Faculty of Science

Uncertainties in characterising historical heatwaves in Europe

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Abstract

Heatwaves are periods of excessively hot weather which can pose a threat to both the people and the agriculture affected by them, for this reason it is important for us to understand and be able to predict heatwaves. This study will therefore investigate historical heatwaves in Europe and compare the quality of different 2m surface temperature datasets and examine the possibility of using 3D temperature data to identify heatwaves. This was achieved by comparing different temperature datasets and evaluating their uncertainty at different temperature and pressure levels. The results show that there is uncertainty between datasets when looking at 2m surface temperatures, this uncertainty also grows at more extreme temperatures such as those experienced during heatwaves. The report also shows that one possible culprit for this uncertainty is the urban heat island, and as such raises the value of evaluating maximum & minimum temperatures further in future studies. Additionally, the 3D temperature data was found to be impossible to compare accurately due to significant differences in the datasets. It was also found that with the datasets used for this study it was not possible to improve the quality of identification for heatwaves using 3D temperature data.

Sammanfattning

Värmeböljor är naturligt förekommande perioder av överdrivet varmt väder som kan utgöra ett hot mot både de människor och det jordbruk som drabbas av dem, av denna anledningen är det viktigt för oss att förstå och kunna förutsäga värmeböljor. Denna studie kommer därför att undersöka historiska värmeböljor i Europa och jämföra kvaliteten på olika temperaturdatauppsättningar och undersöka möjligheten att använda 3D temperaturdata för att identifiera värmeböljor. Detta uppnåddes genom att jämföra olika temperaturdatauppsättningar och utvärdera deras osäkerhet vid olika temperatur- och trycknivåer. Resultaten visar att det finns osäkerhet mellan datauppsättningar när man tittar på 2m yttemperaturer, denna osäkerhet växer även vid mer extrema temperaturer likt de som upplevs under värmeböljor. Rapporten visar också att en möjlig orsak till denna osäkerhet är den urbana värmeön, och lifter därmed vikten av att utvärdera maximum och minimum temperaturer i framtida studier. Dessutom visade sig 3D-temperaturdata vara omöjlig att jämföra exakt på grund av betydande skillnader i datauppsättningarna. Det visade sig också att med de datauppsättningar som användes för denna studie var det inte möjligt att göra några förutsägelser av värmeböljor med hjälp av 3D-temperaturdata.

Contents

1. Introduction

1.1. Background

Europe is a densely populated region located on the eastern side of the North Atlantic Ocean, this is also a region which frequently experiences periods of both droughts and heatwaves (Perkins-Kirkpatrick et al., 2020). These events can pose a threat to European agriculture which would put the food supply of Europe and regions which import food from Europe at risk. They are also a a danger to people in certain risk groups such as the elderly and children who are at a heightened risk of mortality (Åström et al., 2013).

For these reasons it is important to be able to accurately predict future heatwaves as well as their magnitude, this would allow affected regions to anticipate and prepare for future heatwaves and thus limit the negative impacts they might have. Today heatwaves are often defined using 2m surface temperature measurements which can come from both, and different studies use a variety of data sources such as station data, gridded station data, reanalysis products, and satellite data. Until now different studies have used different data (Zhou et al. 2018) which brings up the question of uncertainty in defining or characterising heatwaves using different types of data, which type is most accurate?

One other important factor in identifying and predicting heatwaves is the data itself. To get accurate data certain providers such as the European Climate Assessment (ECAD) go through quality control of data which they have gathered to ensure that inaccuracies get flagged and corrected (ECAD).

To be able to predict a heatwave you first need to be able to identify them. There are many ways of defining a heatwave, many countries have their own definitions of a heatwave based on local parameters. Sweden uses the SMHI definition (SMHI, 2013) which defines it as a cohesive period where the highest daily temperature is at least 25°C for five days in a row, in the USA they use the definition by the American Meteorological Society (AMS) which defines it as 48h where neither the overnight low nor the daytime high fall below the NWS heat stress thresholds (80° / 105° Fahrenheit). For interoperability between different countries this report will be using the international World Meteorological Organization (WMO) definition which defines a heatwave as 5 or more consecutive days during which the daily max temperature surpasses the normal maximum temperature by 5°C.

Existing studies focused on western Europe and Scandinavia have found that by incorporating not just 2m surface temperature data but also including 3D vertical temperature data, they’ve been able to find success in predicting the persistent blocking regime (BL) and the Atlantic Low regime (AL) by up to 2 weeks (Kueh & Lin, 2020). Using the prediction of those pressure regimes made it possible to then predict future warm spells. This did come with some level of uncertainty when it comes to capturing the contribution of the Azores High and NAO pressure regimes, but the study nonetheless shows the value of using both 2D and 3D temperature data to predict heatwaves and as such merits further study.

This report is focusing on 3 different heatwaves which had their epicentres in Europe, these occurred in 2003, 2010 and 2022. The 2003 heatwave was mostly centred on central Europe, with France in particular being heavily impacted. The 2010 heatwave affected most of the Northern Hemisphere, although eastern Europe/central Asia had particularly high temperatures while Fennoscandia mostly avoided it. The 2022 heatwave affected all of Europe with persistent heatwaves, with southwestern Europe experiencing the greatest extremes in temperature. Sites for this project will therefore be selected to include the epicentre of each of these heatwaves in at least one of the selected sites.

1.2. Purpose and Aim of Study

The purpose of this study is to examine the characteristics of heatwaves in Europe using different datasets and to compare the reliability of these different datasets. Additionally, to examine the possibility of predicting the beginning and/or end of heatwaves using 3D temperature data. The aim is the following:

- 1) To quantify uncertainties in characteristics of heatwaves using different sources of near-surface air temperature datasets with ECAD data as a reference

- 2) To quantify differences between different sources of 3D temperature datasets.

- 3) To identify the differences in vertical temperature structure of 3D temperature datasets during heatwaves.

2. Method

2.1. Site Description

Five locations in Europe were selected to represent how 2m surface temperatures in different regions of Europe responded to different heatwaves. Additionally, four different locations were selected in order compare 3D datasets. These locations are:

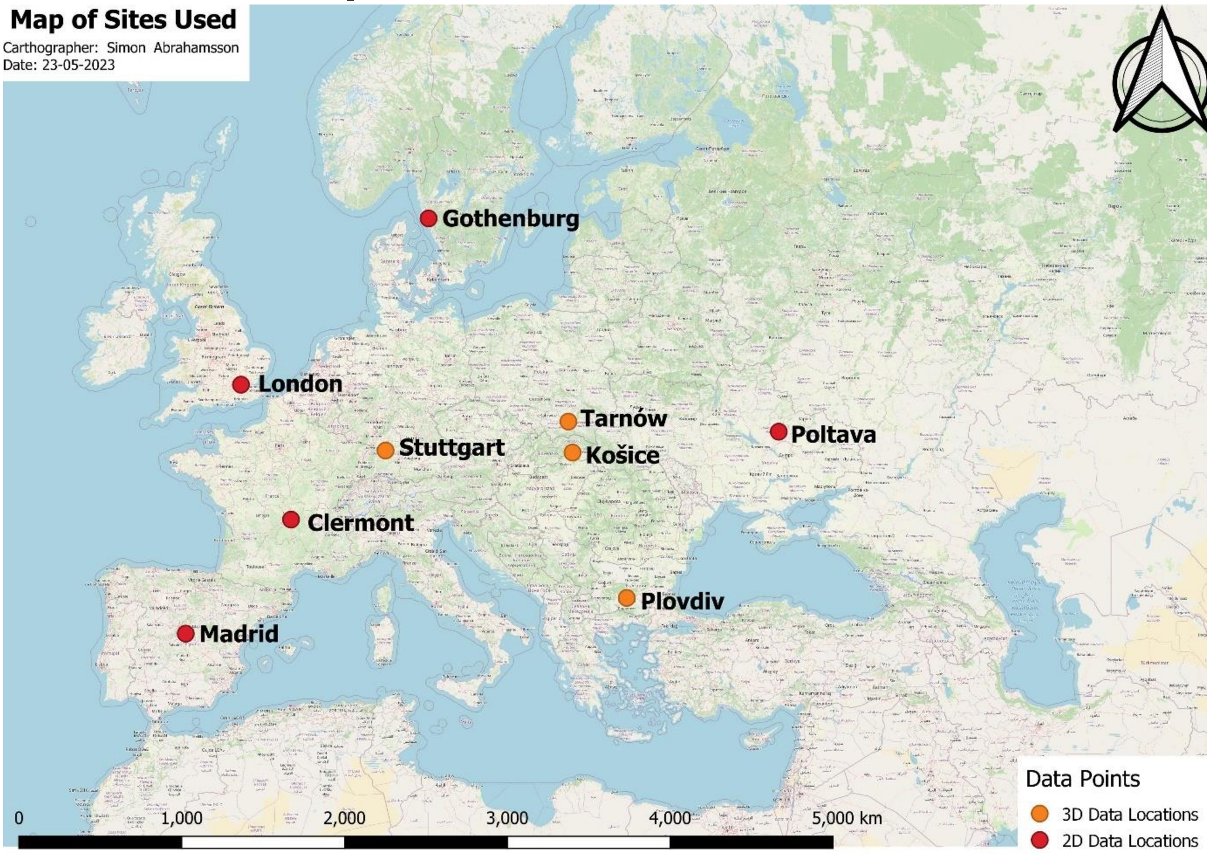

Figure 1. Map of Europe showing locations used for dataset comparisons.

