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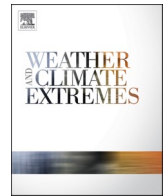
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Using analogue methods to identify trends in circulation patterns of midlatitude heatwaves

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ABSTRACT

Circulation analogues are useful tools for extreme event assessment. They can be used to assess changes in the dynamical conditions associated with a specific extreme event. Here, we use circulation analogues to investigate a set of six midlatitude heat extremes, spanning all midlatitude continents. We objectively assess some of the decisions required when selecting circulation analogues. We show the choice of analogue domain, climatic variable, and similarity metric influence how well the analogues capture the magnitude of the meteorological hazard of the event itself. We show that, due to the complex nature of the climate system, each event requires individual assessment to determine how to select analogues that best represent the hazard. For the six case studies, we present an assessment of analogues using the workflow identified. Some events show significant dynamical changes between 1950-1980 and 1994-2024, which could act to amplify extreme heat.

We show that, for midlatitude heatwaves, circulation analogues can provide useful information about temporal changes in circulation patterns of similar events. We provide a workflow for the use of circulation analogues within operational detection and attribution studies, with a publicly available online Climate Explorer tool.

1. Introduction

As a result of climate change we are increasingly experiencing extreme weather events (Seneviratne et al., 2021). Record breaking heatwaves, heavy rainfall, and drought can often be linked to human induced climate change (Diffenbaugh et al., 2017; Christidis and Stott, 2016; Zhang et al., 2013; Garreaud et al., 2020). Such extreme weather and climate events impact both society and the environment, and are of great concern to policy-makers.

For heat extremes, climate change is increasing the frequency and intensity of events in all recent cases studied (Perkins-Kirkpatrick and Lewis, 2020; Seneviratne et al., 2021). However, the quantification of the attributable part of changes is often challenging (van Oldenborgh et al., 2022), due to systematic differences in model and observations. Changes are driven by both thermodynamical and dynamical changes in the atmospheric conditions. Heat events are closely associated with atmospheric circulation anomalies, and thus circulation changes will impact heat extremes (Adams et al., 2021; Grotjahn et al., 2016). The

observed rate of increase in extreme heat is not uniform globally, and climate models fail to reproduce the magnitude of the observed atmospheric circulation trends in many regions (Kornhuber et al., 2024; Vautard et al., 2023), explaining part of model/observation heat extremes trend mismatches. The large heatwave trend over Western Europe has been shown to be amplified by trends in atmospheric dynamics (Rousi et al., 2022). Over half the trend in heat extremes in eastern Europe has been shown to be linked to an increase in anticyclonic circulation (Horton et al., 2015), often coupled with a cut-off low located over the Eastern Atlantic (Vautard et al., 2023).

Some studies have examined the circulation pattern of specific events, for example the conditions that led to the 2003 European heatwave may be increasing in frequency (Jézéquel et al., 2018). Elsewhere, the Western North America heatwave of 2021 was associated with a strong anomalous high-pressure system (Thompson et al., 2022; Bartussek et al., 2022). It has been shown that in large ensembles of model simulations the hottest days in that region are associated with similar high-pressure systems (Risbey et al., 2023). Heatwaves associated with

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such atmospheric circulation patterns have been shown to increase in intensity faster than background warming (Zhang et al., 2023). Understanding how atmospheric circulation patterns relate to their surface impacts enables us to build confidence in interpreting changes in meteorological hazards. This allows society to be better prepared for heat extremes of the current and future climate.

To characterise atmospheric circulation patterns related to extremes, attribution studies sometimes use circulation analogues. Circulation analogues of a given atmospheric event are defined as circulations bearing similar features of that circulation given a measure of similarity (Yiou et al., 2007; Vautard and Yiou, 2009). The earliest studies highlighted the difficulties in identifying good analogues (Lorenz, 1969). Yet, circulation analogues have been shown to be a useful tool with many applications, such as to investigate the contribution of specific circulation patterns to heatwaves (Jézéquel et al., 2018; Yule et al., 2024; Pons et al., 2024). Circulation analogues of a specific extreme weather event can be used to examine changes in similar events, conditioned to the circulation, within a rapid attribution framework. This has been applied to multiple event types (Cattiaux et al., 2010; Faranda et al., 2022, 2024). However, for some cases of extreme rainfall it has been shown that circulation analogues may not represent the meteorological hazard (Thompson, 2025). We note, circulation analogue methods do not allow for variability in the atmospheric pattern – even if similar hazards occur through different patterns only the events dynamically similar are included.

Despite the usefulness of this approach analogues require a series of potentially arbitrary choices that may affect the output of an event analysis. For instance, choice of the domain size, number of analogues identified, or mathematical formulation of the analogues, can affect the conclusions. Earlier studies have assessed some of these methodological choices for specific case studies. For example, Harrington et al. (2019) assessed the 1947 Central European heatwave with particular attention paid to the quality and timescale of analogues, and Jezequel et al. (2018a) investigated the impact of different circulation variables and spatial domains to identify analogues of European heatwaves. Some studies have combined multiple methodological choices, for instance Kim et al. (2025) identify analogues using Euclidean distance, and then identify a subset of those analogues using spatial correlation.

Mathematically, there are multiple ways that analogues can be selected. Past studies have identified the closest days by minimising the root mean square error between days (Harrington et al., 2019); maximising spearman correlation between days (Yule et al., 2024); minimising Euclidean distance (Jezequel et al., 2018; Faranda et al., 2022); or maximising the Mahalanobis metric (Stephenson, 1997). Any of these methods could be potentially improved by combining with deep autoencoders, as has been applied to European heatwaves using the Euclidean distance approach (Pérez-Aracil et al., 2024). Self-organising maps can also be used to assess changes in dynamics of extreme events (Adams et al., 2021).

This paper assesses the use of circulation analogues to investigate trends in the circulation patterns associated with heat extremes. We set out to assess how best to identify analogues for heat extremes, producing a workflow that could be further developed to use within operational attribution, alongside attribution methods. Building on earlier studies which explore elements of the methodology individually, or for specific events, we assess the choice of atmospheric field, mathematical formulation of field similarity, domain size, and number of analogues. For some of these methodological choices, rules to identify analogues with greatest impact can be defined, allowing us to move towards a semi-operational system, as has already been produced for probabilistic extreme event attribution (Philip et al., 2020) and a simplified analogues approach (Faranda et al., 2024). We use the findings to analyse both differences between periods and long-term trends in the circulation patterns associated with six midlatitude heat extremes. This can assist efficient and transparent attribution and assessment of impactful weather events, facilitating global collaboration (Coumou et al., 2024).

In this study we focus only on heat extremes in the midlatitudes. In principle, the methodology presented can be applied to many different types of climate extreme such as rainfall, windstorms, and cold events which arise from distinct circulation patterns. However, different event types create different challenges due to the complexity of the climate system and therefore a different set of rules might be better applied to different event types.

