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Published Version

Emerton, R., Brimicombe, C., Magnusson, L., Roberts, C., Di Napoli, C., Cloke, H. L. ORCID: https://orcid.org/0000-0002-1472-868X and Pappenberger, F. (2022) Predicting the unprecedented: forecasting the June 2021 Pacific Northwest heatwave. Weather, 77 (8). pp. 272-279. ISSN 0043-1656 doi: https://doi.org/10.1002/wea.4257 Available at https://centaur.reading.ac.uk/105695/

To link to this article DOI: http://dx.doi.org/10.1002/wea.4257

Publisher: Wiley

Predicting the unprecedented: forecasting the June 2021 Pacific Northwest heatwave

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The June 2021 Pacific Northwest heatwave

In late June 2021, an extreme heatwave impacted much of western North America, including British Columbia (and later, Alberta, Manitoba, the Northwest Territories, Saskatchewan and Yukon) in Canada, and Northern California, Idaho, Western Nevada, Oregon and Washington in the USA. This heatwave saw temperatures reach 49.6°C, the highest temperature ever recorded in Canada (in the town of Lytton, BC, where the climatological average daily maximum temperature for June is 22°C, based on ERA5 reanalysis data from 1991 to 2020) (Abraham, 2021; Copernicus, 2021). In this area, which is largely unaccustomed to life-threatening high temperatures, impacts included a rise in heat stress (a build-up of body heat as a result of exertion and/or external environment; McGregor and Vanos, 2018), over 1000 excess deaths (Romanello *et al*., 2021), overwhelmed hospitals, power outages due to melted power cables, and buckled roads (Milman, 2021). This land heatwave also coincided with a marine heatwave, causing the death of an estimated 1 billion marine creatures (Shivaram, 2021).

A land heatwave is defined as '*a period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting for at least 3 consecutive days during the warm period of the year based on local climatological conditions, with thermal conditions recorded above given thresholds*' (United Nations, 2022). A marine heatwave can be defined as a period of at least five consecutive days with anomalously warm water (typically exceeding the 90th percentile of the climatological distribution; Hobday *et al*., 2016). This article will focus on the forecasting and climatology of the land heatwave.

A key factor in this heatwave was the area of high pressure located over the region (Neal *et al*., 2022), shown in Figure 1 for the ERA5 and ERA5-HEAT reanalysis datasets (Box 1; Hersbach *et al*., 2018; Di Napoli *et al*., 2021), which persisted for several days. This so-called 'heat dome' can be seen in geopotential height at 500hPa (Z500) contours, which indicate that the geopotential height reached 5984m – up to 356m above average (based on ERA5 data indicating the maximum hourly Z500 during the peak of the heatwave, and mean climatology for June 1991 to 2020). This led to record-breaking temperatures across the region (maximum temperatures shown in Figure 1a), with temperature anomalies of up to 25 degC in any one location (up to 18 degC across a wide region, shown in Figure 1b), and exceeding the maximum temperatures in ERA5 in June from 1991 to 2020, by up to 10 degC (not shown). This heatwave also occurred 1 month before the climatologically warmest part of the year in the Pacific Northwest (late July/early August) and exceeded the annual maximum climatological temperatures by ~5 degC. For the region, this event '*was unprecedented in the observational record in terms of absolute magnitude and heat stress level*' (Thompson *et al*., 2022). The development of a La Niña (the cold phase of ENSO, the El Niño-Southern Oscillation) can be a precursor to this type of synoptic situation, as was the case in 2021, with heat extremes in North America occurring more frequently during La Niña developing summers (Luo and Lau, 2020).

Heat stress, or thermal comfort, indices can be used to represent the effect of the environment on the human body. In this article, we discuss two such indices: the Universal Thermal Climate Index (UTCI) and Humidex. The UTCI is a widely used biometeorological heat stress index that takes into account temperature, dewpoint temperature (which, together with air temperature, represents the humidity), wind speed and incidence of radiation on an individual (known as mean radiant temperature), alongside modelling how the human body responds to different thermal environments (Jendritzky *et al*., 2012). Humidex is used by Environment Canada in public messaging around the effects of heat, and accounts for both temperature and dewpoint temperature to indicate the combined impact of temperature and humidity (Smoyer-Tomic and Rainham, 2001; Government of Canada, 2019). Both indices use scales based on impacts on the human body and use units of °C as an indication of a 'feels-like' temperature, helping to predict and explore the likely heat stress pathways of a heatwave (Blazejczyk *et al*., 2012; Zare *et al*., 2018). These scales are provided in Tables 1 and 2. During the Pacific Northwest heatwave, the UTCI indicated extreme heat stress (with values exceeding 46°C; Figure 1c), and Humidex values (Figure 1d) reaching 46°C corresponded to a 'dangerous' degree of thermal discomfort, across a wide region. At this point of extreme heat stress, it is imperative to cool yourself down immediately and take actions to avoid heat stroke (Smoyer-Tomic and Rainham, 2001; Di Napoli *et al*., 2019).

