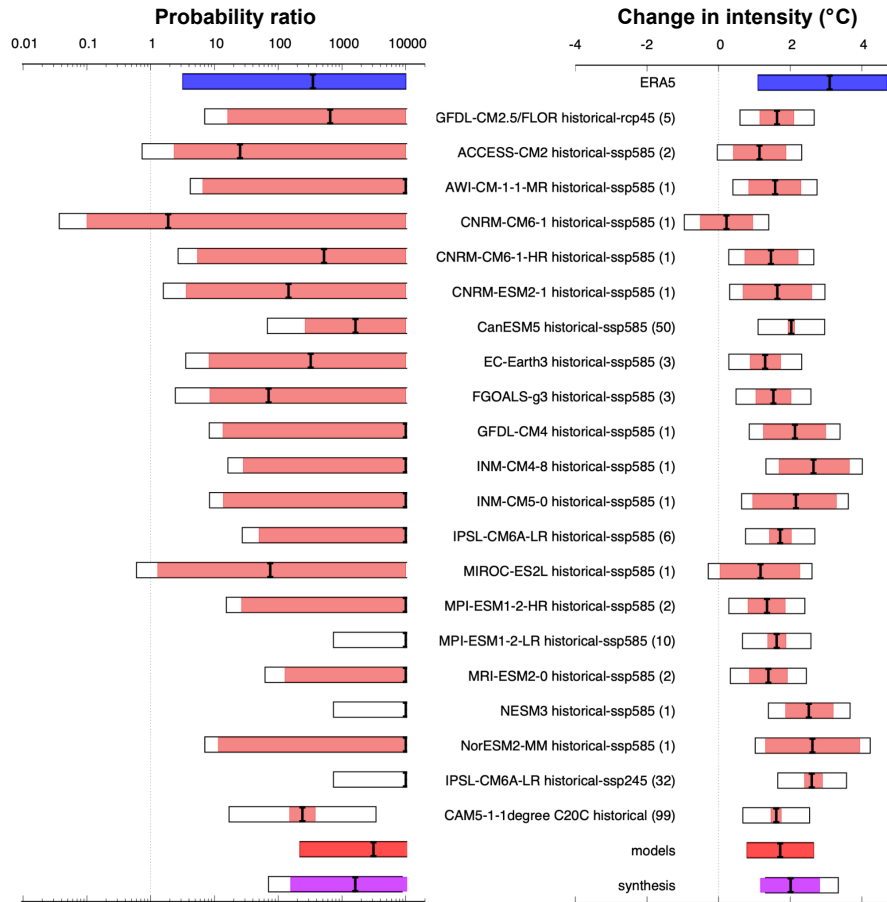


Figure 12. Synthesis of the past climate, showing probability ratios (left) and changes in intensity in °C (right), comparing the 2021 event with a pre-industrial climate. The blue bars show ERA5 results, the light red bars the model results, with common model uncertainty shown as white bars around them. The model average is shown by the bright red bars. The magenta bars are the synthesized values, and the white box accompanying the magenta bar indicates the more conservative estimate of an unweighted average of observations and models. Model names include the model experiment and scenario and the number of ensemble members in brackets.

can expect on the entire globe. In this study our analysis focuses on the Pacific North West heatwave event for the specific-area
 315 45°N-52°N, 119°W-123°W. We can give a very rough estimate of the global return time for an event of similar scale, with a
 sudden jump in Txx with a similar return time. The entire heatwave covers an area of $O(1500 \text{ km})^2$, which has been strongly
 affected by the heatwave. However, the entire area affected by heat is larger - about 1500km x 1500km which is about 1.5%
 of the land area of the world. Assuming it was just a chance event that the event occurred just by chance, we can estimate the
 return time of a similar heatwave roughly estimate the global return time, i.e. the worldwide interval at which we would expect
 320 a heatwave similar to the one observed in terms of probability and area covered, as spatial extent and probability to occur at the