2. Data and methods

2.1. Data

We use the fifth generation ECMWF atmospheric reanalysis of the global climate (ERA5) dataset as a proxy for observations (Bell et al., 2021). We use the climate variables: sea level pressure (SLP), 500 hPa geopotential height (Z500), and 2m temperature (T2m). T2m is used, rather than maximum daily temperature (Tmax), to allow the method to be directly used for cold extremes. We tested using Tmax and found it did not influence the conclusions. Therefore, we chose to present results using T2m. All data is on a daily temporal resolution (calculated as a mean of hourly data) and 0.5° spatial resolution, with data from 1950 to 2024 used. We use 0.5° as it allows the development of an operational system – using higher resolution slows the computational processing considerably without notable changes to results.

2.2. Event selection: hazard index

We assess six extreme heat events – one from each midlatitude continent, listed in Table 1 and shown in Fig. 1 and Fig. S1. These events are selected to include both record smashing events and marginal records, and both recent events and some from earlier decades.

To assess whether analogues adequately reproduce the meteorological hazard of the extreme events studied we define a hazard index. As we are assessing heat extremes, the meteorological hazard is based on T2m averaged over a specified region. The domain used for the hazard index is taken from earlier studies where possible, or from anomaly maps of the event date (Table 1, Fig. 1). The influence of the choice of hazard domain is not explored in this study. To calculate the hazard index, daily mean T2m over the determined domain is calculated to produce a timeseries (Fig. 1).

2.3. Determining methodological choices

An analogue is defined as a day with similar atmospheric circulation to the event day. Past studies have used a range of circulation variables to identify the analogues. Here, we compare only two circulation variables: Z500 and SLP. As we aim to produce a method applicable operationally we choose to use variables available directly from ERA5 without further postprocessing.

To determine the domain over which we assess analogues, we

Table 1
The case studies of midlatitude extreme heat events.

EVENT	Date	Hazard Region	Comments
NW America	29th June 2021	45-52 °N, 119-123 °W	Impact region from Philip et al., (2022)
Western Europe	25th July 2019	47-52 °N, 0-8 °E	Impact region from Vautard et al., 2023
China	22nd June 2023	35-43 °N, 114-121 °E	Hottest recorded June day in Beijing
Argentina	11th March 2023	32-36° S, 56-61 °W	Hottest recorded day in Buenos Aires
South Africa	4th Jan 1993	30-35° S, 18-23 °E	Hottest January day (Fazel-Rastgar & Sivakumar, 2024)
Australia	31st Jan 1991	31-35° S, 115-123 °E	Hottest recorded January day in Perth

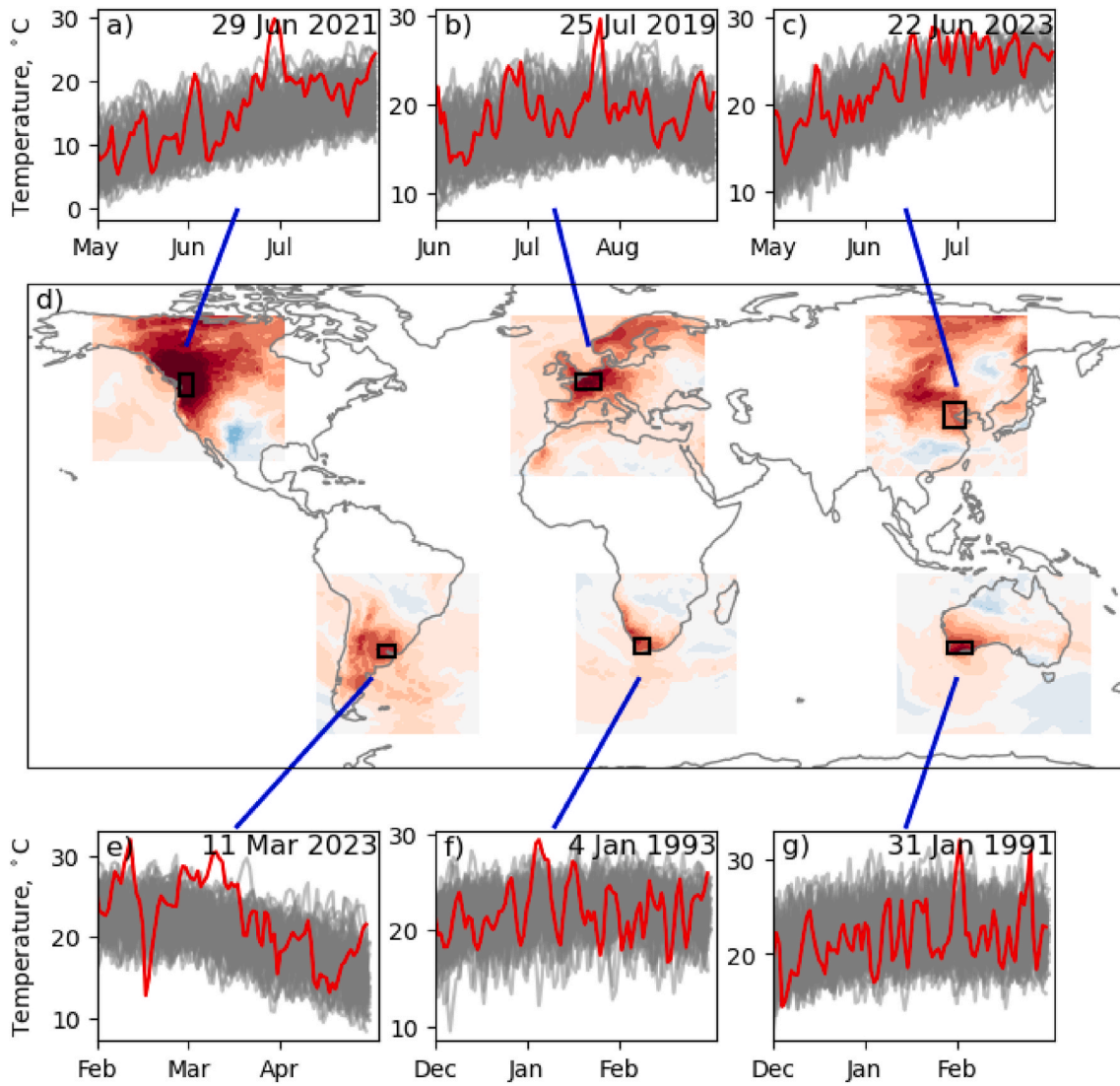


Fig. 1. Heat extreme case studies. (a–c) Timeseries of the daily mean 2m temperature evolution for the season of the event in all years (grey) and the event year (red) for Northern Hemisphere events listed in Table 1. (d) Map of the temperature anomalies for each of the events in Table 1, relative to 1950–2024 for the season of the event (small boxes indicate the hazard regions used in the timeseries in a–c and e–g. (e–g) as in (a–c) for the Southern Hemisphere events.

correlate the daily timeseries of every gridpoint globally for each variable with the hazard index timeseries (see Section 3.1, Fig. 2). This enables us to identify the region where the circulation variable has greatest correlation with, and therefore greatest impact on, the meteorological hazard. From the correlation maps we identify the point of greatest correlation and then take a box of at least $10 \times 10^\circ$, with that point in the centre, which has approximately 80:20 split in the sign of the correlation, ~80% of gridpoints must be positively correlated and 20% negatively or vice versa (as shown in Fig. 2). Using trial-and-error, domains at 5° steps are tested, to find the smallest region that meets the 80:20 criteria. These criteria are chosen to ensure the large scale circulation will be represented by the domain. A smaller box -encompassing only the high pressure system - would lead to analogues being determined solely by the strength of the high pressure rather than the spatial structure of the circulation. The domain will not necessarily be the same for each circulation variable, and so two different domains (for Z500 and SLP) are identified for each event.

