DIURNAL CLIMATE CHANGE: A CASE STUDY FROM THE DURHAM OBSERVATORY.

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Installation of an automatic weather station at the Durham Observatory in 1999 has allowed analysis of hourly air temperatures and hourly rainfall. Changes in mean air temperature and in the diurnal cycle to 2023 are analysed. Analysis of hourly rainfall totals is also presented. The use of data from the UK Environmental Change Network's Moor House weather station allows comparison between lowland Durham and an upland location in the Pennine Hills. Durham has become warmer and wetter, particularly in the most recent period studied. Moor House also has clear signs of warming but there has been no significant change in rainfall. The mean hourly temperature difference between the two sites has increased: from 3.12 °C in the 2000s, to 3.39 °C in the 2010s to 3.48 °C in the 2020s. The mean difference in hourly rainfall totals has fallen from 0.161 mm in the 2000s, to 0.148 mm in the 2010s and to 0.144 in the 2020s, showing that rainfall totals have increased at the lowland site compared to the uplands. Recent changes in temperature and rainfall at Durham are seen in the afternoon, perhaps indicating the generation of cloud and rain because of increased air temperatures which are likely to render the air more unstable. This change in afternoon rainfall is not seen at Moor House, perhaps indicating that warming has less effect at an upland location where orographic uplift is the dominant mechanism for generating precipitation.

INTRODUCTION

Until recently, consideration of the impact of global warming in ecology and physical geography was limited to the use of daily temperature data, almost always based on the maximum and minimum temperatures measured once each day. The same can be argued for the use of rainfall data, using a single daily total (Burt, 2012). Recently, with the advent of data loggers, researchers have begun to use hourly data, as this approach offers a more sensitive link between cause (e.g. fewer hours of ground frost) and effect (e.g. earlier flowering in spring). An early use of such data was Malamud *et al.* (2011) which examined hourly temperature trends at the Mauna Loa Observatory, Hawaii. A more recent example, Sanford *et al.* (2024), considered how changes in the diurnal temperature range can affect microbially-mediated carbon and nitrogen cycling processes. They argued that, in order to improve our understanding of climate change effects on soil greenhouse gas emissions, nutrient cycling and other biogeochemical soil processes, the important role of diurnal temperature fluctuations must be taken into account.

Until the advent of electrical temperature sensors, the measurement of air temperature was largely achieved using liquid-in-glass thermometers. With full-time observers, it is possible to achieve frequent observations over long periods of time; for example, procedures at "full synoptic stations" in the UK require observations every 3 or 6 hours (Meteorological Office *Observer's Handbook*, 1982). However, at most "climatological stations" (mainly operated by voluntary observers) observations are made just once a day at 0900 GMT every morning. From the observation of maximum (usually mercury-in-glass) and minimum (usually spirit-in-glass) thermometers, a daily mean air temperature is derived as a simple average of the two readings. Note that in some rare cases in the past, a bimetallic thermograph was also used, providing a paper chart each week that could then be analysed to provide an effectively continuous temperature record for the site, although of course it takes the observer some time to extract even hourly measurements from the chart. Thus, in most cases, the basis for a long temperature record comprises just two observations each day: maximum and minimum temperature, with the maximum "thrown back" to the day preceding the observation. For rainfall totals, a similar situation pertains with daily totals from manual raingauges plus, in a very few cases, an autographic raingauge providing a chart which can be analysed to provide hourly totals.

The use of electrical sensors in combination with data loggers has enabled frequent measurement of air temperature to be easily achieved. Since air temperature does not change as quickly as some other meteorological variables (e.g. solar radiation, wind speed), very frequent monitoring is not required. Sampling air temperature at intervals and logging 60-second averages (i.e. the average of four 15-second samples) meets all the requirements of the World Meteorological Organisation. The highest and lowest of the 60-second averages are taken to be the day's maximum and minimum air temperature (Burt, 2012). By far the most common type of recording raingauge used in modern automatic weather stations is the tipping bucket type, with a bucket capacity equivalent to 0.2 mm depth. The logger counts the number of tips on a regular basis (usually one hour) and the rainfall total is simply derived from the number of tips and the bucket capacity. Tipping bucket gauges are least effective for very low-intensity drizzle, due to the incremental nature of the mechanism, and for very high-intensity rainfall which may prevent the bucket from operating properly (Burt, 2012).