Heatwaves at 2°C global warming compared to today

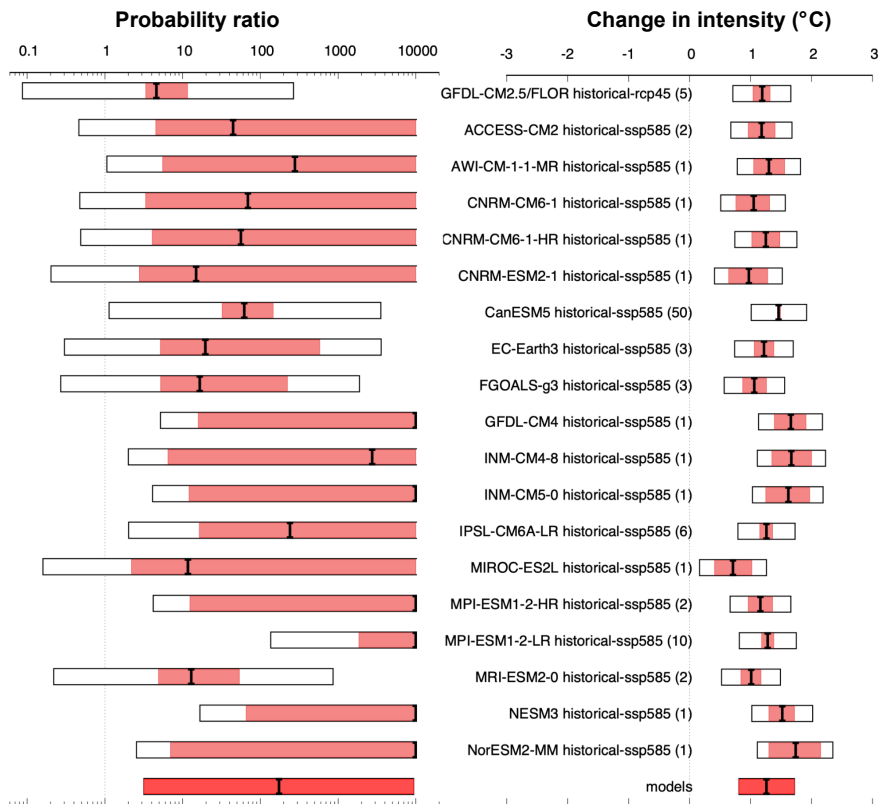


Figure 13. Same as Figure 12 but comparing 2°C of global warming (above pre-industrial) with present-day values ([models only](#)).

325 [given location. On the global land masses](#) there are about $1/(1.5\%) \sim 60$ independent areas in which [it-a heatwave of similar spatial resolution](#) could have occurred. This implies that the return time of an event as rare as [this-one-the Pacific northwest heatwave](#) or rarer, [to occur](#) somewhere over land, is about 60 times smaller than the [Θ\(estimated 1000 yr\)-that-it-occurred-years interval for such an event to occur](#) at the specific location [that-it-did](#). This gives a very rough estimate of [Θ\(a return period around 15 yr\)-years](#) with a lower bound of [Θ\(1.5 yr\)-years](#) (not shown) to [have experience](#) such a heatwave somewhere on the land of the earth. [It-is-therefore-conceivable-that-it-was-pure-chance-that-it-happened-at-this-location](#) A heatwave of this extent and extremity [might therefore no longer be considered very rare if it could be expected anywhere around the globe in one or two decades](#). Further research on this and other exceptional heatwaves is needed to determine whether this estimate is indeed realistic, i.e., whether or not we should reject the assumption that this heatwave occurred by chance at this location.

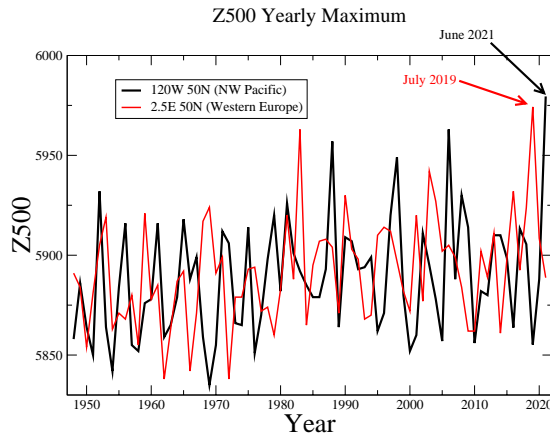


Figure 14. Annual maximum 500 hPa height (m) for two points at the same latitude in two continents. Black: Pacific NW (as above) and red: Western Europe (2.5E; 50N). Data source: NCEP initialized reanalysis.

330 6.2 Meteorological analysis and dynamics

The evolution of this event can be explained by a confluence of meso- and synoptic-scale dynamical features, potentially including antecedent low soil moisture conditions and anomalously high column specific humidity that are a hallmarks of extreme heat in western North America (Stewart et al., 2017; Bumbaco et al., 2013). At the synoptic scale, an omega-block developed over the study area beginning at roughly 00UTC on June 25th centred at $\sim 125^\circ\text{W}$, 52°N , which then slowly
 335 progressed eastward over subsequent days. This ridge featured a maximal 500 hPa geopotential height of ~ 5980 m, which is unprecedented for this area of western North America for the period from 1948 through to June 2021 at least (Figure 14).