There are multiple mathematical metrics that could be used to assess the similarity between two fields, as discussed in the introduction. In this study we compare only the two most commonly used methods: Euclidean distance and spatial correlation. For both methods we first

remove the daily spatial mean across the chosen domain. This ensures long-term trends in the circulation fields do not impact the results – without this adjustment days closer in time to the observed event may be more likely to be identified as analogues, despite less similar large scale spatial patterns. We assess how this choice affects the meteorological hazard within identified analogues.

Euclidean distance is calculated:

$$ED = \sqrt{(A_{x1,y1} - B_{x1,y1})^2 + (A_{x1,y2} - B_{x1,y2})^2 + \dots + (A_{xn,yn} - B_{xn,yn})^2}$$

Where ED is Euclidean distance between 2D-fields, A_{xy} (event date) and B_{xy} (any other date). Spatial mean removed from both A_{xy} and B_{xy} .

Spatial correlation is calculated:

$$r = \frac{\sum_{i=1}^n (A_{xi,yi} - \bar{A})(B_{xi,yi} - \bar{B})}{\sqrt{\sum_{i=1}^n (A_{xi,yi} - \bar{A})^2} \sqrt{\sum_{i=1}^n (B_{xi,yi} - \bar{B})^2}}$$

Where r is the correlation coefficient between 2-D fields A_{xy} (event date) and B_{xy} (any other date), paired as $\{(A_{x1,y1}, B_{x1,y1}), (A_{x1,y2}, B_{x1,y2}) \dots$

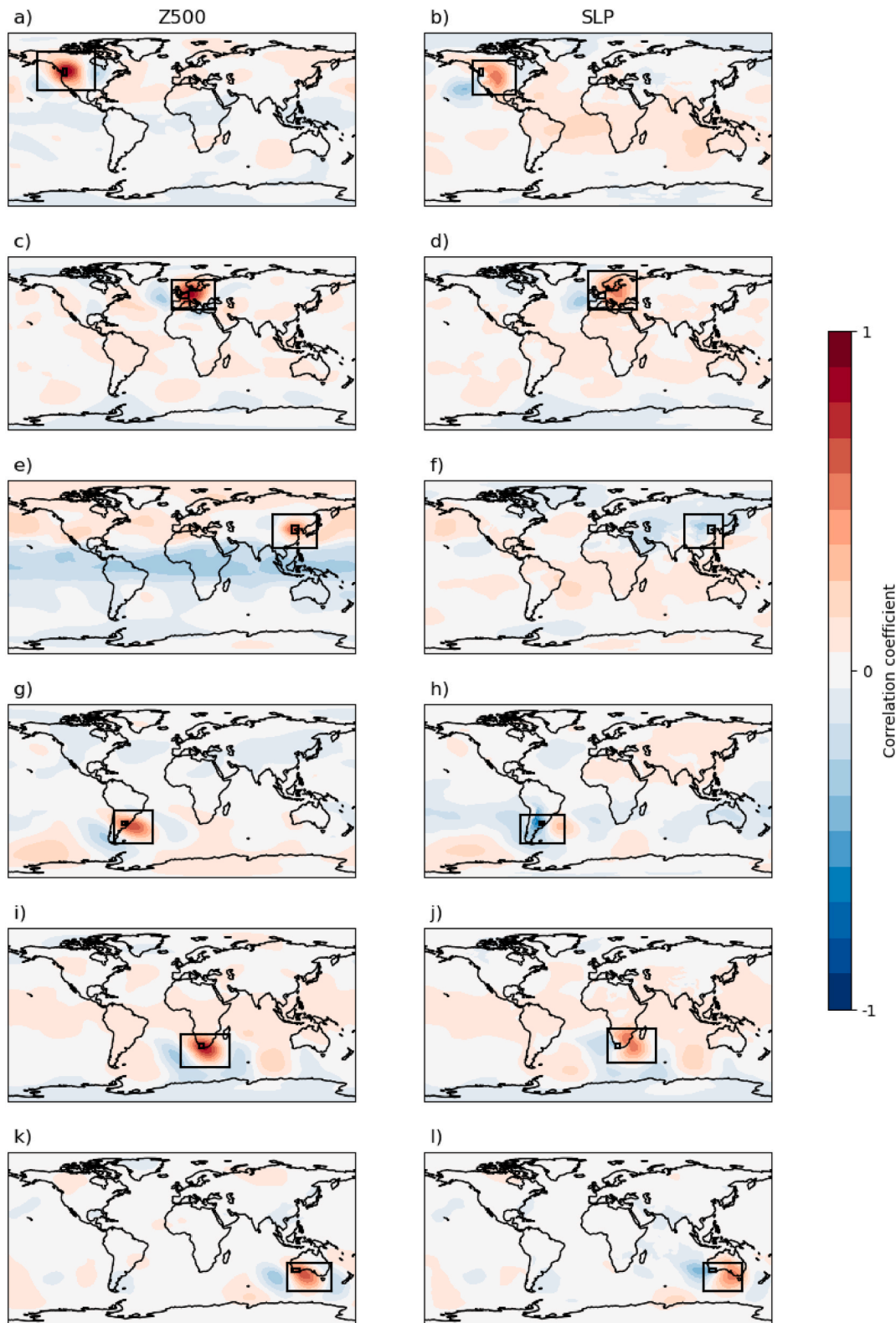


Fig. 2. Correlation of hazard index with circulation variable globally. (a) North Western America and Z500 and (b) SLP. (c) Western Europe and Z500 and (d) SLP. (e) China and Z500 and (f) SLP. (g) Argentina and Z500 and (h) SLP. (i) South Africa and Z500 and (j) SLP. (k) Australia and Z500 and (l) SLP. Small boxes indicate the hazard index region (also shown in Fig. 1 and listed in Table 1), larger boxes indicate the analogues domain.

$(A_{x_n, y_n}, B_{x_n, y_n})$ and n is the sample size (gridpoints within each 2D-field). Spatial mean, \bar{A} and \bar{B} , removed from both A_{xy} and B_{xy} .