The availability of hourly data from automatic weather stations (AWS) means that a novel aspect of climate change can be investigated: looking for local changes in the diurnal cycle as a result of regional and global climate change driven by increased CO_2 emissions. As already noted, prior to the advent of data loggers, production of hourly weather data, where possible, was a time-consuming and potentially costly exercise; consequently, relatively few such analyses have been reported. Of course, AWS data only exist from the 1990s onwards, so it is not possible to undertake longer-period analysis, such as the comparison of standard averaging periods, e.g. 1961-1990 data, compared to the current standard averaging period in the United Kingdom: 1991-2020. Here, we use data from Durham Observatory (54.7681°N, 1.5859°W, 102 m above sea level; Burt & Burt, 2022) to examine changes in hourly temperature and rainfall for the decades 2001-2010 and 2011-2020. In addition, we analyse data for the years 2021-2023 to include any recent changes, acknowledging immediately that three years is a much shorter period than a full decade. As an upland comparison, we use data from the UK Environmental Change Network site at Moor House (54.6895°N, 2.3755°W, 556 m above sea level), approximately 50 km west of Durham near the summit of the Northern Pennine hills.

DATA AND METHODS

Following the withdrawal of manual observations at the Durham Observatory on 30 September 1999, an automatic weather station (AWS) was installed, with the first records available from 1 October 1999. At first, the AWS was owned and operated by Durham University's Department of Geography; the UK Meteorological Office took over ownership and responsibility for maintenance in 2006 (Burt & Burt, 2022). The AWS has proved largely reliable, connectivity via telephone lines being a bigger problem than the AWS itself. Table 1 shows that the loss of remotely accessed data from the Durham AWS is approximately one percent for both hourly temperature and hourly rainfall, an acceptably low amount. Data losses at Moor House are rather higher, at 4 -5 percent, still an acceptably low figure for a remote, upland station.

The MIDAS Data User Guide for UK Land Observations (Met Office 2012) states that temperature measurements are taken every 15 seconds, with an average of four consecutive readings logged to provide the underlying 1-minute data. Summary data are provided each hour. For rainfall, bucket tip times are converted into a rainfall accumulation on a minute-by-minute basis and then compiled into hourly values.

Table 1. Hourly losses of AWS data at Durham and Moor House since 2001.

Decade	Durham temperature	Durham rainfall	Moor House temperature	Moor House rainfall
2001-10	775	1440	8442	1680
2011-20	1313	488	1671	1670
2021-23	19	0	14	5282
Average hours lost per year	92	84	440	375
Percentage loss per year	1.05%	0.96%	5.03%	4.28%

RESULTS

Changes observed at Durham

Figure 1 shows mean hourly temperatures at Durham for the periods 2001-2010, 2011-2020 and 2021-2023. Comparison of the two full decades show that there was minimal warming in the morning with larger increases in the afternoon and at night. The mean difference is 0.19 °C. The temperatures for the early 2020s are considerably higher than in the earlier decades; the mean difference between the 2010s and 2021-2023 is 0.49 °C, with the increase seen right across the diurnal cycle.

Figure 2 confirms that the differences between the 2010s and the 2000s are smaller in the morning with larger increases at night and the largest change in the afternoon. For the differences between the 2020s and the 2010s, the differences are largest through the middle of the day and least at night, but generally the change is much greater. A progressive increase in temperature over the study period is not unexpected, relating to the global increase in atmospheric carbon dioxide concentration. There could be many reasons for these changes. Night-time warming could indicate calmer, cloudier conditions, but might also indicate a change in the synoptic origin of air masses, bringing warmer air to the region. Daytime warming could indicate fewer clouds with enhanced warming by incoming solar radiation.