Gothenburg (SE), City in Sweden lying on the west coast of the country.
Madrid (ES), Capital city of Spain lying in the centre of the country.
Clermont (FR), City in France lying inland in the southeast of the country.
London (UK) Capital city of the United Kingdom lying on the southeast coast of the country.
Poltava (UA). City in Ukraine lying in the northeast of the country.
Košice (SK) City in Slovakia lying in the east of the country.
Stuttgart (DE) City in Germany lying in the southwest of the country.
Tarnóv (PO) City in Poland lying in the south of the country.
Plovdiv (BG) City in Bulgaria lying in the centre of the country.

2.2. Datasets

For the dataset comparison 3 observation datasets were selected as well as 1 reanalysis dataset and 1 satellite dataset. The observation datasets are the European Climate Assessment & Dataset (ECAD), the National Oceanic and Atmospheric Administration (NOAA) and Berkeley Earth. The Reanalysis dataset is the Copernicus ERA5 dataset (ERA5). The satellite dataset is the UCAR GNSS-RO. For each of the observation datasets as well as ERA5, data from each of the selected sites was acquired. GNSS-RO data was instead selected based on availability instead as due to it being satellite data it has global coverage but with lower location availability further from the equator and it lacks a 24h temporal resolution for each datapoint (UCAR), with ERA5 sites corresponding to the available GNSS-RO locations also being added.

2.3. Heatwave Definition/Confirmation

A heatwave is according to World Meteorological Organization (WMO) defined as 5 or more consecutive days during which the daily maximum temperature surpasses the normal maximum temperature by 5 degrees Celsius.
Three historical heatwaves were then selected based on previously identified heatwaves, afterwards the maximum temperature for one of the used sites which corresponded to the area affected by the heatwave was analysed to confirm that it in fact counted as a heatwave by this definition.

2.4. 2D Dataset Comparison

To quantify the uncertainties between each 2m surface mean temperature dataset a historical baseline mean temperature based on ECAD data using WMO criteria was created. Each dataset was then visualised on a graph for each of the heatwave years and each site to analyse how they compared to each other. Following this the differences between the datasets was analysed using ECAD as a base by subtracting the ECAD mean temperature from the Berkeley, NOAA and ERA5 mean temperatures respectively. These differences were then plotted against the ECAD mean temperature to show how each of them differs at different temperatures. A Trendline was then created to easily visualise how each dataset behaves during the heatwaves for each site.

2.5. Max/Min/Mean Temperature Comparison

To identify possible differences in behaviour between mean temperature and maximum or minimum temperature the ECAD data for each was compared to the historical mean. This was achieved by subtracting the historical mean temperature from the ECAD mean, maximum and minimum temperature. These differences were plotted against the historical mean temperature and a trendline was created to see differences in how mean, maximum, and minimum temperature behave when examining the temperature differences between datasets at different temperatures.

2.6. 3D Dataset Comparison

GNSS-RO data was analysed to find temperature measurements with coordinates matching to sites in Europe. After locating an acceptable number of sites in Europe, temperature measurements from the ERA5 data with coordinates matching to the GNSS-RO data were acquired. Temperature for these two datasets were plotted against their corresponding pressure levels and compared with each other, this shows differences/similarities in how each dataset has temperature develop over pressure.

2.7. 3D Temperature Data Heatwave Prediction

To examine possible differences in the vertical structure of 3D datasets during heatwaves ERA5 data was gathered from Clermont, France. Temperature and pressure level data was gathered at 12:00 from five days, before, during, after as well as during the transition between each state of the heat wave. These days were: July 31 & August 02, 08, 14, 15. The temperature of for each date at different pressure levels was then compared on one graph to compare differences in their vertical structure.

3. Results

3.1. Heatwave Definition/Confirmation

The results from the maximum temperature analysis (*figure 2*) shows that the maximum temperature for each of the sites fulfil the criteria of being 5 °C over the historical maximum temperature for at least 5 days in a row. Clermont in 2003 fulfilled the criteria on three occasions over the period, Poltava in 2010 three times and Madrid in 2022 two times.

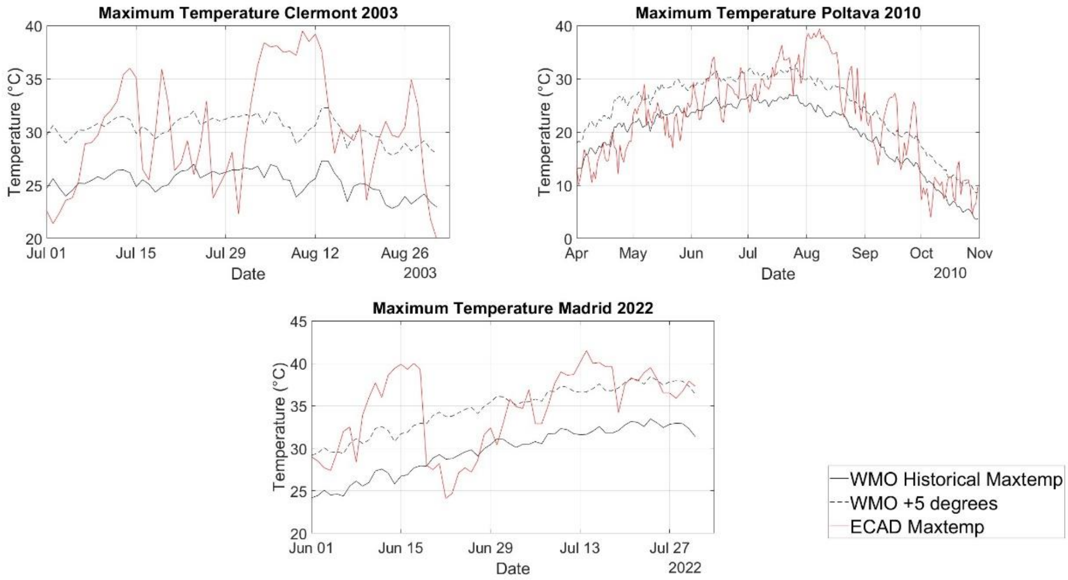

Figure 2. Maximum temperature at given year compared to the historical maximum

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3.2. 2D Dataset Comparison

The results (*figure 3*) show that each dataset generally follows the same trends in mean temperature, but that they can differ noticeably in the exact temperature reported.

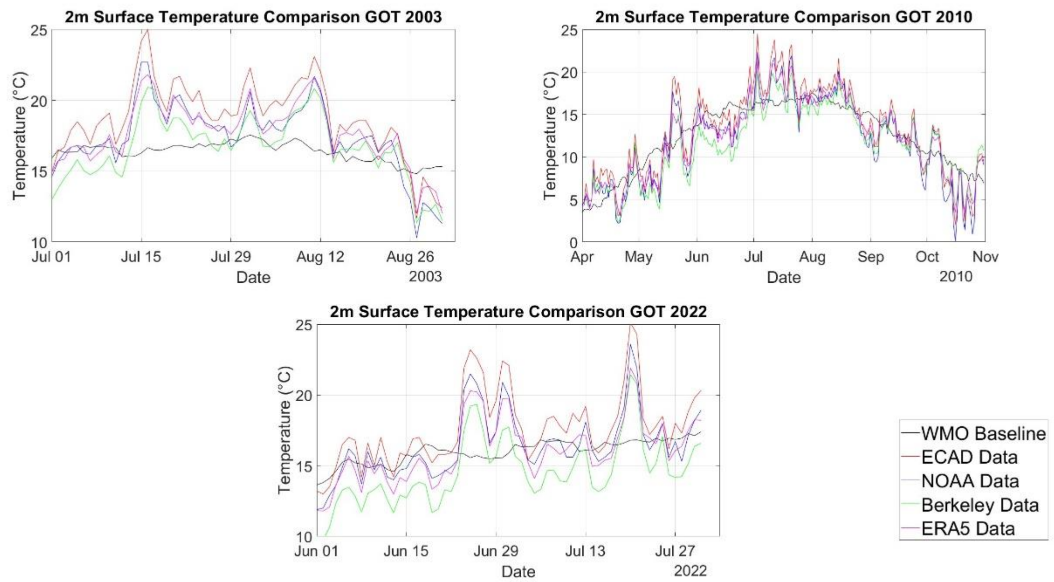

Figure 3. Mean temperature comparison between 2D datasets in Gothenburg, SE.

