# *Storm Ciarán's effect on the boiling point of water in the south-east of the UK*

# Storm *Ciarán*'s effect on the boiling point of water in the southeast of the United Kingdom

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## Introduction

Storm *Ciarán* yielded an unusually deep low pressure in the southern United Kingdom for November, and with it, an opportunity to compare the associated measured and derived pressures obtained from isolated pressure sensors, observing networks and the derived values found by reanalysis. Beyond the dynamical meteorological response to a storm, the reduction of absolute pressure also directly affects the boiling point of water. Although specialised instruments are generally necessary for accurate boiling point measurements, such as the *hypsometer* once used to determine altitude, or in some radiosondes (Richner *et al*., 1996), the depression of the boiling point of water during the passage of *Ciarán* was readily detectable.

Modern data monitoring and recording systems provide accurate pressure data at typical resolutions of minutes or even less, and many values over a region are assimilated into meteorological reanalysis products of different forms. Not all such data sources are, however, assimilated, allowing measurements independent of the assimilation to be compared to reanalysis results at similar locations. In this work, Storm *Ciarán* pressure data derived from the ERA5 reanalysis are compared with, firstly, the Reading University Atmospheric Observatory standard barometer, and, secondly, those obtained from an independent roadside measurement network using Vaisala sensors. The timing of the *Ciarán* pressure minimum was soon after dawn in the populated southeast of the United Kingdom, implying that a boiling point reduction would have been present during breakfast time. Possible consequences arising from this are considered.

## Data from ERA5 reanalysis and University of Reading Atmospheric Observatory

On 2 November 2023, *Ciarán* tracked along the English Channel, moving north and inland from the Isle of Wight, passing across the southeast of the United Kingdom into the North Sea. Its influence yielded new record pressure minima, such as the lowest November pressure in England of 953.6hPa at St Catherine's Point on the Isle of Wight (Kendon, 2024). While lower pressure minima have been measured in other months, an extreme low pressure in November is rare (Burt, 2007). The principal features and progression of *Ciarán* are evident from the ERA5 reanalysis data in Figure 1.

The reanalysis was also compared with single point pressure measurements made at the Reading University Atmospheric Observatory (RUAO). RUAO uses a Druck DPI150 barometer (accuracy ± 0.02hPa), at 1s sampling. Figure 2 shows a comparison between the measured DPI150 pressure, corrected to sea level, and the hourly ERA5 pressure reanalysis at the nearest grid point to the university site. The RUAO station pressure (at 66m altitude) was adjusted to mean sea level (msl) using a standard formula (WMO, 2021), which estimates the additional pressure arising from a moist, uniform air column between the site and sea level.

Figure 2(a) shows the hourly reanalysis msl pressure as points, and the much greater time resolution data from the RUAO

