Describing the historic indoor climate: Thermal monitoring at Hardwick Hall

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Abstract

This paper presents data collected at Hardwick Hall between July 2018 and August 2019, in which air temperature and relative humidity (RH) levels were monitored at five locations within the house and at one external reference point. By reference to historic weather records documenting the climate of the Elizabethan period, and with careful consideration of the changes that have been made to the fabric of the house in the intervening time, it is possible to recreate a picture of the environment of the house at the date of its construction.

The monitoring data has been used as an input to model the role of the 35 fireplaces and 156 windows in improving thermal comfort in key spaces of the house, including specifically the High Great Chamber and the Long Gallery. This allows us to build a more complete description of the inhabitation of the house, informed by the building records, inventory, and other contemporary accounts from the period. The outcome is to provide a new understanding of the environment of the house, made possible by combining modern building science with studies in the history of architecture and archival material from the Elizabethan era.

Keywords

Thermal monitoring; climate; thermal comfort; solar gains; fireplaces; Elizabethan architecture.

Background

Hardwick Hall, 'more glass than wall', was built for Elizabeth ('Bess'), Countess of Shrewsbury, to a design by Robert Smythson[1], between 1591 and 1598.[2] Rising above the Doe Lea river valley to the west, its apparent symmetry, and the scale of its 156 windows[3] rising over three principal floors and topped off with six turret rooms, develops the Elizabethan interpretation of Renaissance proportion and scale that Smythson had first experimented with at Longleat and Wollaton (Figure 1).

Figure 1 Hardwick Hall, west front. Author 2.

In an earlier article Hardwick Hall was examined from an environmental perspective, demonstrating how in formal disposition the Hall exploits the orientation of its site, with long fronts to east and west either side of a spine wall displaced off centre, accommodating rooms and spaces of varying scale suited to inhabitation in the morning, afternoon and evening respectively, with the most important state rooms, the High Great Chamber and the Long Gallery, also benefitting from prospects to the south through the towers that form each end of the plan (Figures 2 and 3). In this manner the internal planning of the Hall departs from the perfect symmetry of its elevational treatment to take advantage of the path of the sun across the sky, in a house designed at the peak of the Little Ice Age in Britain.[4] The construction of the house is of massive masonry walls with oak beams and trusses to support the floors and roofs. The wall construction is of ‘roughwall’ stone core with ashlar external facing. The principal structural walls, the external walls and the central spine wall, are 4’ 6” (1.37 metres) thick. The oak boarding of the floors is typically finished with a coat of lime plaster. The construction provides significant thermal mass.[5]

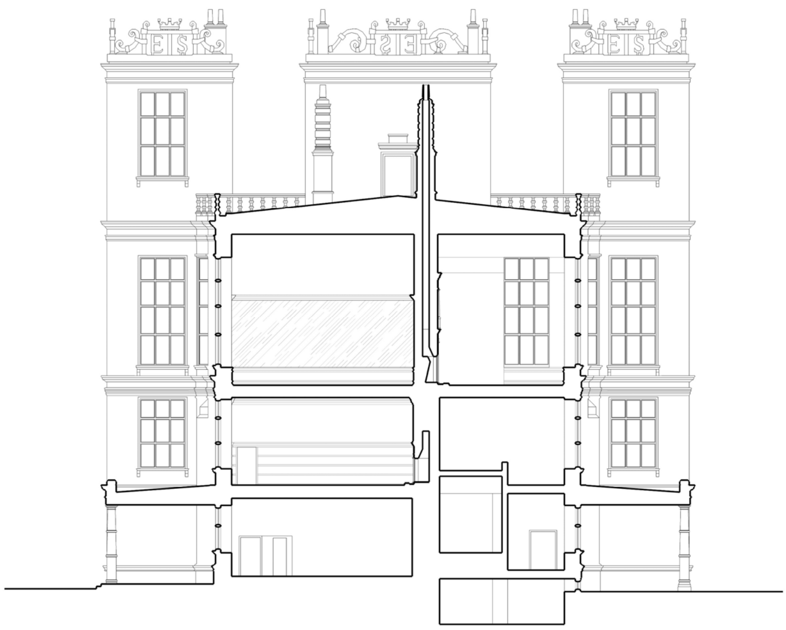

Figure 2 Section. Author 1.