For each metric, and for each circulation variable, we extract analogue sets. We identify the closest analogues within a 3-calendar

month window of every year, centred on the month of the event. This is justified as we assess only event in the midlatitudes, regions with a strong seasonal cycle. For other regions this choice may need further exploration. We impose a gap of 5-days between the analogue days, and

we exclude the event itself, resulting in a set of unique events to ensure that persistent events do not get a greater weighting. Without such a rule the analogue sets could include just a few, persistent, events, and with a smaller sample of independent events assessment of changing dynamics could not be applied (Thompson et al., 2024). This provides 4 sets of analogues, one for each combination of circulation variable and calculation metric. We assess the hazard index of the analogue sets. We aim to identify analogues displaying characteristics of the meteorological hazard of the event – extreme heat based on daily T2m.

To determine if one combination of circulation variable and calculation metric identifies analogues that are statistically significantly hotter than other combinations, we assess the sets, in pairs, using a two-sided *t*-test. If the *p*-value is smaller than 0.05 the difference is deemed significant.

To determine how many analogues to use in each set we initially take the number of years assessed – 75 (1950–2024). As we assess only the season of the event this approximately equates to 1% of events, as has been used in earlier studies (Faranda et al., 2022; Thompson et al., 2024). Note, because we enforce a 5-day separation between analogues the events are not necessarily the closest 1% of days. We compare the hazard (temperature) of composites using different numbers of analogues, from 5 to 75 (~0.05 to 1% of days) to evaluate the sensitivity.

2.4. Detection of trends in analogues

Once the methodological choices are determined we can assess how the dynamics of similar events vary through time. We assess the difference in analogues of the past and the present, and interannual variability in the frequency of analogues. Similar methods have been used previously (Barriopedro et al., 2020).

To evaluate dynamical changes between two 30-year periods we take a past period (1950–1980) with weaker climate change signal and a present period (1994–2024) with a stronger climate change signal. The later period has a mean global temperature 0.71 °C greater than the earlier period (NASA/GISS). Using the already determined choices for analogue domain, circulation variable, and similarity metric (Sections 2.3 and 3.2) we identify the 27 analogues for each period (within a 3-calendar month window centred on the event month) – the closest ~1% of days. We composite the analogue sets, plotting the past analogues, present analogues, and the difference. This enables the evaluation of dynamical changes between the period, for instance spatial shift or intensification of the high-pressure system. It also enables us to assess changes in T2m between the analogues sets – though we do not differentiate between dynamical and thermodynamical drivers of changes in T2m. Statistical significance of the differences between the two analogue sets is assessed by performing pointwise two-sided *t*-test (equal variance not assumed) on the two sets of analogues. When the *p*-value is < 0.05 the difference is deemed statistically significant.

To assess changes in frequency of analogues a different set of analogue events is used. We determine the thresholds for the closest 5, 10, and 20 % of analogues for the event throughout the record (1950–2024) - no longer the 27 best analogues. We then count the number of days above the thresholds within each season and assess the variability within the timeseries produced. We note, we do not remove multiple days within the same event, and so if the persistence of similar events varies through time it will influence the timeseries. We are assessing changes in the frequency in terms of similar days, not similar events (some events may span multiple days).

This method can be implemented through the use of the analogues tool on Climate Explorer, accessible at <https://climexp.knmi.nl/analogues.cgi> (Appendix 1).

3. Objective methodological choices

By identifying the closest analogues – days with similar weather patterns - within given periods we can assess dynamical changes in

similar events between periods. We can also assess the temporal distribution of the closest analogues – creating a timeseries of analogues per year to allow assessment of possible temporal trends. For both, we must first assess the methodological choices required to identify the analogues.

Ideally, circulation analogues should reproduce not only the atmospheric circulation of the event but also the meteorological hazard. This ensures that changes in dynamics could lead to changes in the hazard. If the dynamical analogues of a particular extreme event do not show similar meteorological hazards then other factors than dynamical factors may be more important drivers for the hazard.

As case studies, we use a selection of midlatitude extreme heat events (Table 1, Fig. 1). The key meteorological hazard is the daily T2m over the most impacted region. We assess the meteorological hazard of the single hottest day of the event, and identify circulation analogues of a single day, as using multi-day definitions reduces the number of potential analogues – making it less likely that highly similar analogues will be able to be identified. The events selected are short-lived heat extremes with a clear single day maximum. Most events are the hottest day within the ERA5 record for that region, though the event selected for China is the hottest June day – hotter days have occurred later in the summer season.

3.1. Analogue domain

The domain over which the analogues are identified will affect which dates are selected. A larger domain will lead to less similar analogues being available – for the full Northern Hemisphere it would take 10³⁰ years of data to find two matching analogues (van den Dool, 1994). If the domain is too large, the local circulation in the analogues will not be as similar to the event itself – and the surface impact would be unlikely to be extreme. If the domain chosen is too small then we are assessing very local processes and may miss changes in large scale dynamics. We assess using two different circulation variables – SLP and Z500.

Earlier studies often use expert judgement to determine a region based on the meteorological features thought to be relevant – such as a high pressure system. Some studies have explored the impact of varying domain size (Jezequel et al., 2018). Faranda et al. (2022) suggest the use of an analogue domain spanning the European continent for heat extremes – though state that methods are qualitatively insensitive to modest changes in domain size.

To identify analogue domains for each circulation variable we produce a hazard index (T2m timeseries over the hazard region, Table 1) and correlate with the circulation variables globally (see Methods). These correlation maps (Fig. 2) also enable us to determine which circulation variable is more closely linked to the hazard, which would likely lead to analogues with greater temperatures. We use the correlation maps to identify analogue domain, by taking a rectangular region encompassing the region of greatest absolute correlations (Table S1). It is assumed that the circulation pattern within that region is influencing the hazard index – although the relationship is likely often more complex. The regions are defined for each event and each circulation variable separately (Fig. 2). The correlation threshold will vary by event and variable. We see that for the China and Argentina cases (Fig. 2e–h) opposite correlation is shown with SLP and Z500. Caution is required when interpreting such cases, as circulation analogues – taken from a single variable - may not capture the vertical structure of the flow.

3.2. Analogue variable and similarity metric

In this study we compare the use two similarity metrics of Euclidean distance and spatial correlation – the two most commonly used methods. We determine whether analogues selected from Z500 or SLP better represent the hazard. Some earlier studies have used different fields, such as 250 hPa stream function (Vautard et al., 2023; Thompson et al., 2024) but we choose to use variables available directly from ERA5

without further postprocessing. We compare the results from two different circulation variables – due to the complexity of the climate system it is not clear that one circulation variable will always provide the best analogues in terms of meteorological hazard.