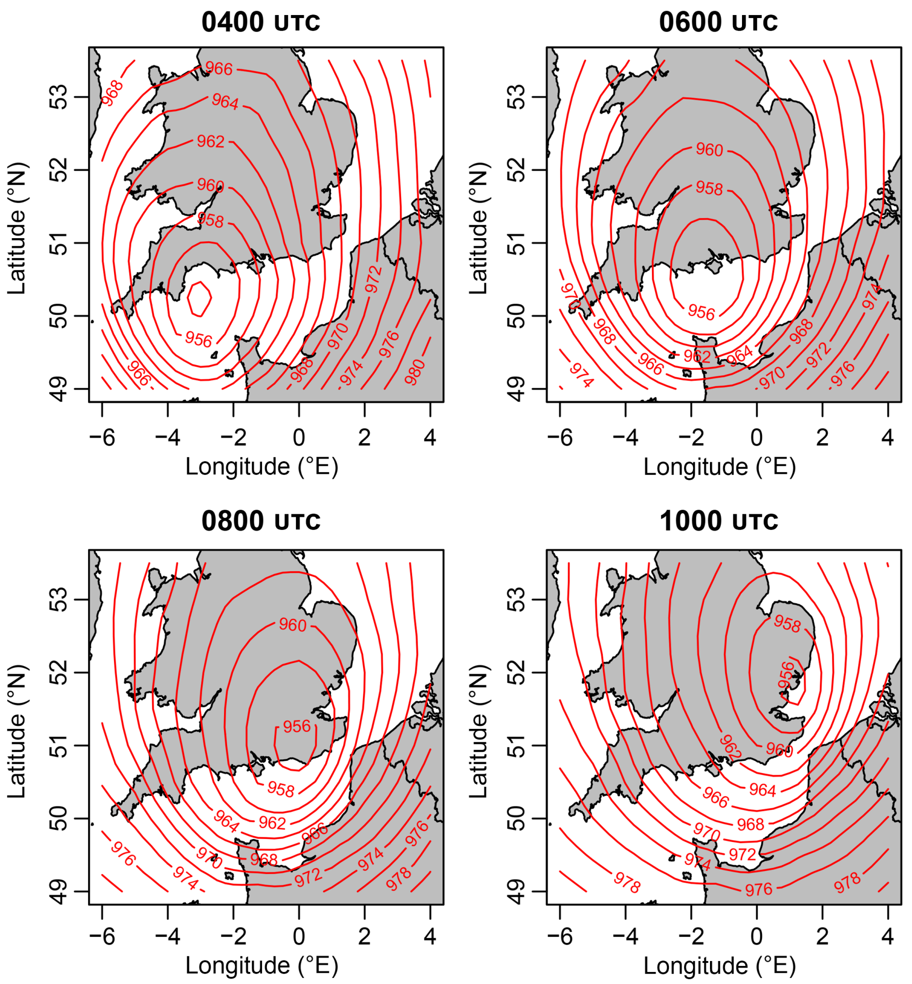


*Figure 1. Surface pressure map (ERA5 reanalysis of mean sea-level pressure, contours drawn every 2hPa) during the progression of* Ciarán *on 2 November 2023.*

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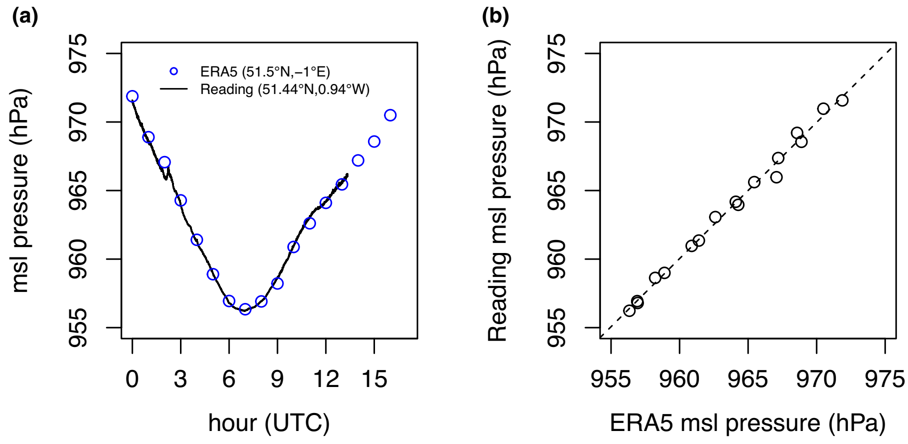


*Figure 2. Comparison between mean sea-level (msl) pressure measured at Reading using a Druck DPI150 barometer and the ERA5 reanalysis pressure for the nearest grid point. (a) Time series (black line from Reading data sampled at 1s, and blue open points ERA5 hourly values), and (b) ERA5 hourly values against instantaneous Reading measurements at the hour concerned time (dashed line represents 1:1).*