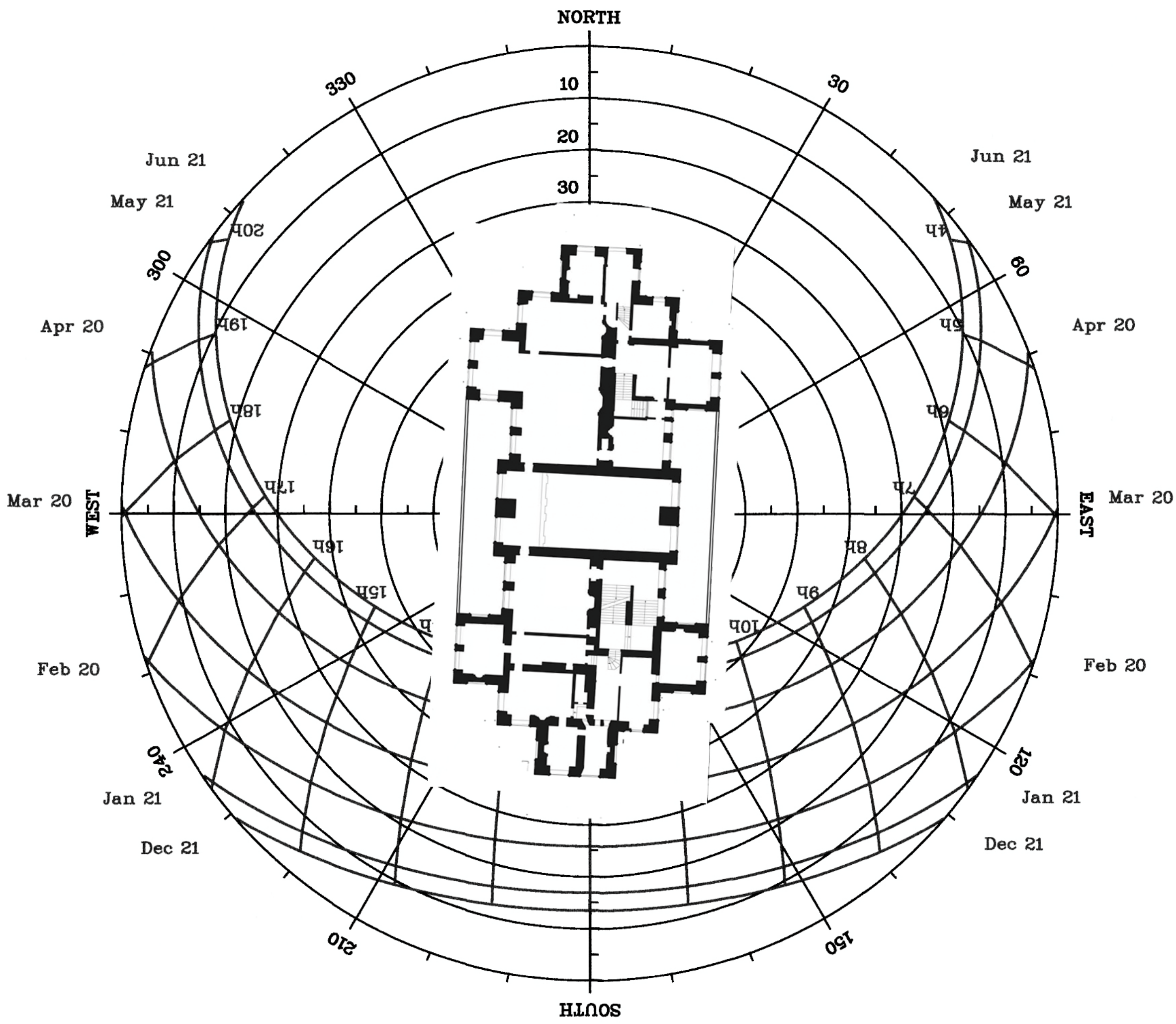

Figure 3 First Floor Plan with sunpath diagram. Author 2. Plan drawing by Luke Kon.

Thermal monitoring

Literature concerning the environmental management of historic buildings often focusses on the technical interpretation of condition surveys by conservators and engineers. The aim is to establish strategies to break the 'cycle of reactive repair'[6], and the conflict between the urgent need to improve energy efficiency without reducing the perceived heritage value of historic buildings or their contents.[7] Cassar, for example, has established performance standards for English Heritage, including the use of Building Management Systems to control heating and humidity, while acknowledging 'the interdisciplinary nature of decision making for environmental control', and that 'a historic building itself may be the first and most important object'.[8]

Examining Brodsworth Hall (architect: Philip Wilkinson, 1863) as a case study, Cassar and Taylor describe how archives can be used 'to complement relative humidity and temperature data on the indoor environment and surveys of the condition of collections in historic houses (…) in order to begin to create a picture of what the indoor environment was like in the past.'[9]

Similarly, in their study of the timber-framed Burmeister House, Visby, Sweden, completed in 1652, Eriksdotter and Legnér argue that 'embodied materialities of thermal comfort in a *particular* single dwelling may relate to cultural and climate change in a larger context'. They describe how the orientation of the key rooms of the house are disposed according to their function in relation to the position of the sun, and the role of various devices such as window shutters and fireplaces in providing thermal comfort during the late Little Ice Age.[10]

In a British context, various authors have described how, beginning in the eighteenth century, new technologies of heating and ventilation transformed the architect's understanding of how the environment inside buildings could be conceived and controlled.[11] However, there is a significant gap in the literature as far as the early modern period is concerned, when architects still predominantly relied upon the sun for light and warmth, augmented by the direct burning of fuel.