Rapid attribution studies, based on peer-reviewed methodologies (Philip *et al*., 2020), found that while it is challenging to quantify just how rare this event was, it would have been 'virtually impossible' without climate change (Philip *et al*., 2021). Other studies demonstrate how heatwaves are increasing in intensity, frequency and duration with global warming (Perkins-Kirkpatrick and Gibson, 2017; Rogers *et al*., 2021), although observed and projected increases in heat extremes are 'almost always' caused by changes to the mean background state due to climate change, and are not becoming

RMetS Royal Meteorological Society

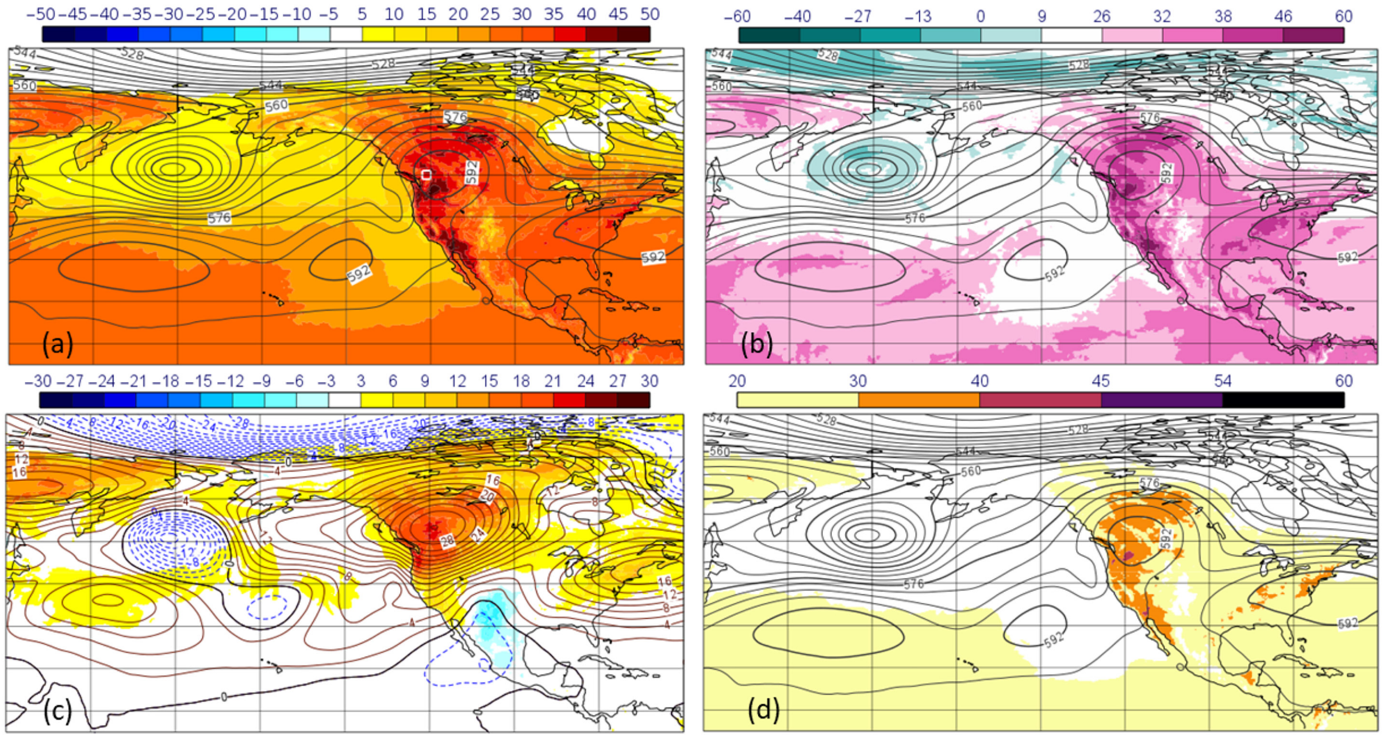

Figure 1. Climatological perspective of the daytime maximum (2m) temperatures and thermal heat stress, during the peak of the June 2021 Pacific Northwest Heatwave (28–30 June 2021). (a) Maximum temperatures, (b) maximum Universal Thermal Heat Index, (c) temperature anomaly – difference between the maximum temperatures for this event and average daytime maximum temperatures for June (1991–2020) and (d) maximum Humidex. In (a), (b) and (d), contours represent the mean Z500 for 28–30 June 2021, and in (c), contours represent Z500 anomalies from climatology (1991–2020), where brown indicates values >0, blue dashes indicate values <0, and black indicates values equal to 0. All data are from the ERA5 and ERA5-HEAT reanalyses (see Box 1). (a) Also indicates the box around Lytton used for the forecast evaluation (white box; 49–51°N, 120-122°W).

Table 1

Universal Thermal Climate Index (UTCI) thermal heat stress scale and recommended protection measures, adapted from Di Napoli et al. (2019). For more detailed information on physiological responses and protection measures, see Di Napoli et al. (2019). Colour scales used on UTCI maps in this article are based on this scale.