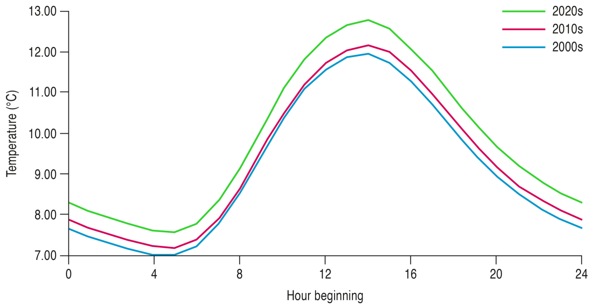

Figure 1. Mean hourly temperatures (°C) at Durham 2001-2023.

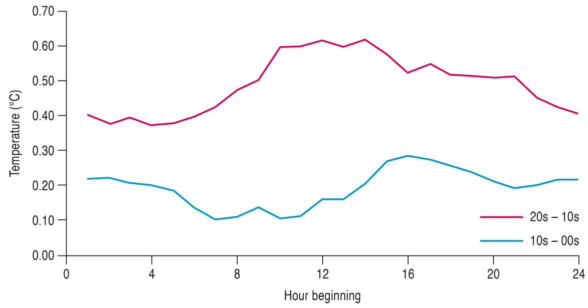

Figure 2. Differences in mean hourly temperatures (°C) at Durham for the data plotted in Figure 1.

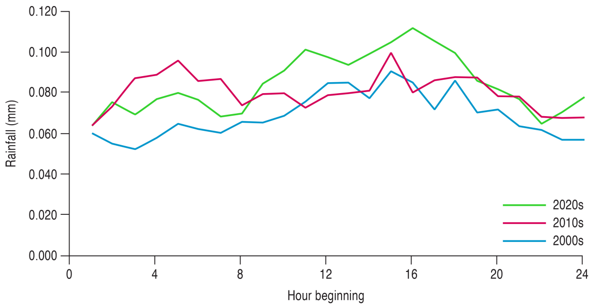

Figure 3 Mean hourly rainfall (mm) at Durham, 2001-2023.

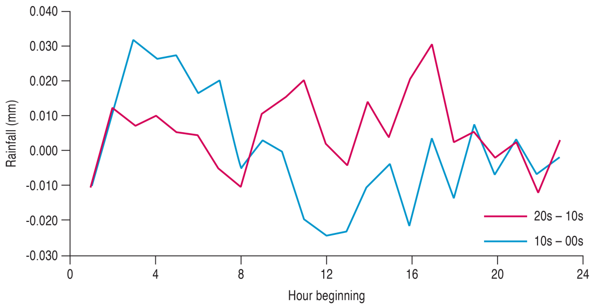

Figure 4. Differences in mean hourly rainfall (mm) at Durham for the data plotted in Figure 3.

Figure 3 shows mean hourly rainfall at Durham since 2001. Rainfall totals have generally increased during this period. For the decade 2001-2010, the mean hourly rainfall is 0.069 mm, equivalent to a mean annual total of 604 mm. For the decade 2011-2020, the mean hour rainfall increases to 0.08 mm, equivalent to a mean annual total of 701 mm, whilst the mean hourly rainfall for the period 2021-2023 is 0.085 mm, equivalent to a mean annual total of 745 mm. If daytime warming in recent years relates to a change in the synoptic origin of air masses, these air masses might also be moister as well as warmer. Figure 4 confirms the timing of changes in hourly rainfall amounts during the study period.

Changes observed at Moor House

Figure 5 shows mean hourly temperature at Moor House since 1991. It is clear that the 1990s were a little cooler than more recent decades, notably in the middle of the day. The 2000s and 2010s have very similar diurnal profiles with the most recent years being rather warmer, especially during the day, as at Durham. For hourly rainfall at Moor House, no clear pattern of change emerges (Figure 6) and the mean hourly rainfall is almost identical in all three periods (0.23 mm). It seems therefore that warming at Moor House has not been accompanied by any significant change in hourly rainfall regime.