It is important to construct a more accurate picture description of the past indoor environment to inform:

a) Our understanding of people's lives in the past and significant historical events.
b) The relationship between people and climate, and how this has changed over time.

While historic buildings provide spatial evidence of the context of historic objects and events, a complete understanding also requires an appreciation for how these environments have changed over time. The reliance on technology to maintain narrow comfort conditions indoors in the present diminishes our appreciation of the impact of diurnal and seasonal changes in the past, and the significance with which they were ascribed. Historic indoor and outdoor environments were inseparable in ways that can seem startling now. Social activities depended on the available hours of daylight. Weather forecasting was connected to astrology, and celestial observations related to everyday events.[12]

The climate of the Little Ice Age

At the end of the sixteenth century, meteorology in its modern sense was unknown. Instruments for the measurement of temperature and barometric pressure were yet to be developed.[13] Modern studies of climate history have reconstructed descriptions of the climate of the period from a variety of sources; documentary accounts of events, tree ring data and so forth.[14] The construction of Hardwick coincided with the lifetime of William Shakespeare. 1564 – 1616, and the climate scientist Mike Hulme has constructed a description of the climate of England of those years that is valuable in establishing the climate of the time.[15] Given the non-quantitative nature of these sources, it is not possible to construct a comprehensive numerical description of the climate, but we may draw out its principal features to set the context within which the house was constructed and first occupied. The graphs show estimated average temperatures in central England for the period AD 800 – 2000 (Figure 4). These indicate the steep decline in temperatures at all seasons in the second half of the sixteenth century and show that the years around the construction and completion of Hardwick were characterised by cold winters and dry summers. Average temperatures in the 1590s were 2°F lower than the long-term average.[16] In contrast the summer of 1598 was very hot, accompanied by drought in the south of England.[17] Specific events include the great storms between July and September 1588, which wrought great damage to the Spanish Armada, and the eruption of the volcano Huanyaputina in Peru in February 1600, ash from which caused the summer of 1601 to be the coldest in the northern hemisphere since 1400. The winter of 1596-97 was accompanied by a severe famine in the north-west of England.[18]

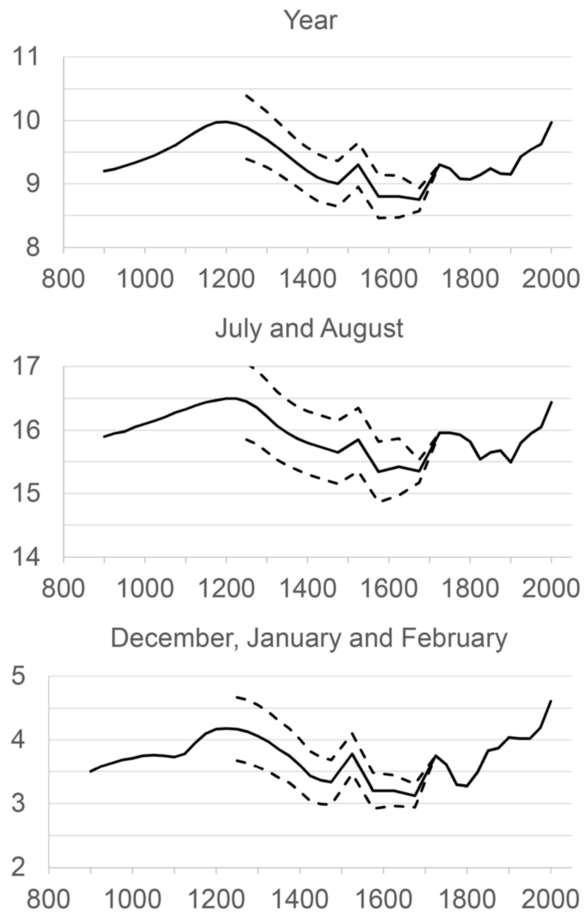

Figure 4 Probable fifty-year average temperatures prevailing in Central England since AD 800 (800 – 1658: H.H. Lamb, *Climate History and the Modern World*, 1995; 1659 – 2000: Hadley Centre Central England Temperature (HadCET) dataset, metoffice.gov.uk/hadobs/hadcet/).