Despite being a record, this extreme high pressure system – a feature sometimes called a "Heat dome" – is not that anomalous given the long-term trend in 500 hPa driven by thermal expansion (Christidis and Stott, 2015). Also, comparing recent heatwaves in the Pacific NW to the extreme heatwave in Western Europe in 2019 (Vautard et al., 2020), the geopotential height
 340 reached similar anomalies and has a similar long-term trend (Figure 14).

The circulation pattern itself also appears typical for hot summertime temperature: using analogues of 500 hPa and a pattern correlation metric to compare fields, we find that about 1% of June and July circulation patterns, defined as the 500 hPa geopotential height pattern within $[160^\circ\text{W}-110^\circ\text{W}; 35^\circ\text{N}-65^\circ\text{N}]$ in previous years have an anomaly correlation larger than 0.8 with the 28 June pattern. This degree of correlation is typical among days with this type of blocking pattern during the
 345 months of June and July. Roughly one third of June and July geopotential height fields have 1% or fewer analogues with an anomaly correlation larger than 0.8. We also find that this fraction does not change when restricting the analogues search within 3 distinct time periods between 1948 and 2020. We conclude that the 28 June circulation is likely not exceptional, while temperatures associated with it were.

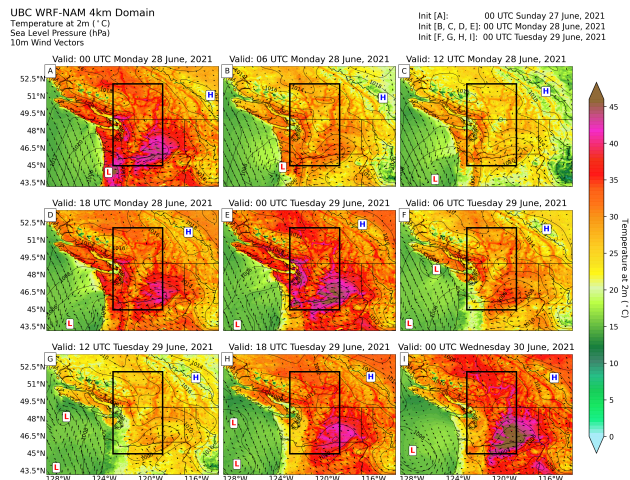


Figure 15. Regional simulation of sea level pressure, 2m air temperature, and 10m wind velocity in the region containing the study area (black box) using the Weather Research and Forecasting (WRF Skamarock et al., 2019) model forced by the North American Mesoscale Forecast System (NAM). Panel Panels (AA-I) shows show the situation during the peak evolution of the event for near-surface dynamics at a 6-hour interval from 00UTC on the part of 28th through 00UTC on the study area south 30th of Portland at 5PM local time June 2021. Of note is Panel (BE) as in (A) but for that shows the 5PM local time on the day of peak temperature for Portland, Seattle, and Vancouver.

At the meso-scale, high solar irradiance during the longest days of the year and strong subsidence increased near-surface air temperatures during the event. As is typical for summer heatwaves in the region (Brewer et al., 2012, 2013), a meso-scale thermal trough developed over western Oregon by 00UTC on the 28th June. This feature migrated northward reaching the northern tip of Washington State by 00UTC on the 29th. Further offshore, a small cut-off low travelled southwest to northeast around the synoptic-scale trough that made up the west arm of the omega block. The pressure gradients associated with the thermal trough and the cut-off low promoted moderate E-SE flow in the northern and eastern sectors of the feature and S-SW flow to the south. Near-surface winds with easterly components crossed the Cascade Range of Washington and Oregon and the southern Coast Mountains of British Columbia where they were lighter but sufficient to displace cooler marine air. The difference in elevation on the west and east sides of the mountain ranges contributed to more adiabatic heating than cooling, which helped drive the warmest temperatures observed in the event along the foot of the west slope of these mountains, near or slightly above sea level. These dynamics are illustrated in Figure 15. By 12UTC on the 29th of June 2021, all but the eastern edge the southwestern portion of the study area was under the influence of southerly to southwesterly near-surface near-surface flows that advected marine air and forced marked cooling. Unfortunately, winds associated with this transition intensified a wildfire that quickly consumed the town of Lytton, BC where Canada's nationwide all time high temperature was set just a day before.