Looking at the trend lines (*figure 4*) we can see that the difference between the other datasets and ECAD increases if the overall mean temperature is more extreme, this effect remains constant for each of the surveyed locations.

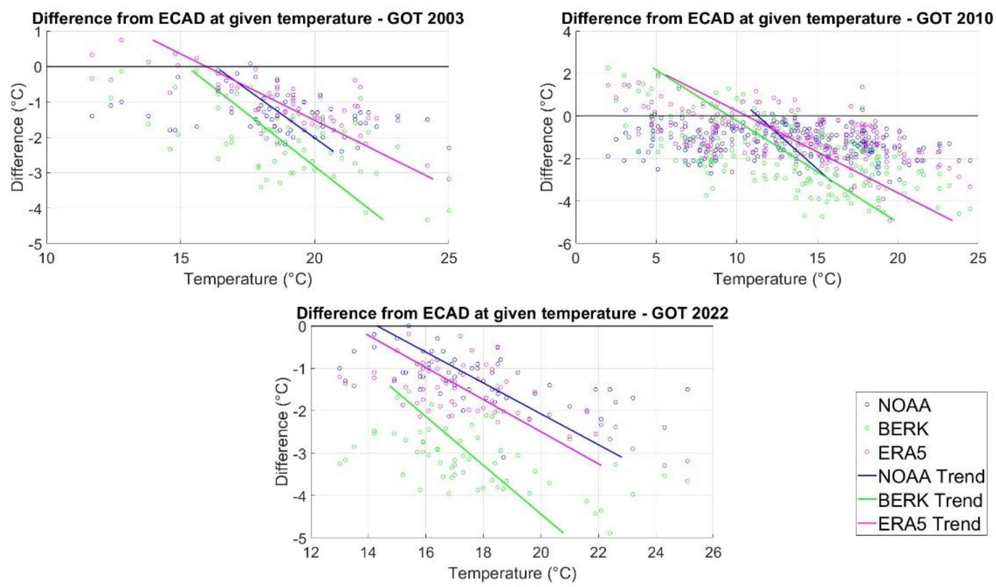

Figure 4. Trends in temperature differences between other datasets and ECAD in Gothenburg, SE

But as we can see in (*figure 5*), although there still is a trend for larger differences between datasets at more extreme mean temperatures, this does have exceptions. Sometimes the trend can be much more minor as ERA5 is in Clermont, or as can be seen with the NOAA data in Clermont 2003 where there is practically no trend between differences compared to ECAD at different mean temperature levels.

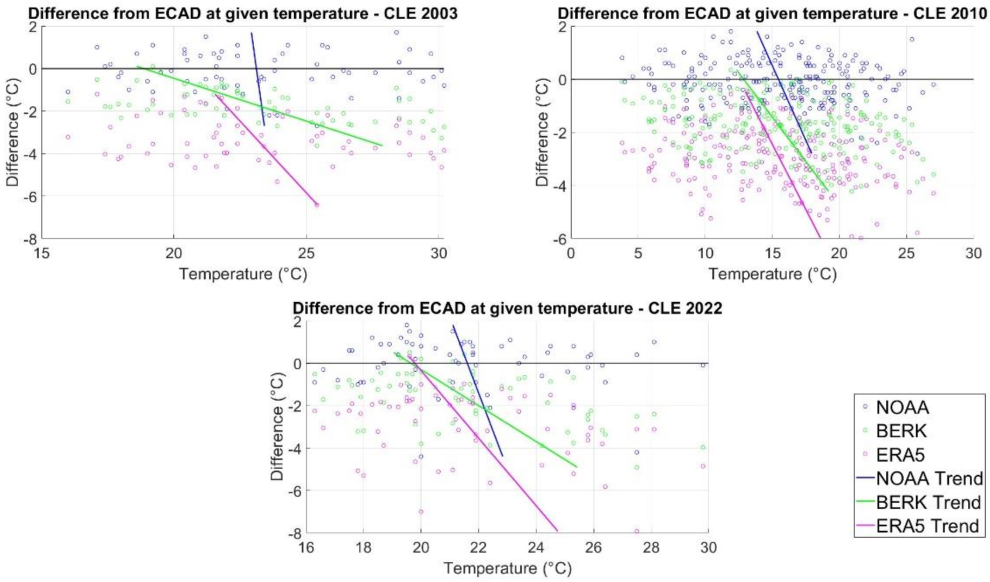

Figure 5. Trends in temperature differences between other datasets and ECAD in Clermont, FR

3.3. Max/Min/Mean Temperature Comparison

The results (*figure 6*) show that mean, maximum and minimum temperatures generally follow the same trends, but with varying degrees of exactness depending on the site in question.

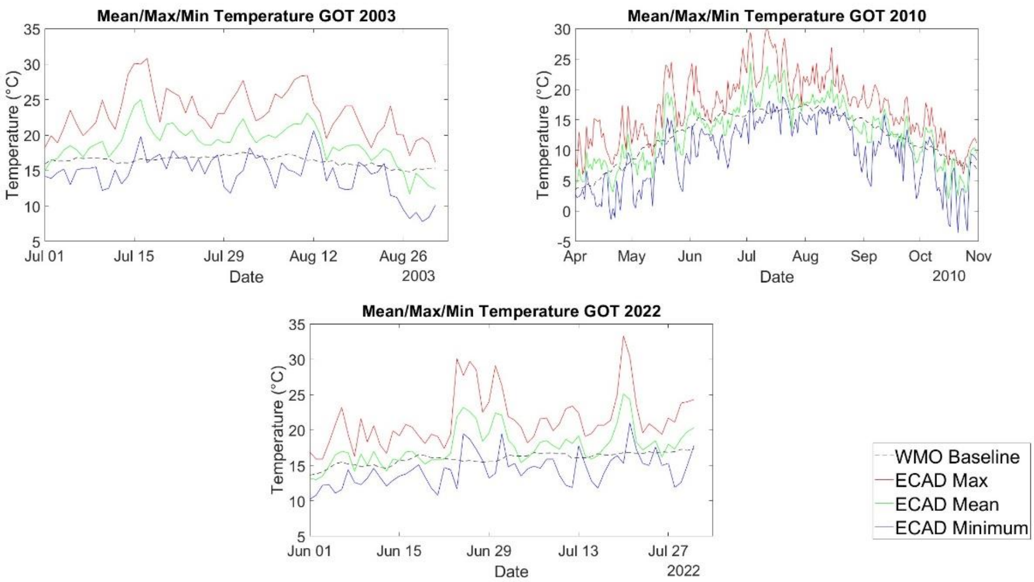

Figure 6. Comparison between max/min/mean temperature in Gothenburg, SE.

As can be seen in the difference for (*figure 7*) the mean, maximum and minimum temperatures compared to the historical average follow the same trends as each other but with small differences in degrees, there are however a few exceptions where the trends do not correlate.

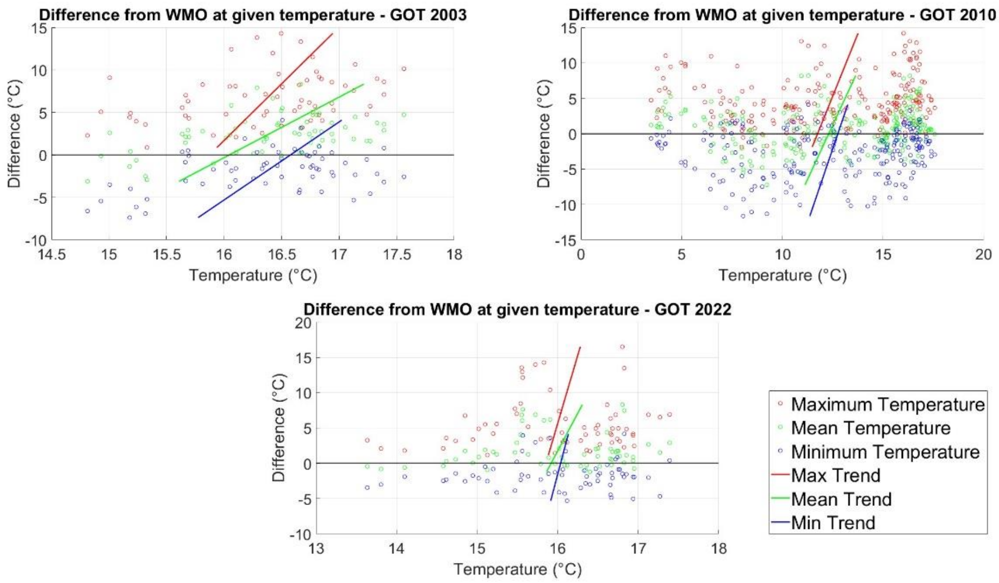

Figure 7. Comparison of the trends for max/min/mean temperature in Gothenburg, SE.