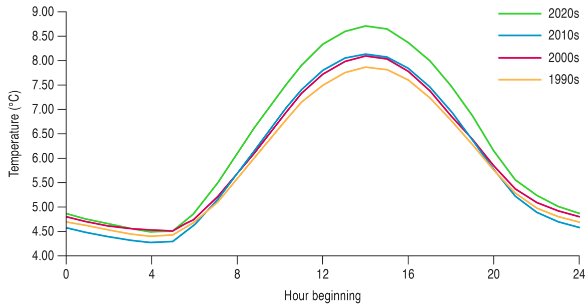

Figure 5. Mean hourly temperatures (°C) at Moor House 1991-2023.

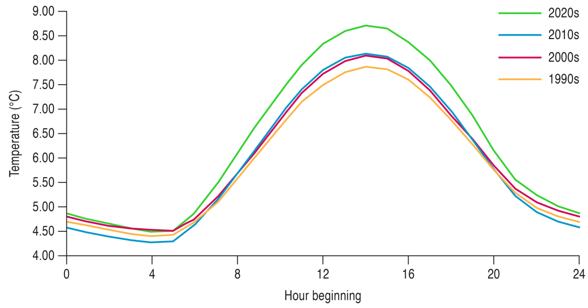

Figure 6. Mean hourly rainfall (mm) at Moor House, 2001-2023.

Differences between Durham and Moor House

Comparing average temperatures for the three periods, Figure 7 shows that Durham has become relatively warmer at night. Night-time warming at Durham (Figure 1 and 2) was not replicated at Moor House (Figure 5). Whatever the cause of nocturnal warming, local or regional, it is interesting that the change was seen at lowland Durham but not at upland Moor House. Overall, the mean hourly temperature difference between the two sites has increased: from 3.12 °C in the 2000s, to 3.39 °C in the 2010s to 3.48 °C in the 2020s.

As noted above, for hourly rainfall at Moor House, no clear pattern of change emerges and the same may be said for differences between rainfall at Moor House and Durham. In the 2000s the differences are largest in the afternoon. Comparing the 2020s with the 2010s, the biggest change is in the morning with relatively higher totals at Durham so that the overall difference becomes smaller. Overall, the mean difference in hourly rainfall totals has fallen from 0.161 mm in the 2000s, to 0.148 mm in the 2010s and 0.144 in the 2020s, showing that rainfall totals have increased at the lowland site compared to the uplands, perhaps because of increased convection at the warmer lowland site.

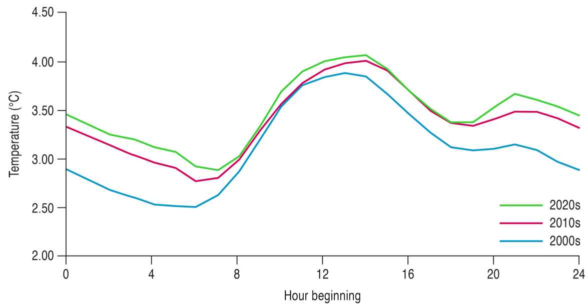

Figure 7. Differences in mean hourly temperature between Durham and Moor House, 2001-2023.

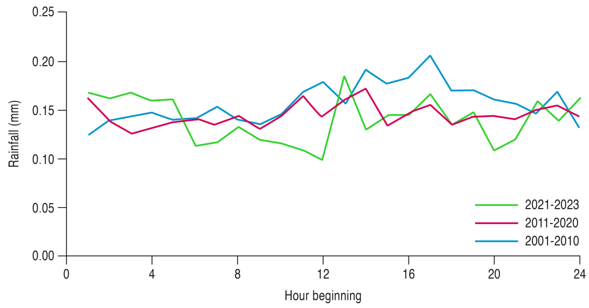

Figure 8 Differences in mean hourly rainfall (mm) between Durham and Moor House, 2001-2023.