UTCI (°C)	*Thermal heat stress category*	*Protection measures*
>46	Extreme heat stress	Temporary body cooling. No physical activity. Drinking >0.5Lh^{-1} water necessary.
38 to 46	Very strong heat stress	Temporary use of air conditioning. Shaded places necessary. Reduce physical activity. Drinking >0.5Lh^{-1} water.
32 to 38	Strong heat stress	Shaded places. Drinking >0.25Lh^{-1} water. Temporarily reduce physical activity.
26 to 32	Moderate heat stress	Drinking >0.25Lh^{-1}.
9 to 26	No thermal stress	
0 to 9	Slight cold stress	Some warm clothing, e.g. gloves and hat.
0 to −13	Moderate cold stress	Intensify activity. Protect face and extremities.
−13 to −27	Strong cold stress	Intensify activity. Protect face and extremities. Warm clothing.
−27 to −40	Very strong cold stress	Intensify activity. Protect face and extremities (frostbite risk). Warm clothing. Reduce time outdoors.
<−40	Extreme cold stress	Stay at home. If necessary to go outdoors, use heavy and wind protected clothing.

more extreme relative to recent climatology (Thompson *et al*., 2022). In this region of North America, the Pacific Northwest, the frequency of heatwaves has doubled since the 1990s and is projected to increase further (from 1 event per year in the 1990s to ~2 in the 2020s and ~2.75 in the 2040s), while the number of heatwave days per year could rise from ~20 in the 2020s to ~60 by the end of the twenty-first century (Lau and Nath, 2012). Previous studies have highlighted that while the likelihood of Canada developing climatological conditions that could result in persistent, severe heat episodes was lower than in Europe or the USA, people living in Canada could find it more challenging to acclimatise to such heat episodes when they do occur (Bassil *et al*., 2007).

In this article, we evaluate the prediction of this extreme heatwave by the European Centre for Medium-Range Weather Forecasts' (ECMWF) Integrated Forecasting System (IFS, Cycle 47r2; ECMWF, 2021a), particularly in the context of predicting an event that surpassed previous records by such significant amounts.

Forecast evaluation

We first investigate the predictability of the heatwave and its magnitude. The first signal for unusually warm temperatures was seen in the seasonal forecasts (SEAS5; ECMWF, 2021b) produced in April and May 2021, which indicated a 50–70% probability of 2m temperatures falling in the top 20% of climatology during June across the Pacific Northwest (Figure 2). Figure 3 demonstrates the ENS and HRES

Table 2

Humidex thermal heat stress scale, adapted from the Government of Canada website (2019) and Lukic et al. (2019). Colour scales used on Humidex maps in this article are based on this scale.

Humidex (°C)	*Degree of comfort*	*Impact notes*
>54	Very dangerous	Continued physical activity leads to unavoidable heat stroke.
45 to 54	Dangerous	Physical activity can lead to possible heat stroke.
40 to 44	Great discomfort	Avoid exertion. Possible heat exhaustion.
30 to 39	Some discomfort	
20 to 29	Little discomfort	

Box 1 Forecasts and data

In this article, we evaluate ECMWF forecasts of 2m temperature, UTCI and Humidex. Forecast charts for temperature are openly available through OpenCharts (see www.ecmwf.int), with plans to make the currently pre-operational UTCI forecasts, alongside other thermal comfort indices, fully operational and openly available during 2023 following a period of testing. Humidex forecasts were computed using the open access *thermofeel* Python library (Brimicombe *et al*., 2021, 2022), which can be used to calculate a range of different thermal comfort indices.

We discuss several types of forecast produced by ECMWF, focussing on the high-resolution (HRES) deterministic forecasts and the ensemble (ENS) forecasts. The HRES forecasts provide a single deterministic forecast run, produced twice per day at 9km spatial resolution, out to 10 days ahead. The ENS forecasts provide a probabilistic forecast, using 50 ensemble members alongside a control forecast (a lower resolution equivalent of the HRES forecast), and therefore providing 51 potential forecast outcomes. The ENS forecasts are produced twice per day at 18km spatial resolution, out to 15 days ahead (the medium-range ENS), and twice per week they are run out to 46 days ahead (the extended-range ENS), at 36km spatial resolution for days 16–46.

Reanalysis datasets combine observational data with state-of-the-art models, to 'fill in the gaps' where we do not have observations and provide a globally consistent dataset of past weather and climate. The ERA5 (Hersbach *et al*., 2018) and ERA5-HEAT (Di Napoli, 2020; Di Napoli *et al*., 2021) reanalysis datasets for the corresponding variables are used to verify the forecasts. Reanalysis temperature and UTCI data are freely and openly available via the Copernicus Climate Data Store (cds.climate.copernicus.eu) and Humidex was computed from ERA5 variables (temperature and dewpoint temperature) again using the *thermofeel* Python library.

forecast evolution of temperature and UTCI for Lytton. This location was chosen because it was severely impacted by the heatwave and resulting fire (Burston and Cecco, 2021). The ENS forecasts began to indicate above-normal temperatures during the peak heatwave period 28–30 June, from 3 weeks ahead (forecast produced 7 June, not shown; Lin *et al*., 2022). From 2 weeks ahead (forecast produced 14 June, leftmost box plot in Figure 3a), the ENS forecasts began to consistently indicate the possibility of temperatures exceeding the maximum of the model climatology (based on 1200 forecasts). Confidence in the likelihood of an extreme heatwave and potentially record-breaking event continued to increase (as shown by the reduction of forecast spread in the blue box plots in Figure 3), such that by the 1200 UTC forecast produced on 18 June, the full ensemble indicated that both temperature and UTCI would be well above average. By 23 June (5 days ahead of the heatwave's peak period and 2 days before the heatwave started), for both UTCI (0000 UTC forecast) and temperature (1200 UTC forecast), all of the 50 ensemble members, and the HRES forecast, were predicting this event would exceed the maximum of the model climatology.