As can be seen in (*figure 8*) that although the max/min/mean temperature might follow the trends most of the time, there are still exceptions such as the minimum temperature in Madrid 2010 where they differ markedly.

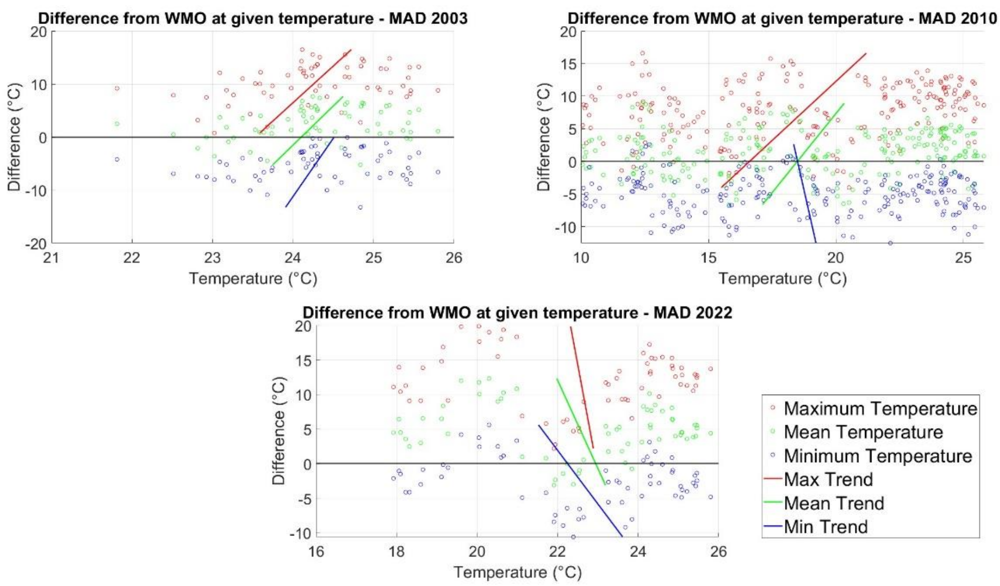

Figure 8. Comparison of the trends for max/min/mean temperature in Madrid, ES.

3.4. 3D Dataset Comparison

Looking at the vertical temperature over differing pressure levels (*figure 9*) we can see that below 400hPa both datasets are very similar. But that at higher pressure levels the ERA5 data shows a linear change until surface pressure is reached, while the GNSS-RO data shows a much more irregular change. The ERA5 data is also for a specific coordinate grid location, while the GNSS-RO data instead moves about 1° in latitude from highest to lowest pressure level.

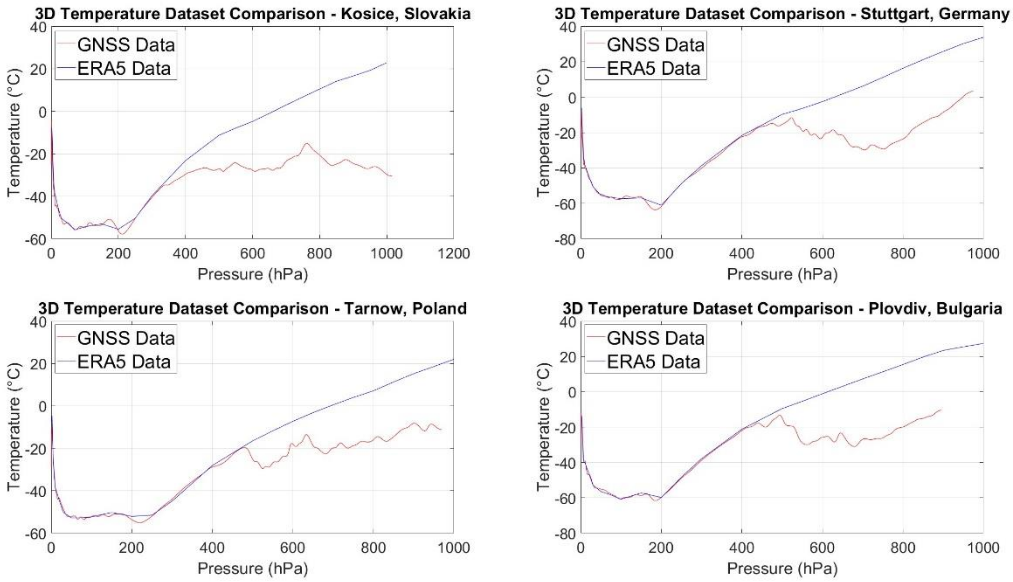

Figure 9. Temperature comparison at different pressure levels between GNSS and ERA5 data,

3.5. 3D Temperature Data Heatwave Prediction

The 3D temperature development during a heatwave (*figure 10*) shows that at surface level pressure (1000hPa) there are differences in temperature before, during and after a heatwave. With temperatures being lowest before and after, highest during, and in between during transitional stages during a heatwave. At lower pressure levels There are no clear differences for different days, and during the transition to the stratosphere between 100-200hPa the dates differ in temperature but without a clear trend.

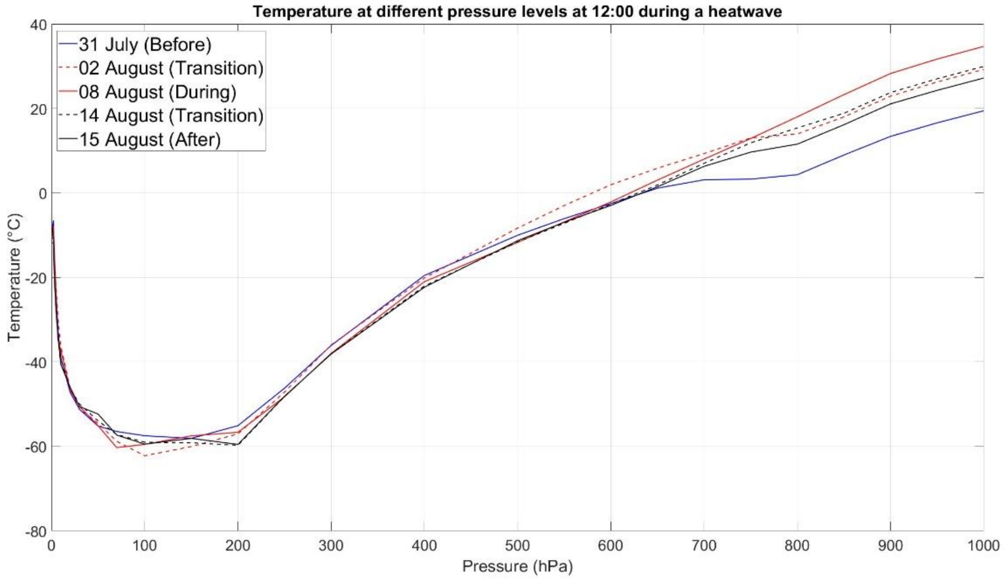

Figure 10. Temperature at different pressure levels during a heatwave using ERA5 data.

4. Discussion

4.1. Heatwave Definition/Confirmation

As we can see in (*figure 2*) each of the selected time periods does fulfil the criteria of counting as a heatwave. This does however not mean that they reach the temperature required for that criterion for the whole duration, but rather that they have a few times where each reaches the required temperature while staying below it the rest of the time. As such the differences between datasets might will include both data from during the heatwave events themself and the time periods around them, this means that the trends in differences between datasets which will be discussed later can be less accurate. These heatwaves were also identified using the WMO criteria for what counts as a heatwave as having a single universal definition for what is a heatwave made working with it much easier. Despite this, many countries do have their own definition of what counts as a heatwave. SMHI defines it as a cohesive period where the highest daily temperature is at least 25 °C for five days in a row and the American Meteorological Society defines it as 48h where neither the overnight low nor the daytime high fall below the NWS heat stress thresholds of 80/105 Fahrenheit (AMS; SMHI, 2013). This means that if I were to have used a local definition of a heatwave the result could possibly have changed when/if the criteria required for a heatwave were met.