There is no scientific consensus whether blocking events are made more severe or persistent because of Arctic amplification or other mechanisms (i.e. Tang et al., 2014; Barnes and Screen, 2015; Vavrus, 2018). We contend that Arctic sea-ice was

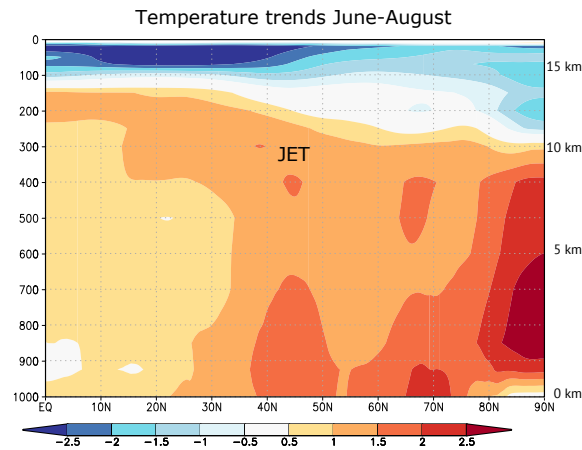


Figure 16. Zonal mean trends in temperature ($^{\circ}\text{C}$ per degree global warming) as function of pressure (hPa) in the ERA5 reanalysis 1979–2019 in the northern hemisphere.

unlikely to have played a large role in this event largely due to the timing. In early summer, Arctic sea ice remains extensive, but is melting thus keeping near surface temperatures near 0°C . This causes summer trends in near-surface temperatures over the Arctic ocean to be smaller than for the midlatitudes. During the months prior to the event, the sea ice extent was below the 1981-2010 mean, but was similar to values observed from 2011 to 2020 (Fetterer et al., 2017 (updated daily)). Instead, Arctic Amplification in summer is characterized by strong warming over high-latitude land areas (as can clearly be seen in Figure 16) and this warming signal reaches into the upper-troposphere. This enhanced warming is likely related to strong downward trends in early summer snow cover. There is evidence, from observations (Coumou et al., 2015; Chang et al., 2016), climate models (Harvey et al., 2020; Lehmann et al., 2014) and paleo-proxies (Routson et al., 2019), that this enhanced warming over high latitudes leads to a weakening of the jet and storm tracks in summer. This weakening could favour more persistent weather conditions (Pfleiderer et al., 2019; Kornhuber and Tamarin-Brodsky, 2021). Regional-scale interactions between loss of snow cover and low soil moisture associated with earlier snowmelt and rapid springtime soil moisture drying, may have had an enhanced warming impact into early summer in the Arctic. At mid-atmospheric levels there is some amplification remaining due to the winter season (Figure 16), but at the jet level (~ 250 hPa) the usual increase of the thermal gradient due to tropical upper tropospheric warming is advected North by the Hadley circulation (Haarsma et al., 2013). The final effect on the jet stream is therefore a competition between factors enhancing and decreasing the temperature gradient.

6.3 Drought

An additional feature of the event is the very dry antecedent conditions that may have contributed to observed extreme temperatures through reduced latent cooling from ~~low evapotranspiration rates~~ inhibited evapotranspiration. Low soil moisture conditions can lead to a strong amplification of temperature during heatwaves, including ~~non-linear~~ nonlinear effects (Seneviratne

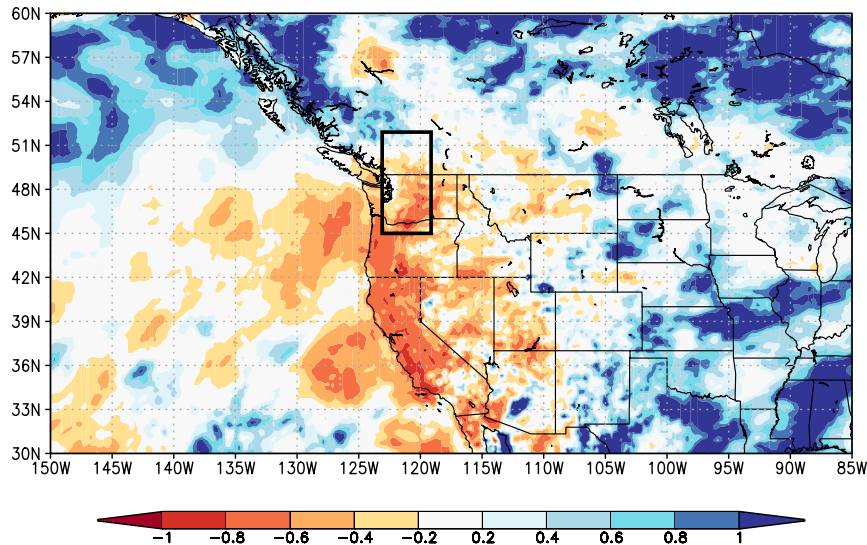


Figure 17. GPM/IMERG satellite estimates of relative precipitation anomalies in March–June 2021 relative to the whole record (2000–2020). The value -1 (dark red) denotes no precipitation, -0.5 (orange) 50% less than normal and zero (light grey) normal precipitation. [FitOrigin: KNMI Climate Explorer.](#)