Earlier studies of circulation analogues for heatwaves have used both SLP and Z500. A relationship between extreme heat and SLP is well established, with high pressure anomalies leading to extreme heat throughout the midlatitudes (Loikith and Broccoli, 2013; Horton et al., 2016; Tomczyk and Bednorz, 2016). The signal is also found in the Z500 field - and Z500 may outperform SLP due to the impact of extreme heat on the SLP field itself. Extreme surface heat acts to reduce local high pressure (through the “heat low” effect), reducing the SLP anomaly (Jezéquel et al., 2018; Yule et al., 2024). For SLP we have more direct observations (e.g. from barometers) and reanalysis data spanning further into the past (Harrington et al., 2019). Using only SLP may enable us to assess analogues further back in time, but could reduce confidence in our conclusions if we are only able to assess one circulation variable. In this study we use ERA5 data, which provides reliable data back to 1950 for both SLP and Z500 (Bell et al., 2021). Also, several studies argue that it is preferable to use SLP to prevent issues due to the long-term trends in Z500 (Faranda et al., 2022; Yule et al., 2024; Boé et al., 2025). To reduce the influence of the trend we remove the spatial mean across the analogue domain for every time step prior to identifying the closest analogues. Assessing the relationship between circulation variables and heat extremes it has been shown that Z500 outperforms SLP both over Europe (Jezéquel et al., 2018) and North America (Adams et al., 2021). We re-evaluate this for our selected heatwaves.

Here, we assess the analogues identified using Euclidean distance and spatial correlation, and selected from Z500 and SLP (see Methods). This gives four combinations of these options, as shown in each panel of Fig. 3. We determine which combination, either Euclidean distance or spatial correlation, and either Z500 or SLP, identifies analogues that better represent the hazard – and whether this is statistically significant.

The differences in the mean temperature of analogues and the p-values (Table S2) show that spatial correlation does not produce statistically better analogues associated with higher temperature (hotter analogues) for any of the heat extremes assessed. For two cases (North America and China) Euclidean distance gives statistically hotter analogues. Therefore, for the rest of the study we assess only analogues identified using Euclidean distance. In Fig. 3 we also show the climatological temperature for the period assessed. This shows that, although the analogues do underestimate the observed temperature, the best analogue sets are considerably more extreme than climatology alone.

In contrast, we find that there is not one circulation variable best for all events. For all except Australia Z500 identifies hotter events, though not all cases show a statistically significant difference. For North America, Europe, and China the Z500 analogues are significantly hotter. Australia exhibits statistical significant hotter events for SLP analogues. Contrary to the findings of Jezéquel et al. (2018b) we do not find that Z500 greatly outperforms SLP for the European heatwave – with no significant difference between the two circulation variables (Note, the specific event we assess is not included in Jezéquel et al. (2018b)).

To ensure the differences between the Z500 and SLP analogues are not due to the different domains used for each, we test domain dependency. We show results for two events – North America and Australia (Fig. S2), for both we find conclusions are unchanged. For North America using Z500 gives more extreme analogues whichever domain is used, and for Australia SLP provides consistently more extreme analogues.

Results may be sensitive to the number of analogues selected. The mean temperature of the analogues decreases as the number of analogues selected is increased, but this stabilises (Fig. S3). If dynamical analogues truly capture the meteorological hazard this is to be expected – as the closer analogues better capture both the dynamics of the case study and the extreme temperature. A balance is required, ensuring that enough analogues are chosen that the differences between periods can

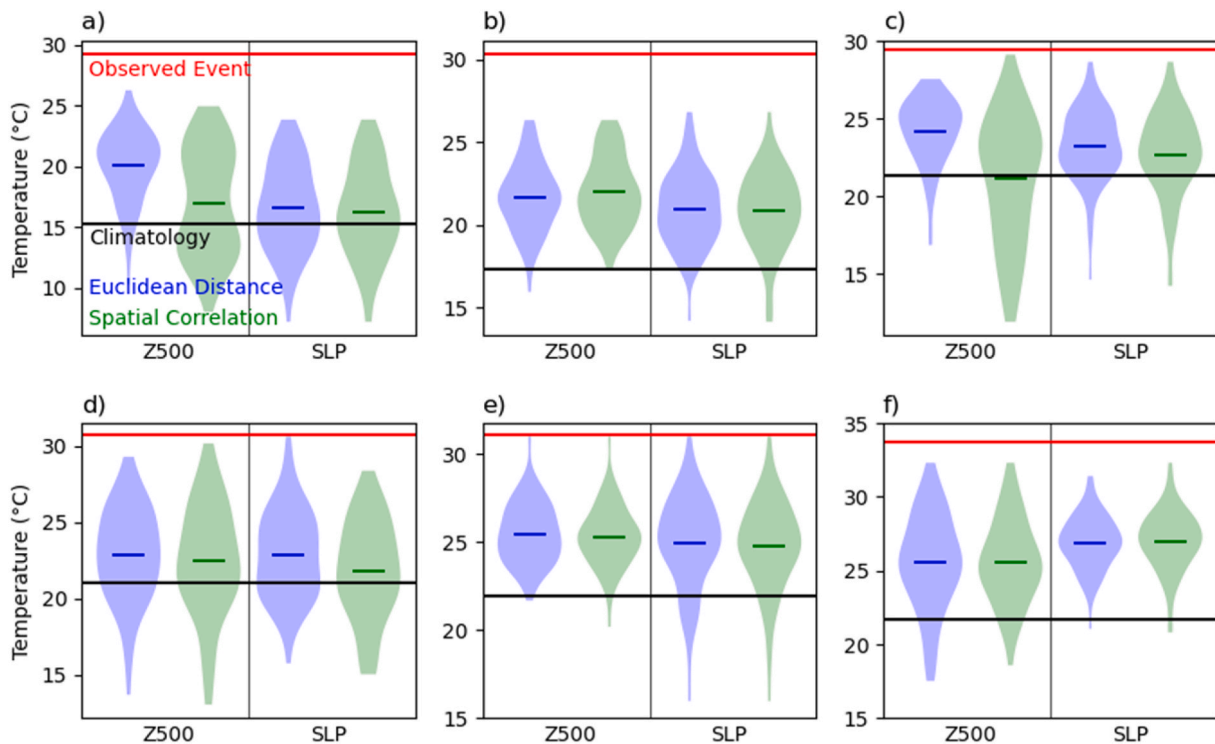


Fig. 3. Relationship between circulation variable and similarity metric that best captures the heat extreme. (a) The hazard index (temperature over the region in Table 1) for the top 1% of analogues (3-calendar month window of the event, 1950-2024) calculated from Z500 (left) and SLP (right) using both Euclidean distance (blue) and spatial correlation (green). The red line indicates the observed temperature of the event, the black line is the climatology of the 3 month window, 1950-2024. The lines within the violins indicate the analogue set mean. (a) NW America, (b) Europe (c) China (d) Argentina (e) South Africa and (f) Australia.

be evaluated, whilst the analogues still provide extreme events. These figures also indicate that the choice of SLP or Z500 is usually unaffected by analogue number – except for one case. For the Argentinian event the SLP and Z500 lines do cross, but both are very similar throughout. Other studies have also shown the results are not overly sensitive to the number of analogues (Yule et al., 2024; Ginesta et al., 2023).