4.2. 2D Dataset Comparison

Looking at the comparison between the different 2D datasets we can see a clear trend for the datasets to differ further at more extreme temperatures. One possible explanation for this difference could be in quality of data. ECAD for example is a European project for the creation of weather datasets, as such it has a greater understanding of the local conditions and can use that understanding during their quality control process to improve the accuracy of their data (ECAD). Other datasets such as NOAA which is based in the USA don't have this local understanding and as a result the accuracy of the quality control could be lower. There are also differences in overall mean temperature between the different datasets for some of the sites. One explanation for this could be the heat island effect, as the observation data does not have the exact same position for their measurements, particularly in Gothenburg, this means that the measuring stations might be impacted differently by the heat island effect (Arnfield, 2003). Additionally, the reanalysis data uses a grid system for their measurements

(Hoffman et al, 2019; Rohde & Hausfather, 2020), and include a wider area which mixes temperatures from both urban and not urban areas, as such observation datasets which are in either one or the other will likely differ somewhat due to the heat island effect.

4.3. Max/Min/Mean Temperature Comparison

As seen in (*figure 6*) there are slight differences in how mean temperature and maximum/minimum temperature relate to the historical mean temperature. Because the effect of the urban heat island can be most extreme during clear skies conditions in the middle of the day as well as during the night, this means that the typical maximum and minimum temperature periods of the day are most likely to be impacted by the urban heat island (Arnfield, 2003). However, due to the rather minor differences when looking at a longer timeframe as well as difficulties in locating data from each dataset that included both mean, maximum, and minimum temperature for each site the decision was made to only use mean temperature data.

4.4. 3D Dataset Comparison

The very similar development between both datasets below 400hPa shows that there is some extent of comparability between the datasets, but the radical difference above 400hPa means that overall, it is hard to compare the two while closer to the surface. This extreme discrepancy between datasets at higher pressure levels indicate that there is something very different about the two datasets, this could also be a question of lack of accuracy for either of the datasets. The fact that the GNSS-RO data is acquired from satellite measurements does mean that the differences between the datasets can be due to the GNSS-RO retrieval algorithm, as previous studies have shown that there can be considerable discrepancies between satellite datasets depending on the retrieval algorithms used (Alavipanah et al, 2017). As such there is likely a need for more accurate and/or standardised forms of data publishing as well as investigating the satellite data retrieval algorithm caused discrepancies for 3D temperature datasets to be comparable.

4.5. 3D Temperature Data Heatwave prediction

The ERA5 3D data shows (*figure 10*) that the temperature at different pressure levels at different dates during a heatwave have differences, but that there are no clear trends in the vertical structure before, during or after a heatwave. With the temperature varying similarly to what would be expected of surface temperatures at high pressure levels, having minimal variance between pressure levels of 0-700hPa but except for the 100-200hPa range having some variance without clear trends. As such no understanding which could help in predicting the beginning or end of heatwaves using 3D temperature data could be found during this study.

4.6. Limitations

The number of stations which was investigated in this study was rather limited due to difficulties in handling the amount of data, because of this the statistical significance is more limited. It was also not possible to acquire both mean & maximum/minimum temperature for most sites, as such to mean temperature was selected for the comparison between datasets to simplify the process of locating feasible stations. Additionally, it was not possible to find the exact same locations for the 3D datasets and therefore the comparisons between 3D datasets have a slight lack in accuracy. Maximum and minimum temperature data for Poltava in 2022 is also absent, as such there is no comparison between maximum, minimum and mean which can be made for that site in 2022.

4.7. Future Improvements

A future study could increase the sample size of locations used for the 2D analysis to get a more reliable result. One improvement which could be made in future studies could be a more extensive inclusion of maximum and minimum temperature data in addition to the mean temperature data used in this study. This could possibly reveal differences between the three which were not apparent during the limited comparison which this study was not able to do, and this could therefore improve future comparisons between datasets. One way of doing this would be to look at the maximum and minimum temperature during the extreme heat events where the temperature is classified as a heatwave rather than the whole period at once. A new study could also add more datasets for the 3D analysis to show if it was one of the datasets used here which was anomalous or if these differences show up in other datasets too. A future study could also investigate the suitability of the used datasets for use in climate modelling and how they would compare to current climate models. Heatwave prediction using both 2D and 3D temperature data has been shown by Kueh & Lin (2020) to be possible, as such a future study could focus on identifying pressure regimes and using them to predict heatwaves rather than focusing on the temperature directly as was done in this study.

5. Conclusion

- Differences in data quality for different 2m surface mean temperature datasets lead to uncertainty between datasets. The urban heat island also is a contributing factor to this uncertainty, and therefore the uncertainty also grows during extreme events such as heatwaves. As such the use of high-quality data is highly important for accurately identifying and characterising heatwaves.
- Maximum and minimum temperature data generally shows the same trends as mean temperature. But occasional anomalies combined with the low sample size show a need for further investigation of the differences in maximum and minimum temperature, particularly during shorter extreme heat events.
- Comparing ERA5 and GNSS-RO 3D datasets shows major differences which indicate that the datasets are not comparable, likely due to the GNSS-RO data seemingly having a significant error at surface level, showing that there is a need for more high quality and comparable 3D temperature data.
- Looking at the ERA5 3D data the surface temperature behaves similarly to 2D data, but higher altitude temperature shows no clear trends which could predict heatwaves in any way.
- A further focus on the 3D pressure levels and identifying pressure regimes could be used to identify and predict future heatwaves.

6. Acknowledgements

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8. Appendices

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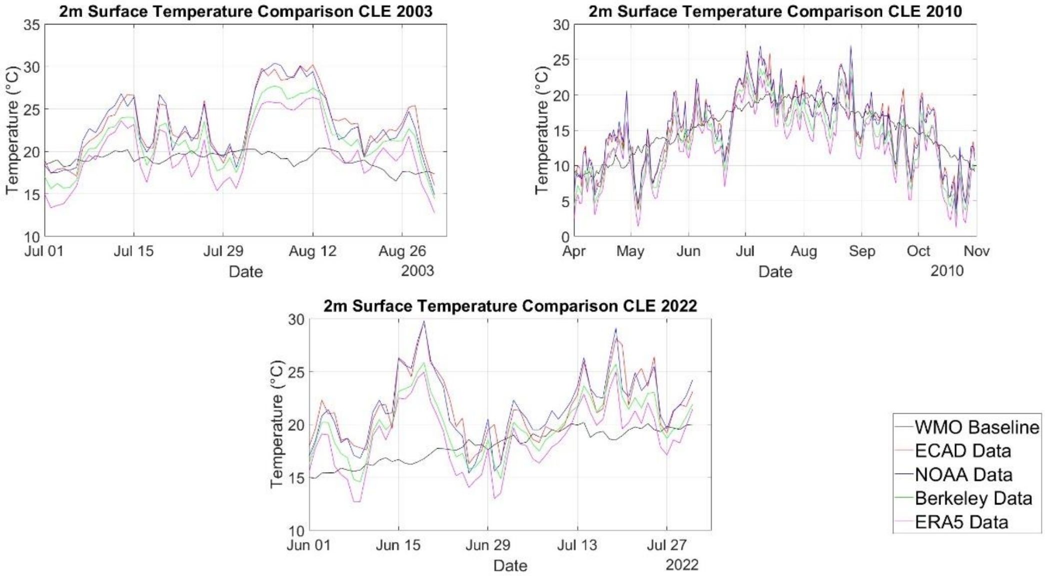