The HRES forecasts also consistently predicted temperatures and UTCI beyond the maximum of climatology, from 21 June onwards (red dots, Figure 3), and while both the HRES and ensemble forecasts underestimated the maximum temperatures, the HRES forecasts provided a slightly more accurate prediction of the highest values. Both were indicating in advance that an extreme event beyond anything the model had previously captured was highly likely. The evolution of both the temperature and UTCI forecasts was very similar.

To investigate whether the forecasts correctly captured the areas most likely to be impacted by the heatwave, the HRES forecasts out to 1 week ahead are evaluated and mapped in detail. At 1 week ahead of the peak of the heatwave on 29 June, the forecasts were indicating extreme maximum temperatures in much of the region of the Pacific Northwest that was impacted by this heatwave. However, the magnitude of the heatwave in some of the locations that experienced extreme temperatures and were severely affected, particularly further to the north, was not apparent at 7, or 5, days ahead. This is because the forecasts placed the region of highest temperatures further to the southeast than was eventually observed, due to placement of the 'heat dome' further to the south and east in the earlier forecasts. This can be seen in Figure 4, which provides a snapshot of the forecast evolution of temperature, UTCI and Z500 using the HRES forecast maps from 1, 5 and 7 days ahead of 29 June 2021 (where 29 June 2021 refers to the 24-h period 0500 PDT 29 June 2021–0500 PDT 30 June 2021).

As the position of the heat dome moves further northwest as the forecasts progress, the maximum temperature forecasts improve, with higher temperatures indicated in more regions to the north. A similar picture is seen in the forecasts of night-time minimum temperature (Figure 4j-l), and UTCI (Figure 4b–d), with the heatwave location improving with decreasing lead time, although the forecasts of UTCI remain more consistent throughout the week leading up the event, and better predict the magnitude of UTCI and extreme heat stress seen in ERA5-HEAT. Both the maximum temperatures and UTCI were underpredicted, particularly further to the north.

Beyond 5 days ahead, the forecasts of all three variables significantly underpredicted the magnitude of the heatwave over the Pacific Northwest, and over-predicted temperature and heat stress further to the southeast (shown in Figure 5, mapping the forecast errors compared to ERA5[-HEAT] for several lead times), again suggesting that the area of high temperatures was incorrectly positioned in the forecasts at longer lead times. At 5 days ahead, there is very little underestimation of the UTCI over the affected area, but at this lead time, the heat stress is overestimated further to the east, while the maximum temperature and Humidex were still significantly underestimated at day 5. By 3 days ahead, the positioning error is significantly improved. While there is some underestimation of the magnitude at 1–3 days ahead in maximum temperature, UTCI and Humidex forecasts, this underestimation is larger in the temperature forecasts, with an underestimation of 2–5 degC across large areas of the impacted

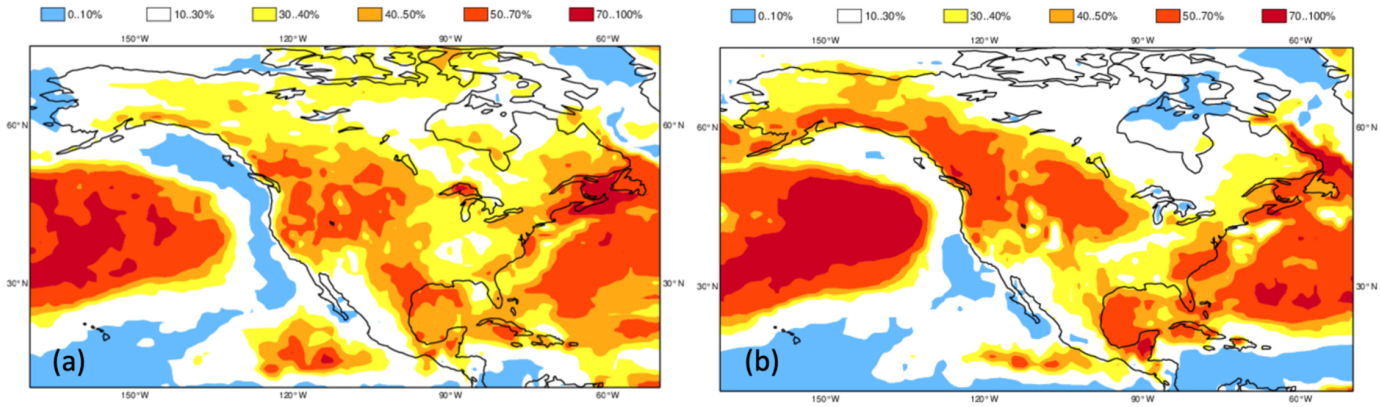

Figure 2. ECMWF seasonal (SEAS5) forecasts of 2m temperature, indicating the probability that the temperature will fall in the top 20% of climatology during June 2021, for the forecasts produced on (a) 1 April 2021 and (b) 1 May 2021. Based on 51 ensemble member forecasts, with a model climatology of 600 forecasts covering the period 1993–2016. These forecast charts were downloaded from ECMWF's suite of openly available forecast products (www.ecmwf.int).