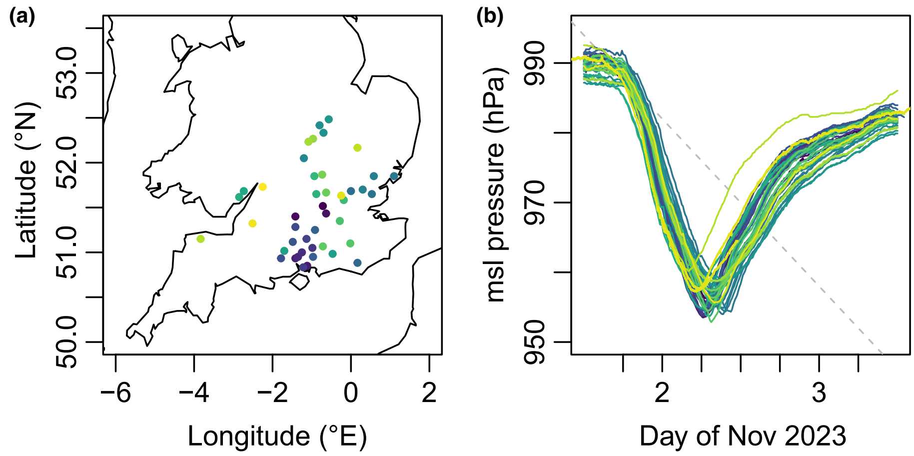


*Figure 3. (a) Distribution of Vaisala roadside network sites providing atmospheric pressure data. (b) Retrieved pressure data from the same sites (10min samples), corrected to mean sea-level pressure. The dashed line shows a rate of pressure decrease of 24hPa per day. (The individual station traces are not intended to be fully identifiable, but the colours used in (a) and (b) are consistent for each site.)*

barometer. Some small and rapid fluctuations occur in the measurements which are not resolved in the reanalysis, but the agreement is evidently excellent. Figure 2(b) considers this further using instantaneous RUAO pressure values selected for the same times as the reanalysis data. A fitted least-squares line to Figure 2(b) has a gradient of 0.994 ± 0.021, where the uncertainty is one standard error. This is therefore indistinguishable from the 1:1 line. The root mean square error (rmse) between the sets of values is 0.40hPa. (If hourly RUAO mean values centred on each hour are used, the gradient is 1.00 ± 0.01, and the rmse is 0.33hPa.)

## Data from the Vaisala roadside network

Many urban locations are monitored by Vaisala roadside measured stations, which are intended to provide data on road conditions for local authorities. Although not fully equipped automatic weather stations, some of the roadside stations include barometric pressure sensors in WXT536 weather sensors. These sensors have a specified accuracy of ±0.5hPa with a resolution of 0.1hPa, and report every 10min. The good temporal resolution and sensitivity of this network has previously provided useful data for analysis of solar eclipse-induced changes (Gray and Harrison, 2016), and detecting the pressure wave moving across the United Kingdom generated by the January 2022 Tonga eruption (Harrison, 2022). As indicated by Figure 1, a cluster of pressure-providing measurement sites in the southern United Kingdom is especially suitable for the region affected by *Ciarán*.

Figure 3(a) shows roadside sites where pressure is measured. Because of the increasing sparseness of the Vaisala network to the west, data from two further western sites was added, from High Littleton in Somerset and Selsley in Gloucestershire. At High Littleton, a Kestrel DROP D3 pressure sensor (accuracy ±1hPa) was logged at 1min intervals. At Selsley, a BME280 sensor operating as previously described (Harrison, 2021) was used, with added data logging and GPS cards. (This sensor was also later corrected against the Druck DPI150 standard barometer at RUAO.) The altitudes of the roadside sites were used to reduce the data to mean sea level, as for RUAO (WMO, 2021). For these calculations, the relative humidity (RH) and temperature were assumed to be 50% and 12°C respectively, as only some of the roadside systems provided these quantities. (The uncertainty in the sea level correction from this assumption is negligible compared with the sensor's accuracy: from RH the uncertainty is <0.001hPa per % and, from temperature, ~0.07hPa per °C.)

Time series of the pressure data from the sites in Figure 3(a) are shown in Figure 3(b). The values show consistent behaviour across the sites, with a pressure minimum at about 0700 UTC on 2 November, with some propagation of the minimum from west to east evident. Although one site, East Grinstead, recorded 952.8hPa at 0730 UTC, the expected uncertainties in both the sensor (±0.5hPa) and the sea level correction argue against it being considered as lower than the St Catherine's Point measurement.

The Vaisala sites provide spatial pressure information at up to 10min temporal resolution. Figure 4 shows a series of half-hourly interpolated pressure fields in the southeast of the United Kingdom, between 0600 UTC and 0830 UTC. Similar features to Figure 1 are evident in this region, in that the pressure minimum propagates north-eastwards during this period. The derived minimum pressure value is also similar. Such a reduction in pressure would lead to a reduction in the boiling point of water over the region concerned. This relatively unexplored consequence from a significant weather event is now considered further.