Figure 11. Mean temperature comparison between 2D datasets in Clermont, FR

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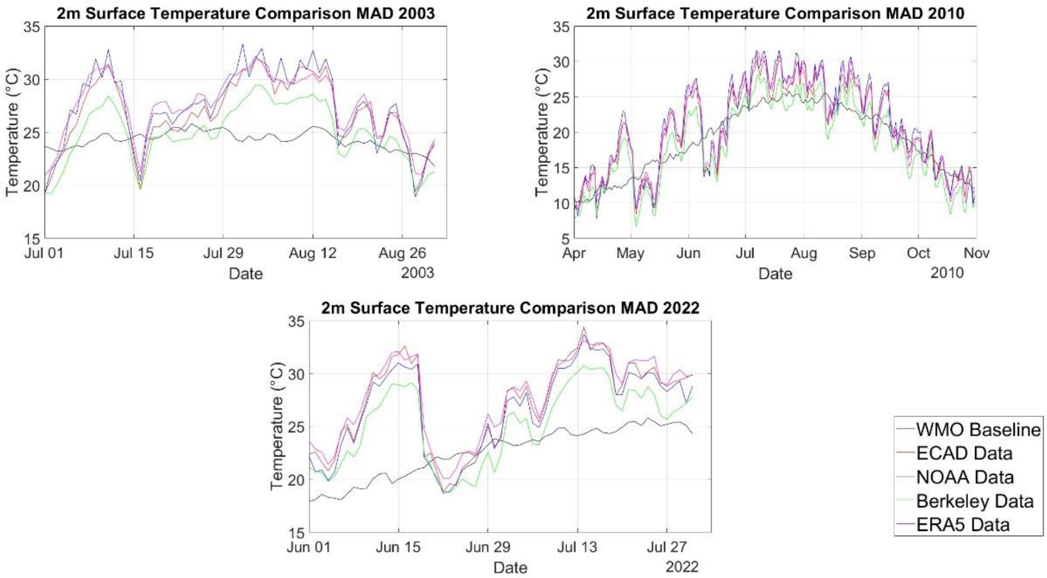

Figure 12. Mean temperature comparison between 2D datasets in Madrid, ES

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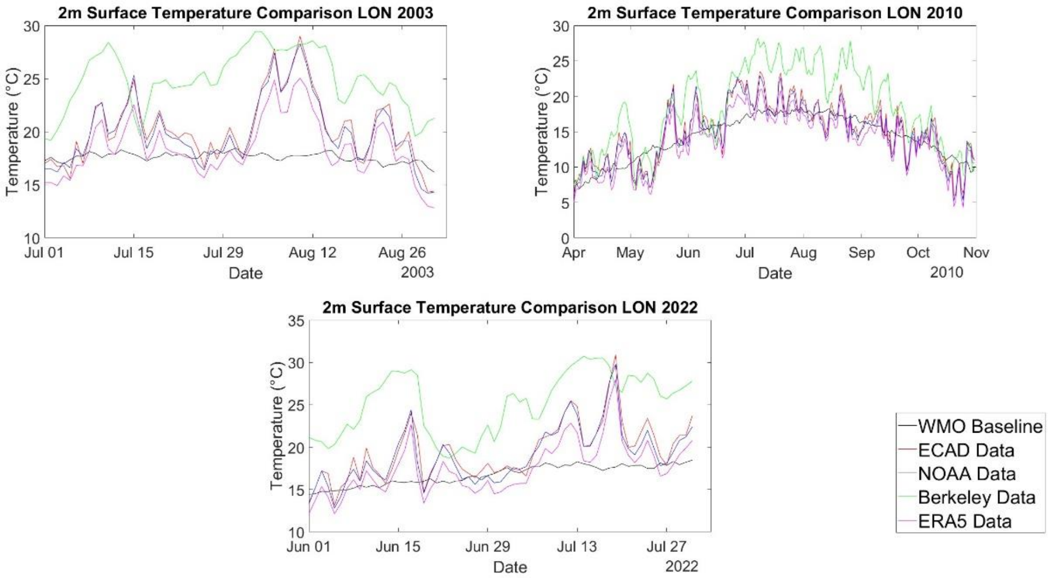

Figure 13. Mean temperature comparison between 2D datasets in London, UK

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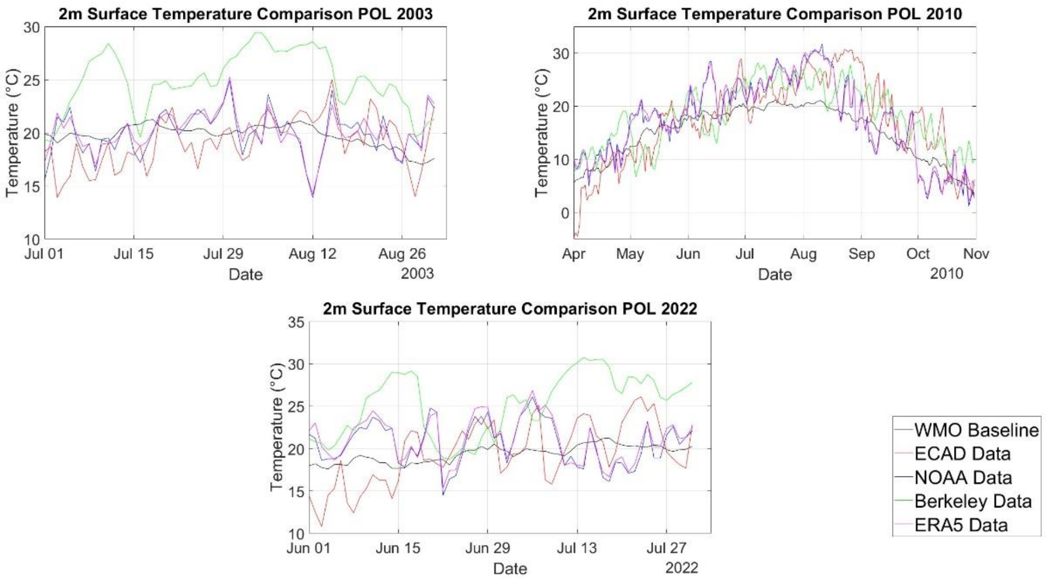

Figure 14. Mean temperature comparison between 2D datasets in Poltava, UA

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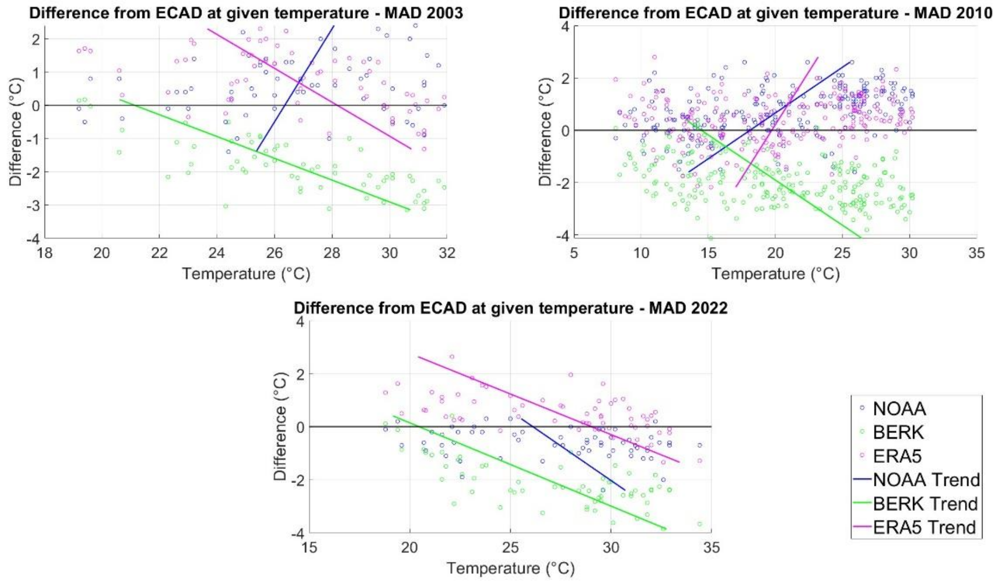

Figure 15. Trends in temperature differences between other datasets and ECAD in Madrid, ES

6:

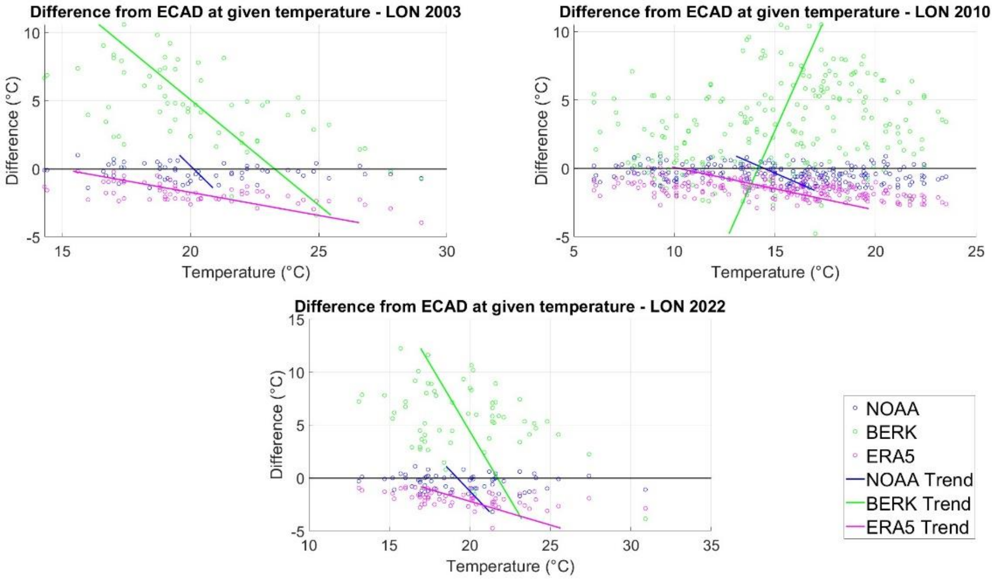

Figure 16. Trends in temperature differences between other datasets and ECAD in London, UK