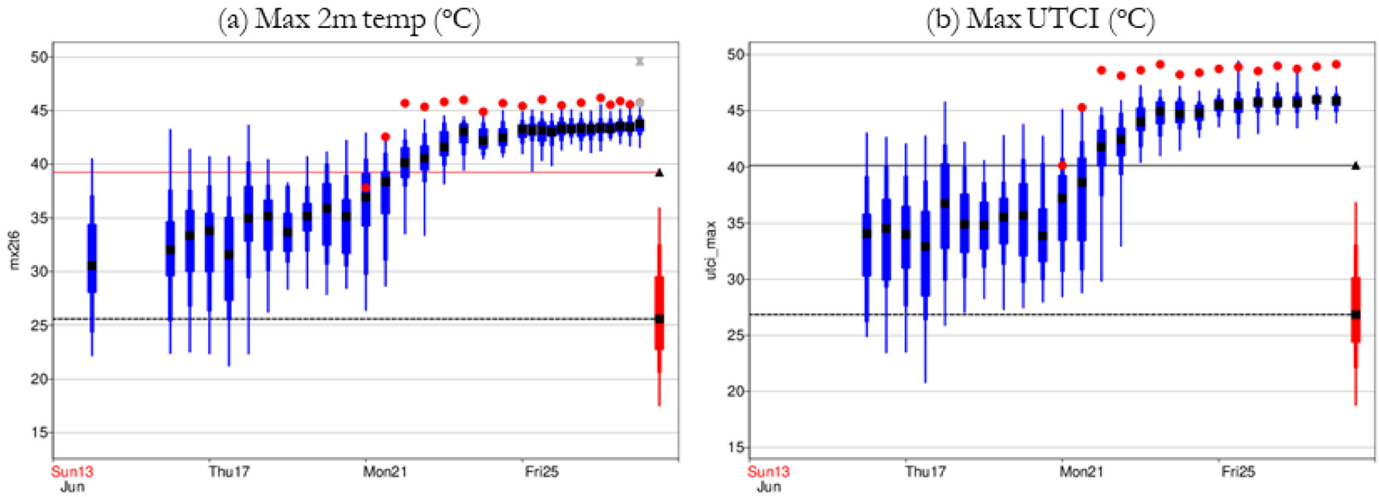

Figure 3. Extended- and medium-range ensemble and high-resolution (HRES) forecast evolution compared to climatology for (a) maximum temperature and (b) maximum Universal Thermal Climate Index (UTCI) in Lytton, BC, Canada over the 3-day period, 28–30 June. Forecasts are shown for a box around the severely impacted town of Lytton (49–51°N, 122–120°W; shown in Figure 1a). Blue box plots indicate the range of forecast values across the 50-member ensemble for the forecast date indicated on the x-axis, moving from further ahead of the event on the left, to the occurrence of the event on the right. Red dots indicate the value in the HRES deterministic forecast produced on the same date (available out to 10 days ahead). Red box plots indicate the range of values that have occurred in the model climatology at this location, based on the 20-year extended-range re-forecast climatology (1200 forecasts). The black dashed line represents the median of climatology, and the red (a)/black (b) solid line (and black triangles) represents the maximum of the climatology. The grey dot in (a) represents the analysis value and the grey 'x' represents the observed maximum temperature of 49.6°C. Equivalent observations are not available for UTCI.

region, compared to smaller pockets of underestimated heat stress in the UTCI forecasts, of 1–2 degC, and in some small areas 2–5 degC. Humidex sits between the two, with a larger area where the magnitude is underestimated than UTCI, but generally smaller errors than temperature.

Previous work has shown that while '*UTCI has some linear dependencies on air temperature, a given temperature can lead to a wide range of UTCI values*' (Pappenberger *et al*., 2015), and it is influenced by both solar and thermal radiation and sensitive to wind speeds. For example, Provençal *et al*. (2016) undertook a sensitivity analysis of the variables used to compute different thermal comfort indices, in Quebec City, Canada. While both indices are highly correlated with temperature, wind speeds were found to have a strong influence on UTCI, followed also by the mean radiant temperature. Since the inclusion of wind speed can limit the capacity of UTCI to reach very high values, Humidex (which does not include wind speed) can sometimes indicate higher values than UTCI, but this can also be said to limit the versatility of Humidex since winds can provide some relief during hot weather (Provençal *et al*., 2016). It has also been shown that radiation is critical in terms of the resulting uncertainty in UTCI forecasts (Schreier *et al*., 2013), with forecast uncertainties lower during clear-sky conditions than cloudy conditions. The difference between temperature and UTCI may also be much larger during a more radiant situation, such as during the early afternoon with clear skies, than in less radiant situations (Novak, 2013). The inclusion of these environmental variables in the calculation of UTCI is likely to impact the forecast skill and predictability compared to forecasts of temperature and other indices that do not account for key drivers of heatwaves, such as radiation (Pappenberger *et al*., 2015).