385 et al., 2010; Mueller and Seneviratne, 2012; Hauser et al., 2016; Wehrli et al., 2019). In addition, low spring snow level conditions can also further amplify this feedback (Hall et al., 2008). [In this section we briefly explore whether precipitation anomalies and evapotranspiration measures could have played a role in the extreme heat via feedbacks related to soil moisture conditions.](#)

390 Integrated Multi-satellitE Retrievals for the Global Precipitation Mission (IMERG) estimates of precipitation during the period from March through June, 2021 indicate anomalously dry conditions from southern BC southward through California (Figure 17). The [relative](#) precipitation anomaly ranges from close to zero over the Puget Sound area including Seattle to values of between -0.6 and -0.8 , meaning that only ~~20-40%~~[20%-40%](#) of the average amount of precipitation fell in these locations, in Western Oregon. Note that in the northern parts of the area affected by the heatwave, i.e., in the coastal mountains north of Vancouver Island, large positive precipitation anomalies occurred over the months prior to the event.

395 The available moisture is also influenced by evapotranspiration, which depends strongly on temperature, radiation and available atmospheric moisture. Evaporation ~~was close to in the study area was below~~ normal in the ERA5 reanalysis ~~March–May in this area from March and became more negatively anomalous until May~~ (not shown), ~~so does not seem to have played a large role in setting the stage for the heatwave.~~ [During the event in late June, unusual amounts of net radiation counteracted the](#)

effects of progressive soil desiccation, and thereby prevented a further decline of evaporation with respect to its climatological expectation.

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Satellite-based measurements of surface soil moisture based on microwave remote sensing from the European Space Agency (ESA) Climate Change Initiative (CCI) provided by the Copernicus service suggest that surface soil moisture was below normal in the region since the beginning of April and that the anomalous conditions persisted until June (<https://dataviewer.geo.tuwien.ac.at/?state=88bf0c>), in agreement with the decreased precipitation and ~~close to~~ somewhat below normal evapotranspiration in the ERA5 reanalysis.

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6.4 Influence of modes of natural variability

The El Niño Southern Oscillation is the dominant source of interannual variability in the region through the Pacific North American teleconnection. The influence is typically greatest in late winter and spring and has less clear impacts during summer and fall. Because ENSO was neutral during the preceding months and the impacts on TXx are minimal ($r < 0.1$) we conclude that it had no influence on the occurrence of the heatwave.

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The Pacific Decadal Oscillation (PDO) can affect some aspects of North American summer weather, although again the connections to heatwaves in this region are very weak. The strongly negative values of the PDO index, as they occurred in May, would slightly favor cooler conditions for this region. PDO thus also is unlikely to have played an important role in the event.

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Altogether, external modes of variability appear to have played little to no role in the formation of the event.

7 Vulnerability and exposure

The Pacific Northwest region is not accustomed to very hot temperatures such as those experienced during the June 2021 heatwave. Heatwaves are one of the deadliest natural hazards, resulting in high excess mortality through direct impacts of heat (e.g. heat stroke) and by exacerbating pre-existing medical conditions linked to respiratory and cardiovascular issues (Haines et al., 2006; Ebi et al., 2021). In addition to more than 1,000 excess heat-related deaths, there was a significant increase in emergency department visits.²³ On June 28, 2021 alone, there were 1,038 heat-related emergency department visits in the U.S. Department of Health and Human Services Region that includes Alaska, Idaho, Oregon, and Washington, compared with nine visits on the same date in 2019.⁴ The mean daily number of heat-related illness emergency department visits in the region for 25-30 June 2021(424) was 69-times higher than during the same days in 2019 (6). Although this region covers about 4% of the US population, it accounted for about 15% of all heat-related illness emergency department visits nationwide during June.

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²<https://www.nytimes.com/interactive/2021/08/11/climate/deaths-pacific-northwest-heat-wave.html>

³<https://www.cbc.ca/news/canada/british-columbia/bc-heat-dome-sudden-deaths-570-1.6122316>

⁴<https://www.cdc.gov/mmwr/volumes/70/wr/mm7029e1.htm>

The June 2021 heatwave also affected critical infrastructure such as roads and rail and caused power outages, agricultural impacts, and forced many businesses and schools to close.⁵ ⁶ Rapid snowmelt in BC caused water levels to rise, leading to evacuation orders north of Vancouver.⁷ Furthermore, in some places, wildfires, the risk of which has increased due to climate change in this region (Kirchmeier-Young et al., 2019), started and quickly spread, requiring entire towns to evacuate.⁸ The
430 co-occurrence of such events may result in compound risks, for example as households are advised to shut windows to keep outdoor wildfire smoke from getting inside, while simultaneously threatened by high indoor temperatures when lacking air conditioning.