7:

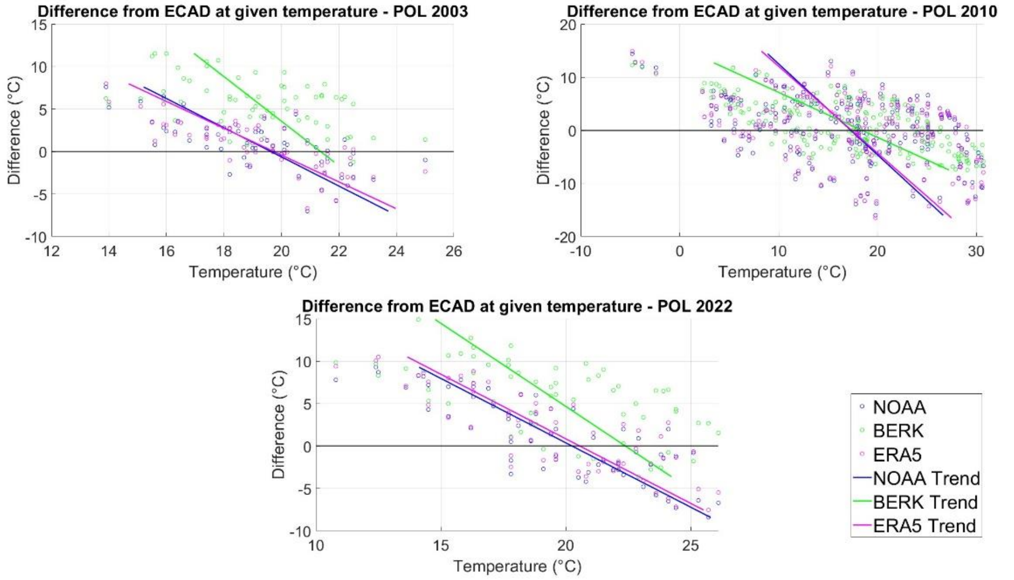

Figure 17. Trends in temperature differences between other datasets and ECAD in Poltava, UA

8:

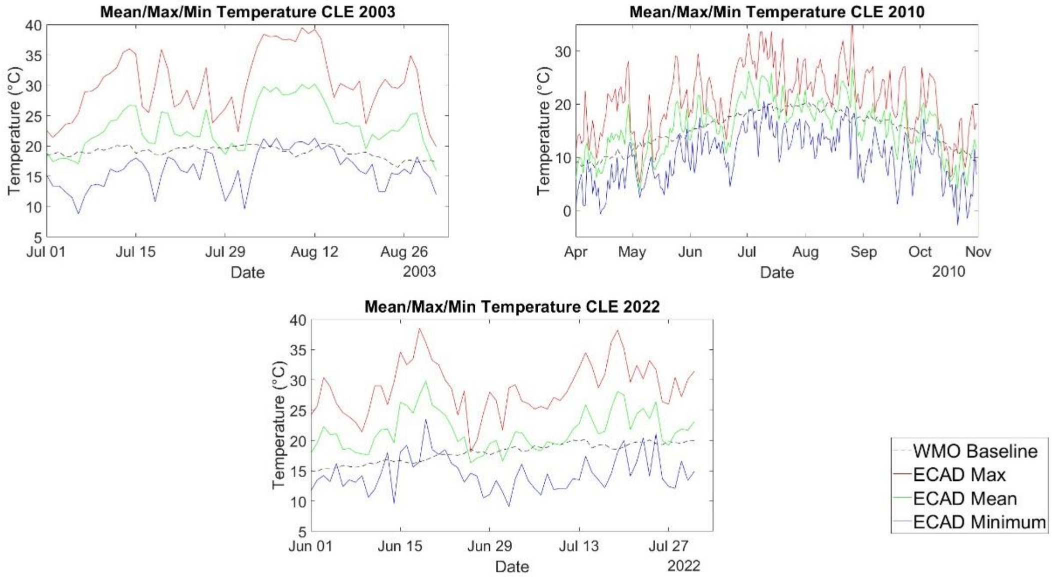

Figure 18. Comparison between max/min/mean temperature in Clermont, FR

9:

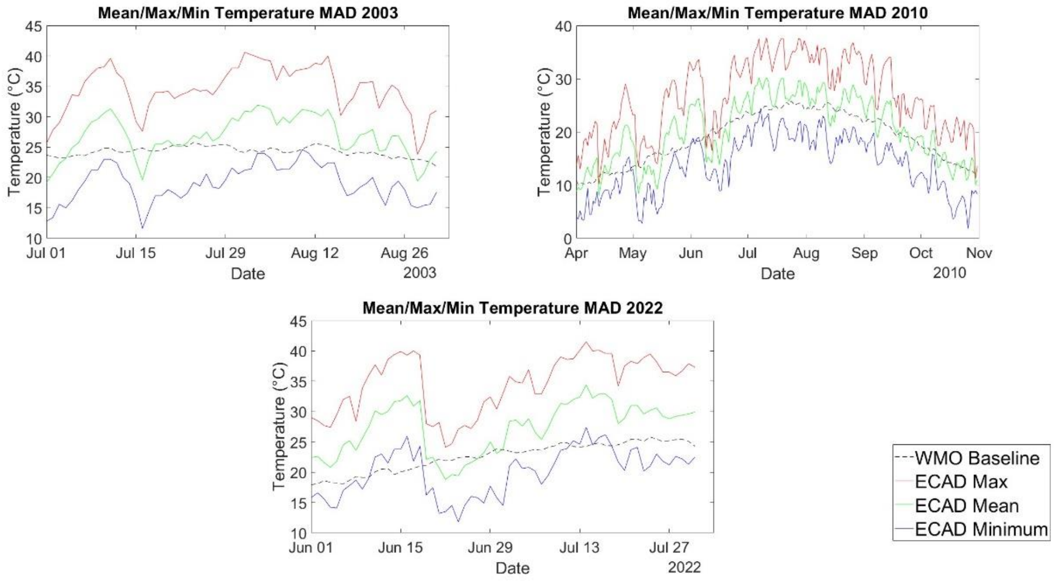

Figure 19. Comparison between max/min/mean temperature in Madrid, ES

10:

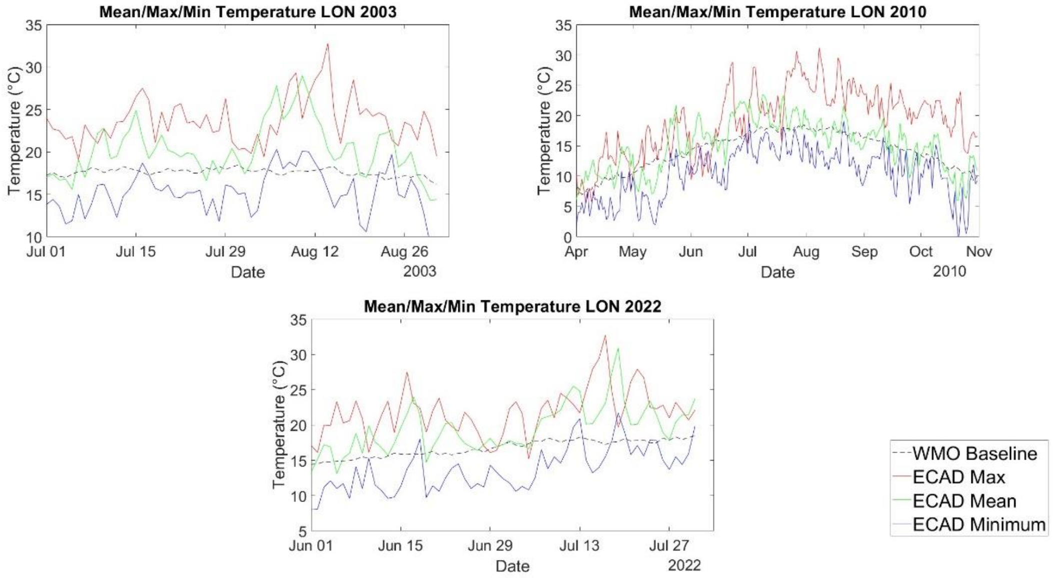

Figure 20. Comparison between max/min/mean temperature in London, UK

11:

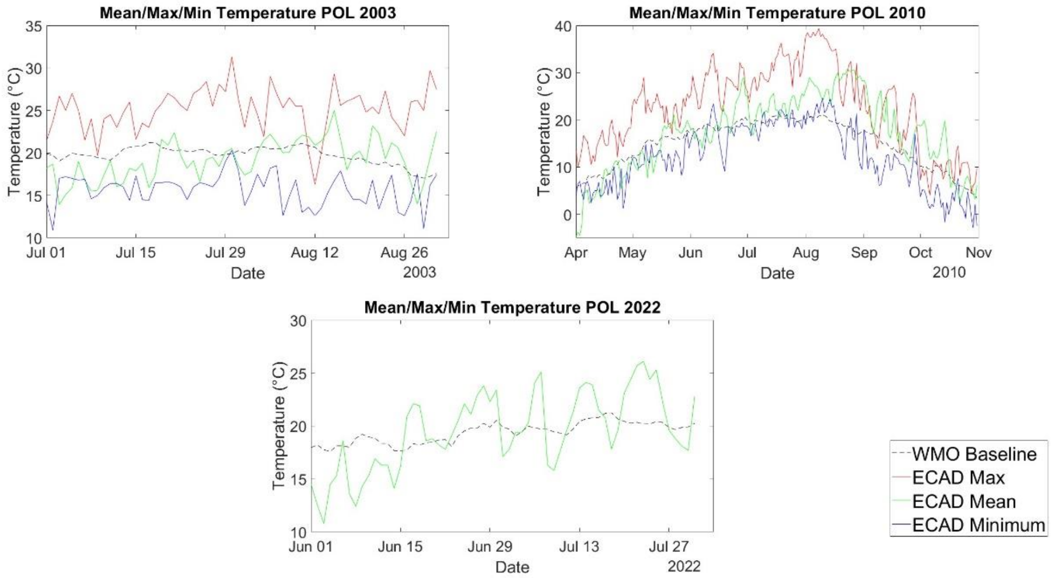

Figure 21. Comparison between max/min/mean temperature in Poltava, UA

12:

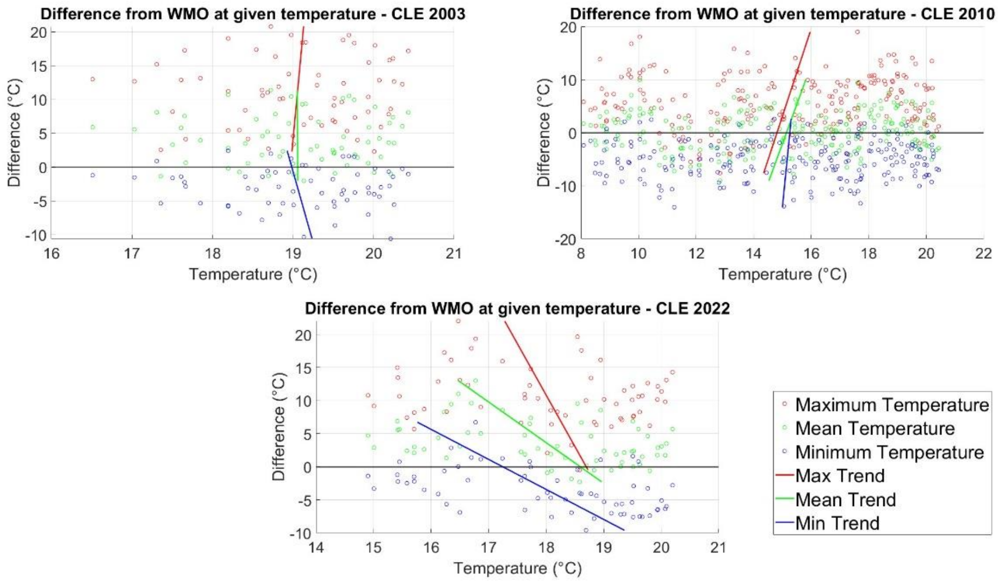

Figure 22. Comparison of the trends for max/min/mean temperature in Clermont, FR.

13:

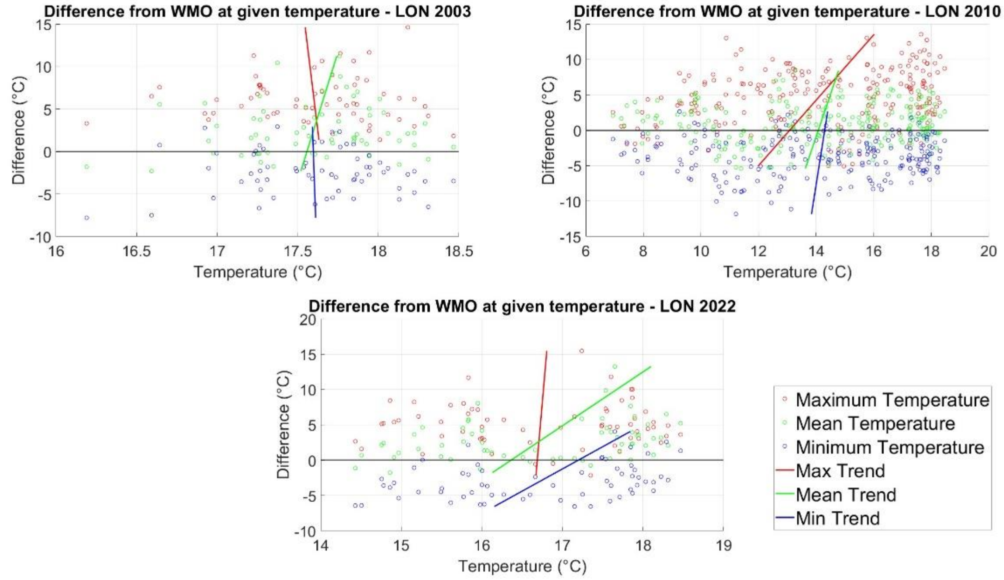

Figure 23. Comparison of the trends for max/min/mean temperature in London, UK.

14:

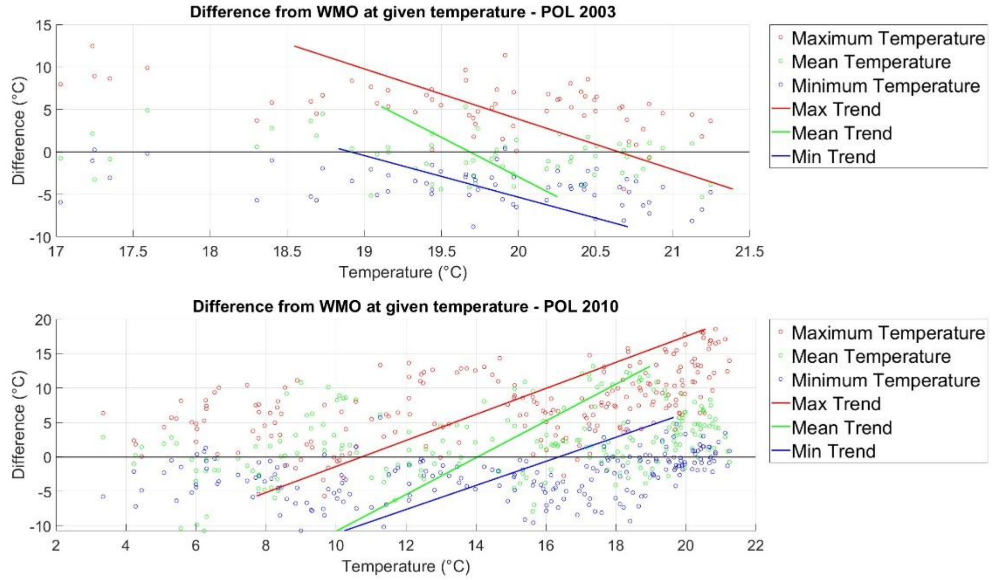

Figure 24. Comparison of the trends for max/min/mean temperature in Poltava, UA.