## Effect on the boiling point

Water boils when its saturation vapour pressure equals the atmospheric pressure. Hence, as atmospheric pressure changes, the boiling point of water also changes: a reduction in pressure from the standard atmosphere value (1013.25hPa) will lead to a reduction in the boiling point. This effect has long been appreciated, e.g. Cavendish et al. (1777), and was once used to measure altitude. For this, boiling point of water measurements were typically provided by a pressure hypsometer, a device specially constructed to allow accurate boiling point measurements with a liquid-in-glass thermometer.

The boiling point of water can of course be obtained using much more basic equipment, such as a kettle and a wide range thermometer (e.g. a thermocouple or resist-

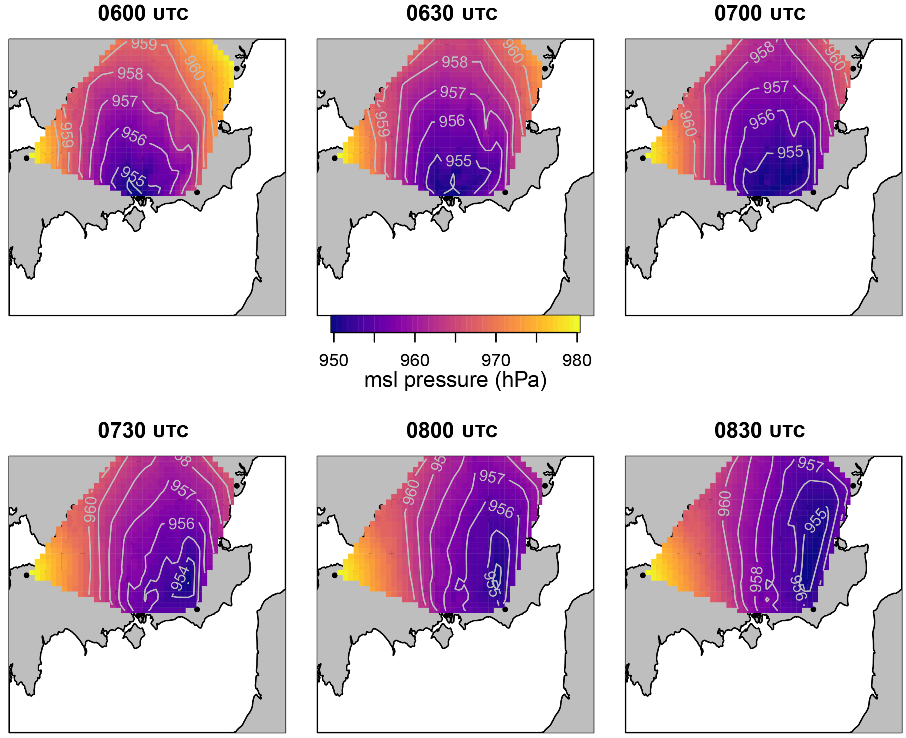


*Figure 4. Progression of the pressure minimum through the southeast of the United Kingdom on 2 November 2023, interpolated from data obtained using the Vaisala network sites shown in Figure 3. (Colour bar is common to all sub-plots.)*

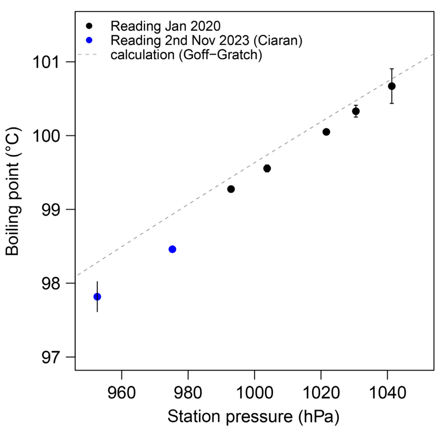


*Figure 5. Observed boiling points of deionised water against station pressure in January 2020 and November 2023, determined using consistent apparatus in the Instrumentation Laboratory in the Department of Meteorology, University of Reading. (Error bars represent the standard error from multiple determinations. The dashed line provides the theoretical expectation, using the Goff and Gratch equations (Goff and Gratch, 1946).)*

ance thermometer). Using such equipment to respond quickly to the circumstances, an increase in boiling point above 100°C associated with the extreme anticyclonic atmospheric pressure during late January 2020 was readily observed (Harrison and Marlton, 2020). The same equipment was deployed in an identical manner on 2 November 2023, determining the boiling point of deionised Reading tap water at two points in the day, around the pressure minimum and later after the pressure had risen a little. Figure 5 shows the values of boiling point obtained, with the previous values from January 2020 included for comparison.