These results show that forecasts were able to predict an unprecedented, record-breaking heatwave event with high confidence from several days before the start of the heatwave. They also highlight the benefits of combined use of a high-resolution deterministic forecast and an ensemble forecast, given the longer lead times at which the probabilistic forecasts are able to indicate the possibility of an extreme event,

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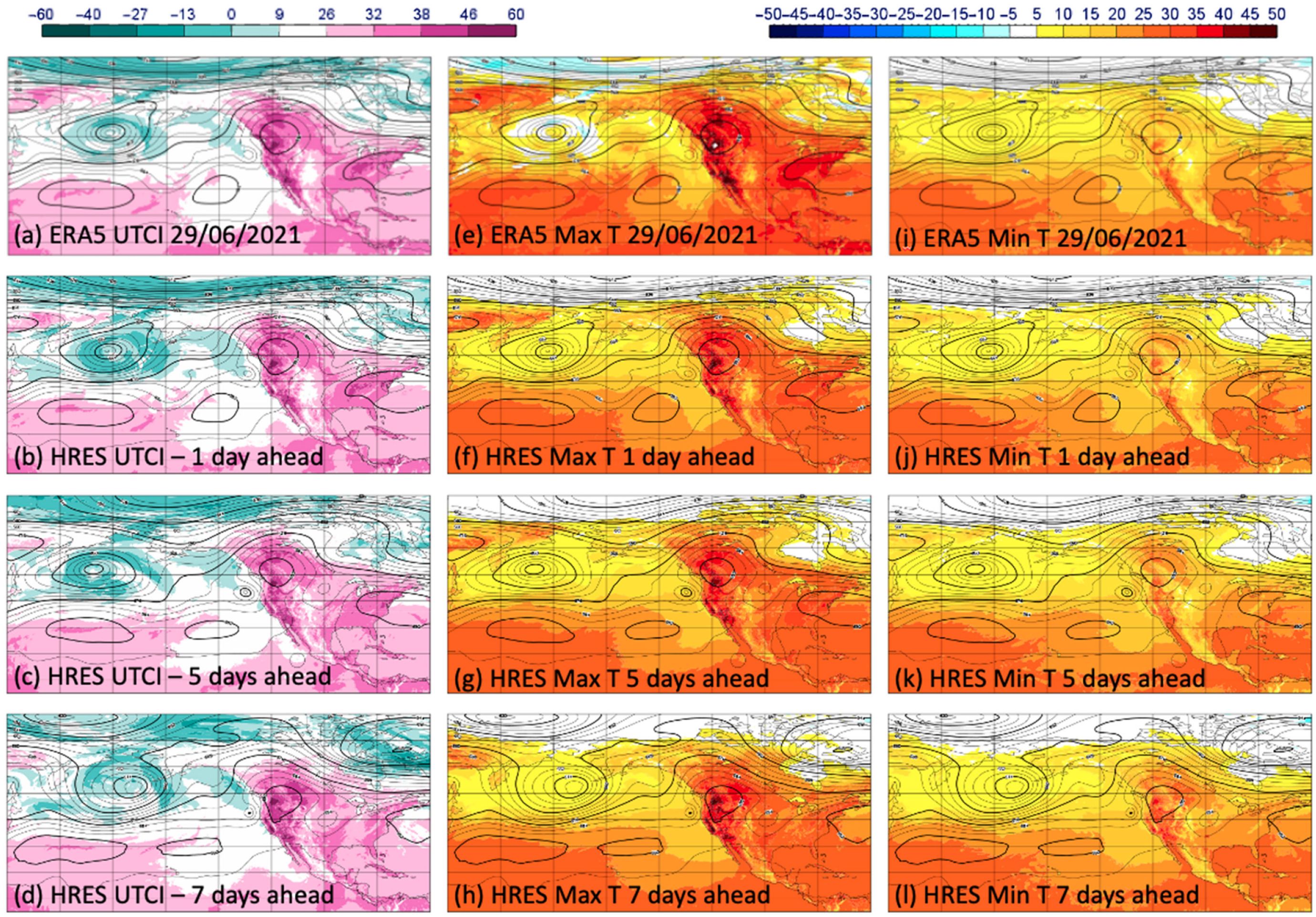

Figure 4. Forecast evolution of the daytime maximum and night-time minimum (2m) temperatures and thermal heat stress, during the week ahead of 29 June 2021, where 29 June 2021 refers to the 24-h period from 1200 UTC 29 June to 1200 UTC 30 June, or 0500 29 June to 0500 PDT 30 June/local time (UTC-7). (a) ERA5 maximum Universal Thermal Climate Index (UTCI) on 29 June 2021, (b–d) ECMWF HRES UTCI forecasts valid on 29 June, produced 1, 5 and 7 days ahead, (e) ERA5 maximum 2m temperature on 29 June 2021, (f–h) ECMWF HRES maximum 2m temperature forecasts valid on 29 June, produced 1, 5 and 7 days ahead, (i) ERA5 minimum 2m temperature on 29 June 2021, (j–l) ECMWF HRES minimum temperature forecasts valid on 29 June, produced 1, 5 and 7 days ahead. In (a), (e) and (i), contours represent the ERA5 mean Z500 on 29 June 2021, and in (b–d), (f–h) and (j–l), contours represent the ECMWF HRES mean Z500 forecasts valid on 29 June, produced 1, 5 and 7 days ahead.

and the ability of HRES to better capture larger temperature and UTCI extremes in this case.