Thus, we have investigated some of the methodological decisions required to identify flow analogues of heatwaves that will best capture the surface impacts of the events. We find in some cases Euclidean distance identify heat extremes that are statistically hotter, but in no cases does spatial correlation. We find the choice of circulation variables cannot be pre-determined for heatwaves. Different individual events show opposing, statistically significant, results in terms of which circulation variable displays hotter analogues.

4. Towards an operational system

Using the methodology investigated, we now present a prototype operational system to assess changes in dynamics of extreme weather events using circulation analogues (Fig. 4). We assess the midlatitude heatwave case studies (Table 1). Here, we present the findings for only one event. Short reports for the other 5 events – such as could be produced in an operational manner – are included in Appendix 2. Similar assessments using analogues have been used by World Weather Attribution for both the LA wildfires (January 2025) and US floods (May 2025) (Barnes et al., 2025; Clarke et al., 2025). We compare the analogues to the event day for two periods, a past (1950-1980) and a present day (1994-2024). This allows us to assess differences in the dynamics of the most similar events in each period, evaluating possible trends.

It is important to note that differences between past and present composites are not necessarily caused by forced changes, such as anthropogenic greenhouse gas forcings. The differences may be due to internal variability, land-use or aerosol changes, or could be statistical artefacts due to the small sample size or a lack of good analogues. We cannot attribute the changes from these results alone, but they can be used to support attribution statements derived from other methods.

For the North America event, on 29th June 2021, the methodology suggests the use of Z500 as the circulation field, with the region 30-70 °N, 100-140 °W as the analogue domain. The observed event displays a high pressure system over western North America (Fig. 5a). The analogue composites show similar dynamics, though the high pressure

system is weaker and less defined (Fig. 5b-c). Looking at the difference between the two periods we find a statistically significant increase in intensity and northward shift (Fig. 5d). The T2m field of the event and analogue composites shows that analogues in the present climate are hotter than in the past (Fig. 5e-h), supported by earlier studies (Bercos-Hickey et al., 2022; Bartusek et al., 2022; Philip et al., 2022). This difference includes both the thermodynamical and dynamical components. Global mean temperature increase between the two periods will lead to warming, but the strengthened high pressure system in the present day analogues could also be contributing to the warming between the composites – and particularly to the coastal warming which vastly exceeds the global warming rate. Methods to separate the contribution of each, such as inferring temperature change associated with the intensification of the circulation pattern, could be used (e.g. Vautard et al., 2023, Noest et al. (preprint)), but are beyond our scope. We note that, particularly for dynamical change, (part of) the change may be caused by internal variability rather than forced climate change.

We also investigate changes in frequency of dynamically similar days, within the 3-calendar month window of the event, through time (Fig. 5i). We show no trends in the frequency, though there is evidence of multidecadal variability with peaks in more similar days occurring around 1980 and 2000. This acts as a reminder that we should be cautious when interpreting the difference between two time periods – changes may be due to climate change between the periods, but could also be driven by multidecadal variability. It is important to note that this method cannot distinguish between the drivers or attribute the changes, it can only detect trends between periods.

5. Discussion

We have investigated some of the methodological choices necessary to select circulation analogues of midlatitude heatwaves, with six case studies spanning the globe. We highlight the challenges in applying one method to multiple events – even when the chosen events are limited to midlatitude heat extremes. We show that analogues of midlatitude heatwaves identified by Euclidean distance display greater extreme heat than those identified by spatial correlation. We suggest an objective method to determine the domain over which analogues are selected, ensuring the region which shows strongest relationship with the meteorological hazard is used. Earlier studies have compared different sizes

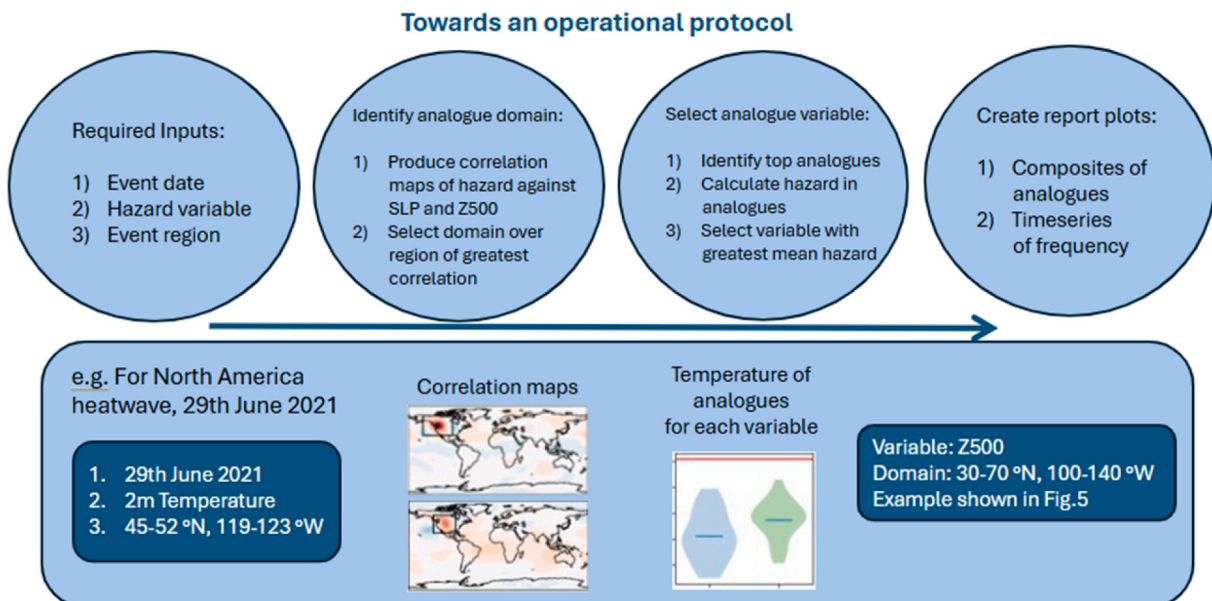


Fig. 4. Flowchart of the workflow presented to assess midlatitude extreme heat events with circulation analogues.