Although expedient in terms of providing immediate measurements, there are limitations with such a simple approach to a boiling point measurement. Firstly, with the platinum resistance thermometer probe merely placed in the kettle's spout, the water region sampled will be at a small distance away from the heating element of the kettle, where the water will be hottest. Secondly, the action of the kettle's boiling point cut-out, which is typically a steam switch, prevents sustained measurements. These factors, and others, probably contribute to the underestimation of the theoretically expected boiling point evident in Figure 5. For this, fits to the saturation vapour pressure curve beyond the usual meteorological range were used from Goff and Gratch (1946), solved for temperature as a function of the saturation vapour pressure by spline interpolation.

Similar calculations can be used to predict the boiling point of water in the southeast of the United Kingdom, using pressure values from the Vaisala network. For this, the region of the Goff–Gratch calculation in Figure 5 was represented by a linear fit, and the boiling point calculated for each reported value of station pressure. Figure 6 shows maps of the calculated boiling points, interpolated over the region. In Figure 6(a), the derived boiling points for the day before *Ciarán* are shown, and in Figure 6(b), during the pressure minimum associated with *Ciarán*. As each individual site's actual boiling point is required, a sea level correction is not relevant. The maps in Figure 6 therefore reflect a contribution from the site altitude, as well as an effect of the reduced atmospheric pressure.

As the pressure minimum was around breakfast time occurring across a densely populated region, the effect of the reduced boiling point might be reflected in reduced electrical power requirements due to boiling of water for making drinks. For water warmed from room temperature of 20 to 98°C, compared with 20 to 100°C, the reduction in the energy required would be ~1%. Such a magnitude of effect would require an abrupt change from one situation to the other, which only be apparent if no other significant changes were occurring simultaneously.

Figure 7 provides the national electrical generation during the morning of 2 November 2023, and the days either side for comparison. There is a steady rise in the generation for all 3 days between 0600 and 0800 UTC, with 2 November's values lying between those of the 1 and 3 November (Figure 7a). Figure 7(b) provides the same data, but detrended using the spline fits shown in Figure 7(a). The exact behaviour of the remaining fluctuations is sensitive to the detrending parameters chosen, but there is a suggestion of steadier supply conditions on 2 November compared with the other days. The small downwards fluctuation around 0700 UTC is not inconsistent with an expected reduction in electrical demand, but it cannot be uniquely attributed to it either: other factors could be causing it, separately or in combination. Further, the pressure was persistently low for several hours either side of the minimum, so the effect is likely to be much less than the 1% estimated above for an abrupt change in pressure.

## Discussion

The passage of *Ciarán* led to usually low surface pressure in the southeast of the United Kingdom during the early morning of 2 November 2023. This is a densely inhabited region, with London and the southeast containing about 20 million people, or ~30% of the UK population. One effect of the pressure minimum is that it suppressed the boiling point of water in this region, which was directly observed at Reading as a reduction of ~2°C.

From the estimates and the brief analysis undertaken of available data, it is unlikely that this small change would be detected in power consumption – the associated change is a needle in a hay-