Timely warnings were issued throughout the region by the US National Weather Service, Environment and Climate Change Canada, and local governments. British Columbia has a "Municipal Heat Response Planning" summary review that gathers
435 information on heat response plans throughout the province, including responses such as increasing access to cooling facilities and distribution of drinking water. In long-term strategies, changes to the built environment are emphasized (Lubik et al., 2017). Not all municipalities throughout the Pacific Northwest and BC have formalized heat response plans, and others have limited planning, thought to be due to low heat risk perceptions throughout the area, as well as a lack of local data for risk assessments (Lubik et al., 2017).

440 The extremely high temperatures that occurred in this heat episode meant that everyone was vulnerable to its effects if exposed for a long enough period of time. Although extreme heat affects everyone, some individuals are more vulnerable, including the elderly, young children, individuals with pre-existing medical conditions, socially isolated individuals, homeless people, individuals without air-conditioning, and (outdoor) workers (Singh et al., 2019). Seattle's King County contains the third-largest population of homeless people in the U.S, with the numbers increasing during the past decade (Stringfellow and
445 Wagle, 2018). Governmental authorities opened cooling centres throughout Seattle, Portland, and Vancouver BC during the June 2021 heatwave.⁹ ¹⁰ ¹¹ Further, electrolytes, food, and water were distributed to homeless people.¹²

The lack of air conditioning contributes to heat risk. The Pacific Northwest has lower access to air-conditioned homes and buildings compared to other regions in the U.S., with the Seattle metropolitan area being the least air-conditioned metropolitan area of the United States (<50% air conditioning in residential areas) (U.S. Census Bureau). Portland and Vancouver also have
450 low percentages of air-conditioned households, 79% and 39% respectively (BC Hydro; U.S. Census Bureau). An increasing trend in air conditioned homes is occurring in all three cities (ibid.).

⁵<https://apnews.com/article/canada-heat-waves-environment-and-nature-cc9d346d495caf2e245fc9ae923adae1>

⁶<https://www.seattletimes.com/seattle-news/weather/pacific-northwests-record-smashing-heat-wave-primers-wildfire-buckles-roads-health-toll-not-yet-known>

⁷<https://globalnews.ca/news/7994540/flooding-record-breaking-heat-rapid-snow-melt-bc-video/>

⁸<https://www.washingtonpost.com/world/2021/07/01/lytton-canada-evacuated-wildfire-heatwave/>

⁹<https://durkan.seattle.gov/2021/06/city-of-seattle-opens-additional-cooling-centers-and-updated-guidance-for-staying-cool-in-extreme-heat%E2%80%AF/>

¹⁰ <https://www.oregonlive.com/weather/2021/06/portland-cooling-centers-provide-relief-from-heat.html>

¹¹<https://thebarea.com/2021/06/26/cooling-stations-set-up-around-b-c-for-record-breaking-heat-wave-this-weekend/#comments>

¹²<https://edition.cnn.com/2021/06/29/weather/northwest-heat-illness-emergency-room/index.html>

8 Conclusions and recommendations

In this study, the influence of human-induced climate change on the intensity and probability of the Pacific Northwest heatwave of 2021 was investigated. We analysed how the annual maxima of daily maximum temperatures are changing with increasing global mean surface temperature, studying the ~~heat in the~~ area 45 °N–52 °N, 119 °W–123 °W that includes the cities Vancouver, Seattle and Portland. ~~Based on the analysis of annual maximum daily maximum temperatures in~~ Synthesizing results from weather observations and modeling model simulations, we conclude that the occurrence of a heatwave of the intensity experienced in ~~that the study~~ area would have been virtually impossible without human-caused climate change. ~~Such an event is estimated to be a one in 1000-yr event~~ Whilst the extremity of this event made it challenging to robustly determine how rare it currently is, this general result is not strongly tied to the exact return period. For this analysis, we defined the probability of the event as one in 1000-yr in the current climate and found that the event would have been at least 150 times rarer without human-induced climate change. Also, this heatwave was about 2 °C (1.2 °C to 2.8 °C) hotter due to human induced climate change. Looking into the future to a world with 2 °C of global warming, an event like this, currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years according to the best PR estimate, albeit with large uncertainties around it.