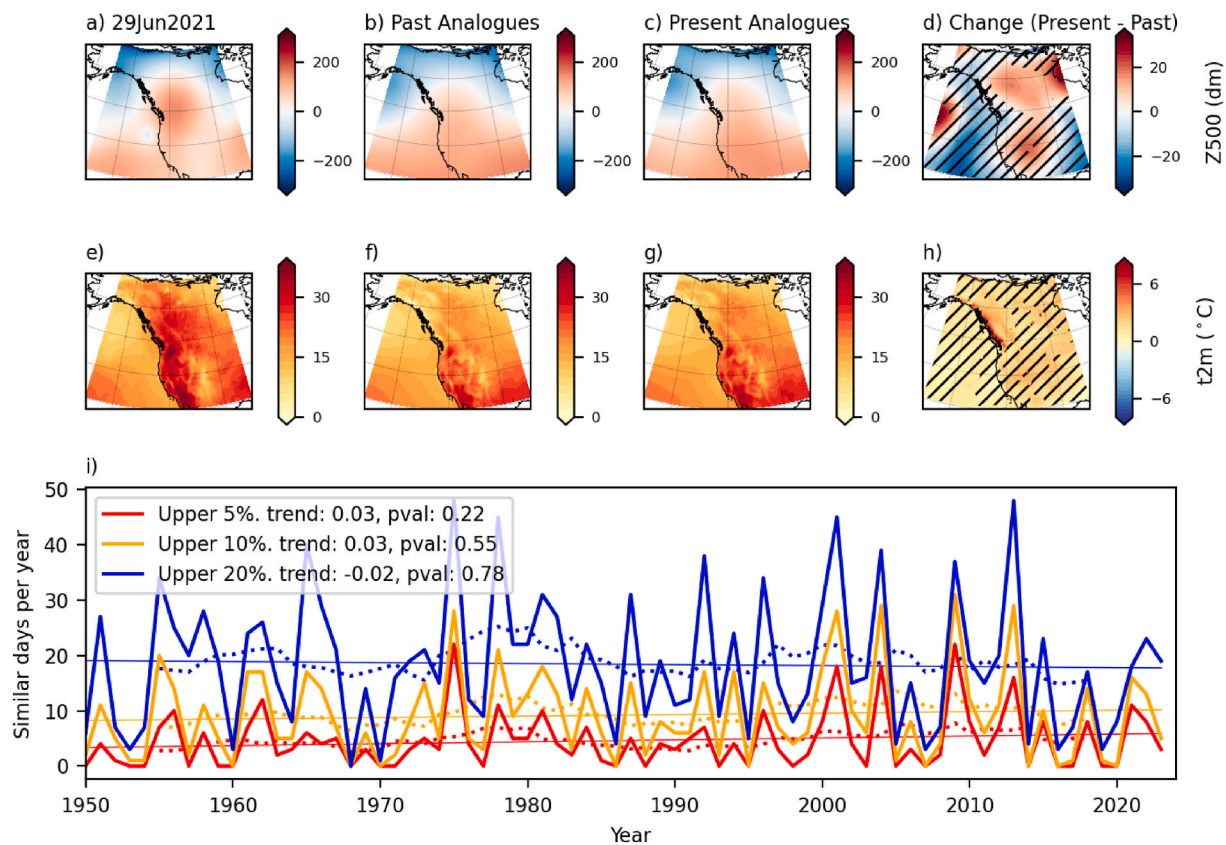


Fig. 5. Trends in dynamical situations similar to the North America heat extreme, 29th June 2021. (a) Showing the Z500 of the observed event, spatial mean removed. (b-c) Composite of the top 27 Z500 analogues (d) Difference between composites (present minus past). Hashed regions indicate difference is not statistically significant, based on a 2-sided t -test ($p < 0.05$). (e-h) as in (a-d) for T2m. (i) Timeseries of frequency of similar circulation days, at 5, 10, and 20% thresholds.

of analogue domain, showing the importance of considering the event characteristics. Cattiaux and Ribes (2018) proposed a method to determine the hazard domain based on extremity in both space and time. However, we are unaware of an objective method to identify the analogue domain based on the event hazard. The size of the analogue sets can influence results, shown for the case studies we assess. Based on the 6 analysed events, we recommend identifying the closest 1% of events, but note that sensitivity testing for individual events may increase the robustness of conclusions (Fig. S3). We find the choice of circulation variable varies, with one event showing a closer relation between SLP and extreme heat whilst for most Z500 is the better choice. We recommend testing this choice for each event.

Whilst similar methods for computing analogues have been used in rapid post-event studies previously (e.g. Climameter; WWA), these have not included a method to optimise the selection of the spatial domain. In contrast to ClimaMeter (Faranda et al., 2024), the method used here removes any identified analogues within 5 days of another analogue, to ensure the analogues selected are independent events. We note that the analogues method presented cannot, in a majority of cases, be used to attribute any changes identified to climate change, it merely detects changes in the circulation patterns of most similar events. There may be cases where analogues are of sufficient quality – and changes align with our physical understanding of climate change – enabling further conclusions to be made (Stott et al., 2016). Outside these cases, the method could still be extended to allow attribution of the changes, for instance by using model data with different forcings to isolate potential drivers.

The results we present for the 6 midlatitude heatwaves are generally consistent with earlier studies, whether using circulation analogues or alternative methods. There are several earlier studies of the European heatwave (Appendix 2.1) which consistently agree that similar events are getting hotter (Vautard et al., 2023; Klimiuk et al., 2025). The results

for the Chinese heatwave (Appendix 2.2) agree with earlier studies showing an increase in intensity, but less certainty about changes in frequency (Qian et al., 2024). For the Argentinian heatwave (Appendix 2.3) we find weaker events in the present climate, unlike Kim et al. (2025) or Collazo et al. (2024). However, consistent with Kim et al. (2025) we show an increase in frequency of similar events through time. This may be due to differences in domain size, the addition of reanalysis data beyond 2020, or the difference in months used. This shows the sensitivity of results to methodological choices. We note that, although we chose test events to cover a range of geographical locations, only 6 events are assessed here. Further testing on a larger range of events would improve confidence in the workflow.

We assess changes in frequency of days with the most similar circulation patterns. In many cases these timeseries (Fig. 5 and Appendix 2) show large interannual and multidecadal variability. Large-scale circulation modes of climate variability, such as the Atlantic Multidecadal Variability (AMV), Pacific Decadal oscillation (PDO), or ENSO, are important drivers for climate extremes including heatwaves (Seneviratne et al., 2021). For instance, summer temperature extremes in Europe have been linked to wintertime NAO forcing (Müller et al., 2020). With further analysis of the frequency timeseries against timeseries of possible drivers it could be possible to show statistical relationships providing evidence of the possible drivers of the changes. This is beyond the scope of this study.

A key underlying assumption when using analogues is that the circulation pattern drives the observed extreme. Our method considers only a 2D element of the climate system (either SLP or Z500 of a single day), but in reality the system is much more complex. Daily weather patterns alone do not determine the characteristics of a heat extreme. We do not consider other known drivers of heat extremes, for example soil moisture (Gessner et al., 2021; Bartusek et al., 2022), or the

preceding conditions. It would be possible to identify analogues using a multi-variate technique, i.e. incorporating both an atmospheric field and soil moisture (e.g. [Trigo et al., 2025](#)). We do not explore this as, within the limited observational records, constraining by more variables is unlikely to identify close analogues. Similarly, to enable the influence of atmospheric circulation changes alone to be assessed, we need a set of analogues occurring under a range of sea surface and soil moisture conditions, but we are limited by the observed ranges within the reanalysis ([Boé et al., 2025](#)).