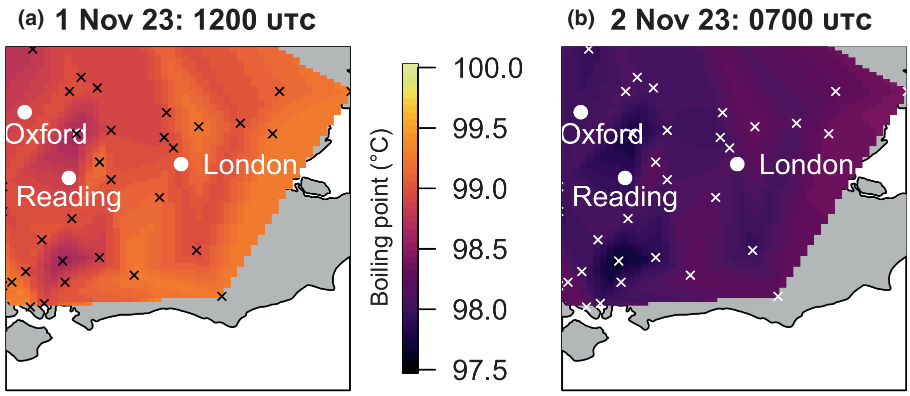


*Figure 6. Calculated boiling point of water in London and the southeast for (a) noon on 1 November 2023 and (b) at 0700 UTC on 2 November 2023.*

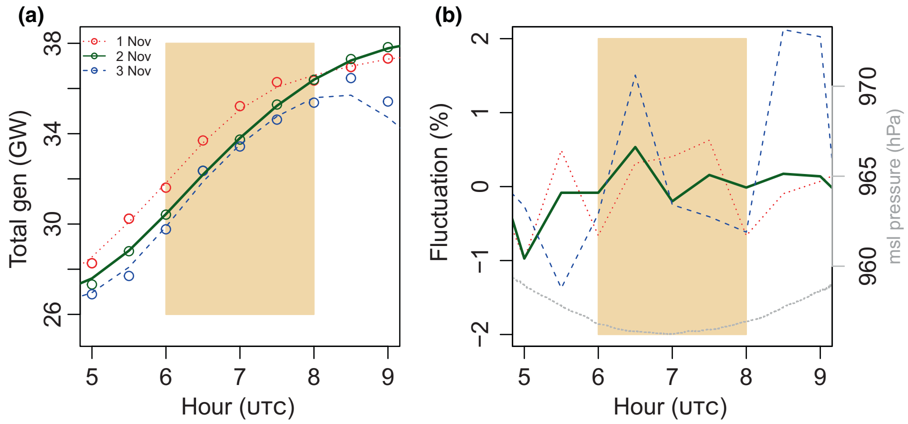


*Figure 7. (a) Half-hourly national total electrical power generation (GW) between 0500 UTC and 0900 UTC on 1, 2 and 3 November 2023 (red, green and blue points, respectively), with a smoothing spline added for each day (red, green and blue lines, respectively). (b) Fluctuation in generation (i.e. instantaneous measurement with smoothed values at the same time subtracted, as a percentage of smoothed value), for the same 3 days also shows the msl pressure determined at Reading (grey line). The shading in both plots indicates the period around the Ciarán pressure minimum.*

stack. However, there is another possible detection method which might resolve an effect, through a discernible change in the taste of tea for the large number of people affected at about breakfast time. This arises because tea is very sensitive to the temperature of the boiling water used in making it, which is related to the effectiveness of the extraction of tannins from the tea. Previous research has found that optimal infusion conditions for white tea at a water temperature of 98°C, following a brewing time of 7min (Pérez-Burillo *et al.*, 2018). Further, for black tea, the recommended water temperature by the UK Tea and Infusions Association[1] is 98 to 100°C. During the passage of *Ciarán*, water's boiling point at some sites in the southeast would have been less than this. It therefore seems likely that some tea at breakfast time on 2 November 2023, in London and the southeast (affecting perhaps 20 million people), would have been made with water temperatures beyond the recommended range.

[1]https://www.tea.co.uk/make-a-perfect-brew.

## Author contributions

**Giles Harrison:** Conceptualization; investigation; writing – original draft; data curation. **Alec Bennett:** Investigation; conceptualization; writing – review and editing. **Caleb Miller:** Investigation; conceptualization; writing – review and editing; validation. **David Bullock:** Investigation; writing – review and editing.

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## Data availability statement

The pressure data used in this paper are available from the University of Reading data archive at https://doi.org/10.17864/1947.001325. Reanalysis data for Figures 1 and 2 were obtained from Copernicus Climate Change Service (C3S), as ERA5 hourly data on single levels, from 1940 to present. Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47 (accessed on 29 February 2024). The power generation data were obtained from https://www.energydashboard.co.uk/historical.

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