Discussion and outlook

In this article, we evaluated and compared forecasts of temperature, UTCI and Humidex for the heatwave that impacted the Pacific Northwest in June 2021. Results highlight that, for this event, while the forecast evolution of the three variables was similar, the underestimation seen in all three was smaller in the forecasts of UTCI at lead times of 1–5 days. While focusing on one heatwave cannot give a wider perspective of forecast skill across a range of events, previous studies have shown that UTCI is successful in predicting 'hazardous heat stress levels' up to 10 days in advance, with regional variations (Pappenberger *et al*., 2015). Many operational forecasting centres have introduced warning systems for heat-related health hazards, based on a variety of indices, and communicate suitable prevention measures (some examples are shown in Table 1) (Kotharkar and Ghosh, 2022). Such indices can be calculated using openly available software such as the *thermofeel* Python library (Brimicombe *et al*., 2021, 2022), which allows for the calculation of 11 different thermal comfort indices alongside supporting variables, from UTCI and Humidex to wind chill. Additionally, ECMWF will begin to provide forecasts of thermal comfort indices, including UTCI, operationally in 2023 after a period of testing and evaluation, for the purpose of heat health hazard forecasting at the global scale.

The results presented show that forecasts were able to, and did, predict an unprecedented extreme event, with a magnitude beyond anything the model had seen before (based on a sample of 1200 forecasts), and with very high confidence. Indeed, 100% of ensemble members exceeded the maximum of climatology from at least 2 days ahead of the start of the heatwave. The possibility of an extreme event was evident in the medium-range forecasts from 2 weeks ahead. Previous work evaluating the potential use of UTCI has demonstrated the utility of global forecasts of UTCI for early warnings and disaster preparedness, particularly in places without higher resolution national forecasts of thermal comfort indices, where much simpler indices are used (without consideration of thermo-physiological effects), or in data-sparse regions (Pappenberger *et al*., 2015; Di Napoli *et al*., 2019).

The Pacific Northwest heatwave surpassed previous records for maximum temperatures by significant margins. Typically, when temperature records are broken, it is by a fraction of a degree, but in this case, temperatures were ~5 degC above the previous maximum temperature recorded in Canada, and up to 10 degC beyond the maximum temperatures in ERA5 for the time of year. Thompson *et al*. (2022) investigated heatwaves since 1950 that have similarly surpassed climatological records by significant amounts, identifying several events globally, but with varying impacts due to factors such as the timescale, population, and adaptation due to policy changes.