~~Adaptation measures~~ This record-breaking extreme event has been analysed under the assumption that it was simply a low probability random event. A rudimentary calculation looking into the probability of a random event of this scale and severity to occur anywhere over the earth's land area, gave an estimated chance of order 1-in-15 years, which at first impression makes a random event seem plausible, but this should be more thoroughly investigated.

The alternative is that nonlinear interactions and feedbacks occurred, which amplified the intensity of this extreme, placing it in a different population of heatwave events with different (and possibly unknown) statistics. We briefly considered dynamical and hydrological (drought) mechanisms and modes of natural variability that could have had an amplifying role. The conditions in the preceding months were dry but not extremely anomalous. The circulation itself was highly anomalous but not exceptional enough to explain the record breaking heat alone, however, local topography and preceding dryness may have amplified the associated temperatures. In addition, there may also be dynamical mechanisms (Arctic Amplification) at work that influence the persistence of blocking conditions.

Further research is planned to investigate whether these or other feedbacks were operating in this outstanding event, and whether those feedbacks are related to human-induced climate change and if they increase the frequency beyond that expected for random events of such extreme temperatures. Also, further research is needed into the limitations of standard GEV analysis on annual maxima with short records and seemingly non-stationary behavior.

Whether or not local or dynamical feedbacks are responsible for amplifying the extreme temperatures in this particular event, this study shows that the human-induced warming that has occurred since pre-industrial conditions does make extreme events like this possible in the current climate and study region, and many times more likely than in the pre-industrial era.

Adaptation measures therefore need to be much more ambitious and take account of the rising risk of heatwaves around the world. Although this extreme heat event is still rare in today's climate, the analysis above shows that the frequency is increasing

with further warming. Deaths from extreme heat can be dramatically reduced with adequate preparedness action – a number of adaptation and risk management priorities emerge. It is crucial that local governments and their emergency management partners establish heat action plans to ensure well coordinated response actions during an extreme heat event - tailored to high-risk groups (Ebi, 2019). Heatwave early warning systems also need to be improved, which includes tailoring messages to inform and motivate vulnerable groups, as well as providing tiered warnings that take into account vulnerable groups may have lower thresholds for risk (Hess and Ebi, 2016). In other words, it is important to start to warn the most vulnerable as temperatures start to rise even though the general population is not yet acutely at risk. In cases where heat action plans and heat early warning systems are already robust, it is important that they are reviewed and updated to capture the implications of rising risks - every five years or less (Hess and Ebi, 2016). Further, heatwave early warning systems should undergo stress tests to evaluate their robustness to temperature extremes beyond recent experience and to identify modifications to ensure continued effectiveness in a changing climate (Ebi et al., 2018).

Data availability. Data are available via the KNMI Climate Explorer (<https://climexp.knmi.nl/>)

Appendix A: Validation tables

Table A1: As Table 1 but showing all model validation results.

Model / Observations (number of members)	Seasonal cycle	Spatial pattern	Sigma	Shape parameter	Conclusion
ERA5			1.70 (1.40 ... 1.90)	-0.200 (-0.500 ... 0.00)	
GFDL-CM2.5/FLOR historical-rcp45 (5)	good	good	2.01 (1.84 ... 2.17)	-0.201 (-0.272 ... -0.144)	reasonable, include as different experiment than most other models
ACCESS-CM2 historical-ssp585 (2)	good	good	1.86 (1.71 ... 2.02)	-0.200 (-0.260 ... -0.120)	good
ACCESS-ESM1-5 historical-ssp585 (2)	good	good	2.69 (2.49 ... 2.90)	-0.240 (-0.290 ... -0.190)	bad
AWI-CM-1-1-MR historical-ssp585 (1)	good	good	1.50 (1.35 ... 1.69)	-0.200 (-0.280 ... -0.110)	good
BCC-CSM2-MR historical-ssp585 (1)	good	good	2.22 (2.00 ... 2.49)	-0.230 (-0.310 ... -0.140)	bad
CAMS-CSM1-0 historical-ssp585 (1)	good	good	1.98 (1.79 ... 2.23)	-0.200 (-0.290 ... -0.100)	reasonable, exclude because enough good CMIP5 models
CMCC-CM2-SR5 historical-ssp585 (1)	good	good	1.29 (1.15 ... 1.46)	-0.0800 (-0.160 ... 0.0300)	reasonable, exclude because enough good CMIP5 models
CNRM-CM6-1 historical-ssp585 (1)	good	good	1.54 (1.39 ... 1.72)	-0.210 (-0.290 ... -0.100)	good