DISCUSSION AND CONCLUSIONS

Table 2. Annual correlations between NAO indices and Durham (DUR) and Moor House (MH) temperature and rainfall. Correlations significant at p<=0.05 are shown in **bold type**. Correlations significant at p<=0.001 are shown in **<u>bold type</u> underlined**. n=23.

	Year	*NAO*	*DURtemp*	*DURrain*	*MHtemp*	*MHrain*
Year	1					
NAO	0.29	1				
DURtemp	0.35	0.41	1			
DURrain	0.26	0.22	-0.36	1		
MHtemp	0.19	0.41	**<u>0.95</u>**	-0.41	1	
MHrain	-0.16	**0.47**	-0.01	**0.46**	0.01	1

At the annual scale (n=23), there is a highly significant correlation ($p < 0.001$) between mean air temperatures at Durham and Moor House, as might be expected. Both sites have shown warming over this period, although neither trend is statistically significant. For annual rainfall totals, the correlation between the two sites is significant ($p < 0.05$), although not nearly as strong as for temperature. The trend has been for rainfall to increase at Durham but to decrease at Moor House; in neither case is the correlation statistically significant. The long-established method for calculating daily mean air temperature is to use the maximum and minimum temperatures as recorded at 0900 hours (with the maximum 'thrown back' to the day before). This method was and remains necessary at most climatological stations because they do not have full-time observers. Now that data loggers are much more common, there may be a case for using the hourly means of 60-second observations as these are commonly stored by the data logger. Table 3 shows comparisons at Durham for the three 'decades' already discussed. It can be seen that the use of maximum and minimum data tends to produce a higher mean than that obtained from hourly data; this is probably because bright sunshine can cause immediate increases in air temperature which may not last very long if the sunshine is intermittent. In the future, it may prove preferable to use the hourly means to provide a more accurate estimate of mean air temperature, since these data also provide a detailed description of the diurnal cycle, as discussed above. Nevertheless, the traditional method must be maintained in order to provide continuity with historical records.

Table 3. A comparison of mean air temperature (MAT) calculated from daily maximum (Tmax) and minimum (Tmin) data with mean air temperature calculated from hourly data.

	Tmax	Tmin	MAT	Hourly mean	Difference
2001-10	13.21	5.84	9.52	9.19	0.34
2011-20	13.51	6.00	9.75	9.38	0.38
2021-23	14.07	6.40	10.23	9.87	0.36

In summary, the use of hourly data greatly improves our ability, not only to identify changes in temperature and rainfall, but also to identify likely causes for these changes. At Durham, the recent increase in air temperature is seen most strongly in the afternoon, perhaps indicating increased sunshine and associated convection at that time of day. Recent changes in mean hourly rainfall are also seen in the afternoon, perhaps indicating the generation of cloud and rain because of increased air temperatures which are likely to render the air more unstable. Further research is needed to identify which changes relate to local effects compared to changes in regional climate.

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REFERENCES

Burt, S.D. (2012). *The weather observer's handbook*. Cambridge, Cambridge University Press. 444pp.
Burt S.D. and Burt, T.P. (2022). *Durham weather and climate since 1841*. Oxford: Oxford University Press, 580pp.
Malamud, B.D., Turcotte, D.L. and Grimmond, C.S.B. (2011). *Climate Past* 7, 975–983. doi:10.5194/cp-7-975-2011.
Meteorological Office (1982). *Observer's Handbook*. London: HMSO, 220pp.
Met Office (2012): Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current). NCAS British Atmospheric Data Centre, date of access: 2 June 2025. http://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0
Sanford R.A., Chee-Sanford J.C., Yang W.H. (2024). Diurnal temperature variation in surface soils: an underappreciated control on microbial processes. *Frontiers in Microbiology*. doi: 10.3389/fmicb.2024.1423984
http://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0
World Meteorological Organisation. https://wmo.int/