It would also be possible to identify analogues over multiple days by identifying the sequences of N days which minimise Euclidean distance, yet we choose to use only a single day to identify analogues. As with multi-variate analogues, exploring analogues which assess the dynamics of multiple days would be best suited to large ensembles of climate models. Increasing the timescale searched for reduces the sample size from which analogues can be selected – and with a smaller sample less similar analogues would be expected. We highlight several topics where future work could focus. We identify analogues from the reanalysis dataset, ERA5, only. We are limited by the length of this record, which provides globally complete climate data from 1950 onwards. Extreme events, such as the heat extremes investigated, are rare within the record. Analogue sets of record-breaking extreme events identified from the observational record will always underestimate the hazard. Therefore, the methodological choices, such as whether to use Euclidean distance or spatial correlation, may seem insignificant compared to the offset of the analogues set and the observed event. Investigating analogues within large ensembles of climate models, providing a larger sample and therefore a greater likelihood of dynamically similar events, could help understand the limitations of analogues within the observational record. Large ensembles of climate models forced with individual forcings (e.g. LESFMIP, [Smith et al., 2022](#)) can provide a method of assessing the processes and drivers of dynamical trends identified through observational analogues.

Although not included explicitly in this study, analogues can be used to assess persistence of dynamical conditions. Multiple methods have been used, such as simple spatial correlation of consecutive days ([Thompson et al., 2024](#)) or dynamical systems theory and the extremal index ([Faranda et al., 2022](#); [Ginesta et al., 2023](#)). There is scope to further develop the tool to assess changes in persistence. We do not assess changes in seasonality of similar events, or the implication of choosing a 3-month window centred on the event month. For mid-latitude heat extremes this is unlikely to have significant implications, but when considering other event types and regions it could be important to consider ([Faranda et al., 2022](#); [Harrington et al., 2019](#)).

Circulation analogues may not be a suitable tool for application to every extreme weather event. Many extreme events are unique, at least within the observed record. This is particularly likely to be true for record-breaking events, where scientific interest is often greatest. If the dynamics of an extreme are unprecedented – such as an extratropical cyclone in a previously undocumented location – there will not be any suitable analogues within the observational record. If the meteorological hazard is not primarily driven by the large scale dynamics then analogues may not be suitable – there must be statistical correlation between the hazard and the analogue measure (e.g. Euclidean distance).

Multiple circulation patterns can induce extreme heat, even within a specific region. The analogues method presented is heavily conditioned on the circulation of the specific extreme event assessed. If a region shows significant variability in the circulation patterns that can induce extreme heat then other methods may be more suitable for assessing the changes in such extremes – such as probabilistic attribution ([Philip et al., 2020](#)). Further comparison of the event sets identified through analogues of circulation – as used in this study - and analogues of the hazard – as used in probabilistic attribution - would aid scientific understanding, providing insights about the links between changing dynamics and intensity of extreme events with climate change. For the most unique events, perhaps both unprecedented in magnitude and with particularly

unusual circulation, storyline approaches such as spectral nudging or pseudo global warming may be more suited ([Thompson et al., 2026](#)).

Although the method presented here could, in principle, be applied to many other event types – such as extreme rainfall or windstorms, it is not a simple task. For midlatitude heat extremes there is a strong, well-understood, relationship between the large scale dynamics (e.g. a high pressure system) and the meteorological hazard (daily temperature anomaly) ([Risbey et al., 2023](#); [Loikith and Broccoli, 2013](#); [Horton et al., 2016](#); [Tomczyk and Bednorz, 2016](#)). Generally, the closest analogues will display extreme heat – though not always, as shown in [Fig. 3](#) where some analogue days are colder than climatology. For rainfall events the hazard is often not fully represented by circulation analogues – the dynamics alone cannot determine the rainfall pattern ([Thompson, 2025](#)). To illustrate this we use the extreme rainfall event of July 14th 2021, which severely impacted Western Europe ([Mohr et al., 2023](#); [Thompson et al., 2024](#)). We can identify analogues based on the dynamics – a cut off low pressure system – but those analogues do not all show extreme rainfall over the region impacted by the observed event ([Fig. S4](#)). Similar cut-off lows may fail to reproduce extreme rainfall because the weather systems alone do not represent a sufficient condition for the occurrence of rainfall extremes. The method of identifying analogues can still be used to assess changes in similar circulation patterns ([Thompson, 2025](#)). Similarly, some of the wettest days are not analogues of the event, showing that different dynamical situations can also lead to extreme rain in this region.

Even for heat extremes we restrict our events to those within the midlatitudes. Analogue methods are likely to perform best in the midlatitudes as circulation variability is greater than in the equatorial regions. This leads to the dynamical situations associated with heat extremes being more distinct from the mean in the midlatitudes, enabling the events to be better captured using analogue methods ([Vautard et al., 2023](#); [Kornhuber et al., 2024](#)). In regions of less atmospheric variability it will be more difficult to identify a set of distinct analogue events.

In conclusion, we show that circulation analogues can be used to identify events with similar meteorological hazards for midlatitude heatwaves. Based on assessment of the two most commonly used metrics, we recommend the use of the Euclidean distance to select analogues. We show the choice of circulation variable depends upon the individual event, not all heat extremes are equally explained by the same variable. We present a method to assess trends in the dynamical drivers of a specified extreme event ([Fig. 4](#)). This allows us to assess if similar events increase in intensity or frequency through time. We note that detection and attribution studies are most useful when a range of methods are used to analyse the event from a range of perspectives ([Coumou et al., 2024](#); [Thompson et al., 2024](#)). Therefore, alongside other methods, the information from analogues can provide information on circulation-conditioned changes in hazard, thereby increasing confidence in attribution studies.

CRediT authorship contribution statement

Vikki Thompson: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Sjoukje Philip:** Writing – review & editing, Methodology, Conceptualization. **Sarah Kew:** Writing – review & editing, Methodology, Conceptualization. **Izidine Pinto:** Writing – review & editing, Methodology, Conceptualization. **Robert Vautard:** Writing – review & editing, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Izidine Pinto is an associate editor of *Weather and Climate Extremes*. Given his/her/their role as associate editor of *Weather and Climate Extremes*, Izidine Pinto will have no involvement in the peer review of this article and no access to information regarding its peer review. Full responsibility for the editorial process for this article will be delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wace.2026.100898>.

Data availability

ERA5 data is available from the European Centre for Medium-Range Weather Forecasts (ECMWF), Copernicus Climate Change Service (C3S) at Climate Data Store (CDS; <https://cds.climate.copernicus.eu/>).

The code used to generate the figures in this paper and the Supplementary Materials is available from github and zenodo: [to be added]. All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

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