CNRM-CM6-1-HR historical-ssp585 (1)	good	good	1.48 (1.33 ... 1.66)	-0.190 (-0.270 ... -0.100)	good
CNRM-ESM2-1 historical-ssp585 (1)	good	good	1.71 (1.54 ... 1.92)	-0.180 (-0.250 ... -0.0900)	good
CanESM5 historical- ssp585 (50)	good	reasonable	1.79 (1.76 ... 1.82)	-0.180 (-0.190 ... -0.170)	reasonable, include because statistical parameters good
EC-Earth3 historical- ssp585 (3)	good	good	1.87 (1.76 ... 2.00)	-0.220 (-0.270 ... -0.170)	good
EC-Earth3-Veg historical-ssp585 (4)	good	good	2.07 (1.95 ... 2.19)	-0.250 (-0.290 ... -0.210)	bad
FGOALS-g3 historical- ssp585 (3)	good	reasonable	1.80 (1.69 ... 1.92)	-0.180 (-0.210 ... -0.140)	reasonable, include because statistical parameters good
GFDL-CM4 historical- ssp585 (1)	good	good	1.43 (1.29 ... 1.62)	-0.210 (-0.300 ... -0.110)	good
GFDL-ESM4 historical- ssp585 (1)	good	good	1.37 (1.23 ... 1.55)	-0.170 (-0.260 ... -0.0700)	reasonable, exclude because enough good CMIP5 models
HadGEM3-GC31-LL historical-ssp585 (4)	good	good	2.00 (1.90 ... 2.12)	-0.210 (-0.250 ... -0.170)	reasonable, exclude because enough good CMIP5 models
HadGEM3-GC31-MM historical-ssp585 (3)	good	good	2.08 (1.96 ... 2.22)	-0.190 (-0.230 ... -0.140)	bad
INM-CM4-8 historical- ssp585 (1)	good	good	1.63 (1.46 ... 1.83)	-0.210 (-0.300 ... -0.110)	good
INM-CM5-0 historical- ssp585 (1)	good	good	1.80 (1.63 ... 2.03)	-0.240 (-0.310 ... -0.140)	good
IPSL-CM6A-LR historical-ssp585 (6)	good	reasonable	1.79 (1.71 ... 1.88)	-0.220 (-0.250 ... -0.180)	reasonable, include because statistical parameters good
KACE-1-0-G historical- ssp585 (3)	good	good	2.27 (2.13 ... 2.41)	-0.241 (-0.282 ... -0.196)	bad
MIROC-ES2L historical-ssp585 (1)	reasonable, peaks about a month early	reasonable	1.46 (1.31 ... 1.65)	-0.190 (-0.300 ... -0.0900)	reasonable, include because statistical parameters good
MIROC6 historical- ssp585 (50)	good	good	1.31 (1.29 ... 1.33)	-0.220 (-0.220 ... -0.210)	bad
MPI-ESM1-2-HR historical-ssp585 (2)	good	good	1.49 (1.39 ... 1.62)	-0.250 (-0.310 ... -0.190)	good
MPI-ESM1-2-LR historical-ssp585 (10)	good	good	1.63 (1.58 ... 1.69)	-0.260 (-0.280 ... -0.230)	good
MRI-ESM2-0 historical- ssp585 (2)	reasonable, peak too flat	good	1.41 (1.30 ... 1.53)	-0.280 (-0.340 ... -0.220)	reasonable, include because statistical parameters good
NESM3 historical- ssp585 (1)	good	good	1.48 (1.34 ... 1.67)	-0.290 (-0.370 ... -0.200)	good

NorESM2-MM historical-ssp585 (1)	good	good	1.90 (1.70 ... 2.12)	-0.250 (-0.350 ... -0.140)	in between reasonable and good, include
UKESM1-0-LL historical-ssp585 (5)	good	good	1.99 (1.90 ... 2.09)	-0.170 (-0.190 ... -0.140)	reasonable, exclude because enough good CMIP5 models
IPSL-CM6A-LR historical-ssp245 (32)	good, from CMIP6	reasonable, from CMIP6	1.69 (1.64 ... 1.75)	-0.220 (-0.250 ... -0.200)	reasonable, observed GMST used, include
GFDL-AM2.5C360 historical (5)	good	good	2.15 (1.99 ... 2.30)	-0.259 (-0.335 ... -0.197)	bad, variability too high
CAM5-1-1degree C20C historical (99)	NA	NA	1.70 (1.68 ... 1.72)	-0.176 (-0.172 ... -0.180)	good, values used with warming level 1.7
MIROC5 C20C historical ()	NA	NA	1.36 (1.33 ... 1.39)	-0.240 (-0.224 ... -0.256)	bad
HadGEM3-A-N216 C20C historical ()	NA	NA	2.00 (1.95 ... 2.05)	-0.240 (-0.218 ... -0.262)	bad

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