This heatwave was not alone in breaking temperature records during 2021

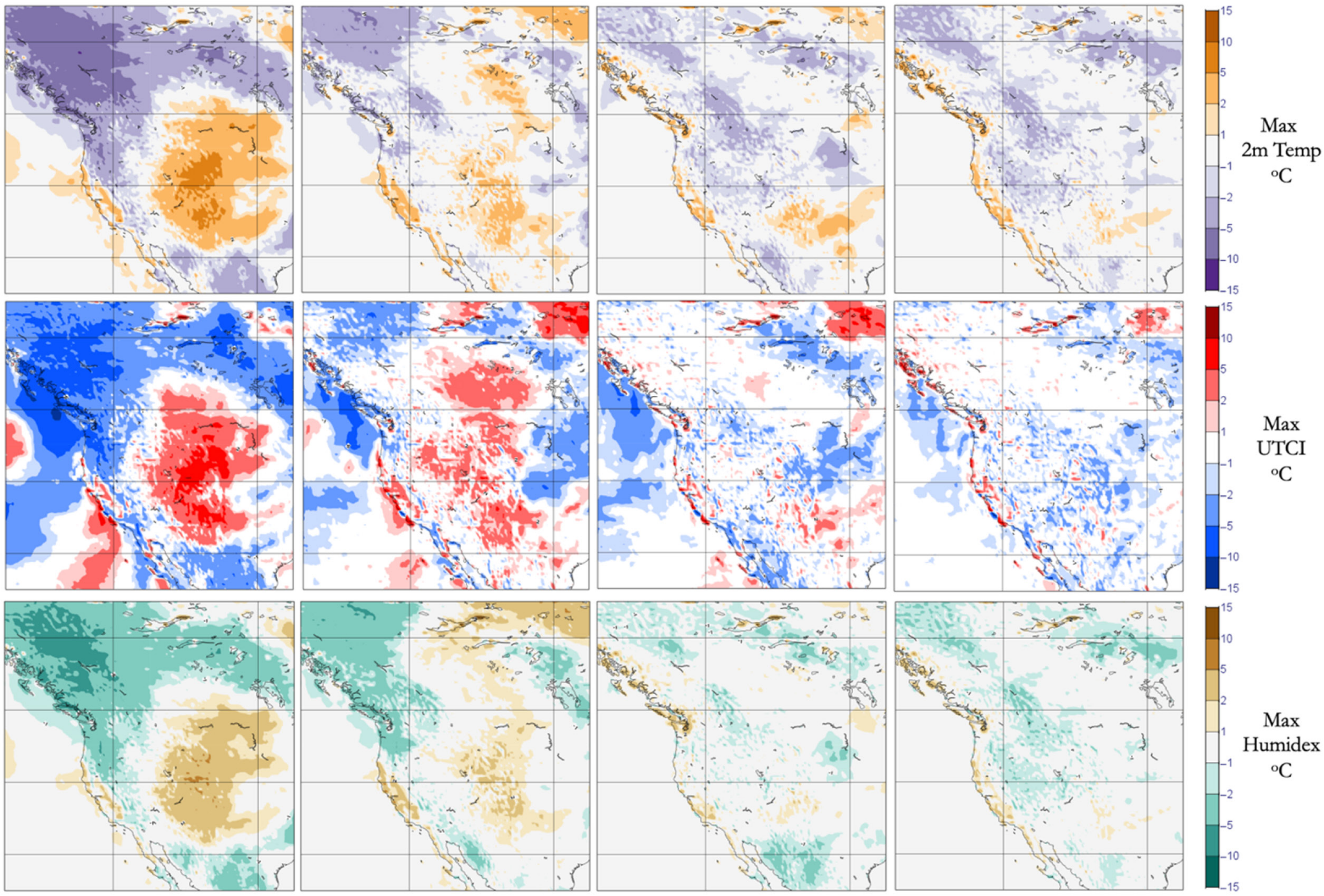

Figure 5. Forecast error of ECMWF's HRES forecast for (from top to bottom) daily maximum 2m temperature, daily maximum Universal Thermal Climate Index (UTCI) and daily maximum Humidex. Forecasts are validated against ERA5 and ERA5-HEAT, and errors are shown for the HRES forecasts initialised at 1200 UTC at lead times (from left to right) of 7, 5, 3 and 1 day(s) ahead of the heatwave period 25–30 June 2021. The errors shown are the average (mean) error for all forecasts at the given lead time, valid during the 25–30 June period. Positive (negative) values indicate an over-prediction (underprediction).

(Brimicombe *et al*., 2021). In June and July, temperatures above the Arctic Circle exceeded 30°C, and a heat dome led to large temperature anomalies over Finland and western Russia (Copernicus, 2021). Large parts of Europe experienced heatwave conditions during June, as part of '*an arc of unusually high temperatures that extended from northwest Africa, through Europe and southeastwards*', also impacting Iran, Afghanistan, Pakistan and Kazakhstan (Copernicus, 2021; OCHA, 2021). A second heatwave also impacted the Pacific Northwest in August. During the first months of 2022, 75 temperature records were set in Argentina during a heatwave affecting Argentina, Brazil, Uruguay and Paraguay, and records in Western Australia have been matched, with temperatures up to 50.7°C recorded in Onslow, WA (Copernicus, 2022; Hannam, 2022).

Heatwaves are not only a threat to health and mortality, but also have multi-sectoral impacts from agriculture to transport and energy infrastructure (Zuo *et al*., 2015). They often coincide with other natural hazards (e.g. wildfires and droughts), and due to climate change, are increasing in intensity, duration and frequency (Perkins-Kirkpatrick and Gibson, 2017; Brimicombe *et al*., 2021). Not only are more intense extremes projected with future climate change, but also events such as the one discussed here, that break records by much larger margins, and their probability of occurrence depends strongly on the rate, rather than amount, of global warming (Fischer *et al*., 2021).

While the focus is often on temperature extremes, it is important to account for the fact that health impacts from heatwaves are influenced by many other factors. The impact of the wind on cooling the body, or of humidity and radiation exposure in heating and preventing cooling through sweating, are key factors in how the outdoor environment impacts heat exchange between the human body and its surroundings (McGregor and Vanos, 2018). Impact-based forecasting, complementing forecasts with impact estimates such as expected damage and human consequences, can provide important advantages for decision-making (Merz *et al*., 2020), and recognising heat stress as a physiology-mediated effect of compound environmental factors could open the pathway to human-centric weather forecasting (Di Napoli *et al*., 2021). Alongside trends in extreme temperature, studies have also shown that areas impacted by heat stress have grown (since 2000, Brimicombe *et al*., 2021), and with increasing populations exposed to heat stress during heatwaves, it is imperative to consider biometeorological forecasts. This can be particularly meaningful in regions, like Canada, where local populations, due to lower exposure to hot summer conditions, could have more difficulty in physiologically adapting to heat extremes when they occur (Bassil *et al*., 2007).

While communication during the heatwave was extensive and measures were put in place such as setting up cooling centres (All Around BC, 2021), some discussions in the media suggested that while it was noticed that forecasts were predicting a record-breaking event, there was potentially a widespread belief that this was not something that could happen in this region (e.g. '*We saw the forecasts and it was hard to believe as we don't really have heatwaves like that*' – Milman, 2021; '*People have recognized that this might happen in theory, but I don't think they expected it to happen, […] They certainly didn't expect it to happen now, and they didn't expect it to be this bad*' – Pulkkinen, 2021). Effective warnings often require those communicating forecast and warning information to inspire the imagination of the people who are making decisions (Cloke, 2022), to understand the possibilities and potential impacts. In a time where our climate is rapidly changing, and it is well known that we will see more, and more extreme, extreme events, how can we increase trust and encourage anticipatory action when forecasts begin to tell us to expect the unprecedented?

Funding information

Claudia Di Napoli is supported by a Wellcome Trust grant (209734/Z/17/Z), and Chloe Brimicombe is funded by the European Union's Horizon 2020 Research and Innovation programme (grant 824115).

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doi:10.1002/wea.4257