In winter, the open fireplace was relied upon for warmth.[19] Wood burned more cleanly than coal, but was more expensive. Pine and other fast-growing softwoods were not native to England at this period. Trees were cut back to encourage growth of multiple branches (coppicing and pollarding), which were easier to harvest and transport than whole logs, which were a relative luxury. According to the Inventory the fireplace in the Great Hall at Hardwick was equipped with "a payre of brass Andyrons, a fier shovel, a payre of tonges."[20] The scale of the fireplace together with the Andyrons imply that whole logs were burned at least some of the time, though coal would have burned for longer and had the advantage of being transportable in clay pots.

Hardwick Hall today

Hardwick Hall, in the county of Derbyshire, is located at the edge of an escarpment above the river Doe Lea, 151 metres above sea level. Just to the south west stand the substantial remains of the 'Old' Hall, which had been built shortly before work began on the present building. The original configuration of the house and its surroundings are shown in a survey of the site made in 1609 – 1610 (Figure 5). Although there have inevitably been changes in the intervening four centuries, the main aspects of the landscape and layout are little changed, with the enclosed entrance court to the west, and the walled garden to the south still as described in the survey. With its high state of preservation, of fabric and context, the house provides a unique opportunity for monitoring to reconstruct a picture of its thermal environment. However, in doing so, it is important to note that the present management of the house, as an historic monument open to the public[21], differs significantly from its historical operation as an aristocratic residence, so that we can account for these changes in our discussion of the results.

Figure 5 Hardwick Hall: estate survey 1609 – 1610 by William Senior. The house and garden are at the centre of the detail. © The Devonshire Collection, Chatsworth. Reproduced by permission of Chatsworth Settlement Trustees.

Two important changes require examination:

1. Originally most of the 156 windows of the house would have been unshaded by blinds or curtains[22], increasing heat gains from sunshine (varying with the position of the sun in relation to the window) and heat losses at night or in cooler weather. The glass employed in the original lights would have had a significant green-blue tint, a product of the use of wood ash as the alkali mixed with sand in production.[23] This would have reduced the transmission of light and heat. In the present operation of the house, daylight is restricted to 150,000 lux-hours a year to protect the valuable tapestries from damage. This is achieved through use of sheer blinds and restricted opening times for visitors. The remainder of the time heavy curtains are drawn shut.[24]

2. The house has a Building Management System operating small hot water column radiators (typically 1kW) to control RH. The heating is not seasonally operated: radiators are only activated when recorded humidity exceeds 60%, regardless of temperature, in order to protect fabric and other textiles. RH sensors are located in chimney flues, and therefore may not accurately reflect RH in adjoining rooms. The radiators are typically installed under the windows to counteract the tendency for cold downdraughts to form, as follows:

   High Great Chamber: six radiators, all under west-facing windows.
   Long Gallery: four radiators at the south end, four under alternate windows along the length of the gallery, four at the north end.
   Withdrawing Chamber: two radiators under the west-facing windows.
   Hall: two radiators at the east end wall and three radiators at the west, entrance end.

   The small number and size of these radiators in relation to the volumes of these rooms demonstrates their role in providing background heating to combat humidity only. This supposition is supported by comparison of monitored RH and temperature data, which will be discussed in more detail below.

Description of Monitoring Installation

The monitoring devices were installed at Hardwick on Monday, 16th July, 2018 and removed on Tuesday, 6th August 2019. The data-loggers used were two-channel, temperature-RH Onset, U10-003 model, made by HOBO. These comply with the ranges and accuracy levels specified in Standard ISO 7726 for measuring the physical variables of the environment.[25] The loggers have an operating temperature range of -20° to +70°C, with a resolution of 0.02°C, and a RH range from 0 to 95%, with a resolution of 0.1%. Accuracy for temperature is ± 0.4°C from 0°C to 40°C and for RH ± 3.5% from 25% to 85% over the range 15°C to 45°C and ± 5% from 25% to 95% over a range of 5°C to 55°C. The time accuracy is ± 1 minute per month at 25°C. Measurements of temperature and RH were taken at each location at 30 minute intervals.

The monitoring locations are indicated at Figure 6. These were as follows:

1. Hall: moulding on fireplace surround, left side.

2. Withdrawing Chamber: moulding on fireplace surround, left side.
3. High Great Chamber: moulding on fireplace surround, right side.
4. Long Gallery: moulding on south fireplace surround, north side.
5. South Turret: ledge beneath window cill, LH window in south face.
6. Service Yard (external reference): above door frame to external store.

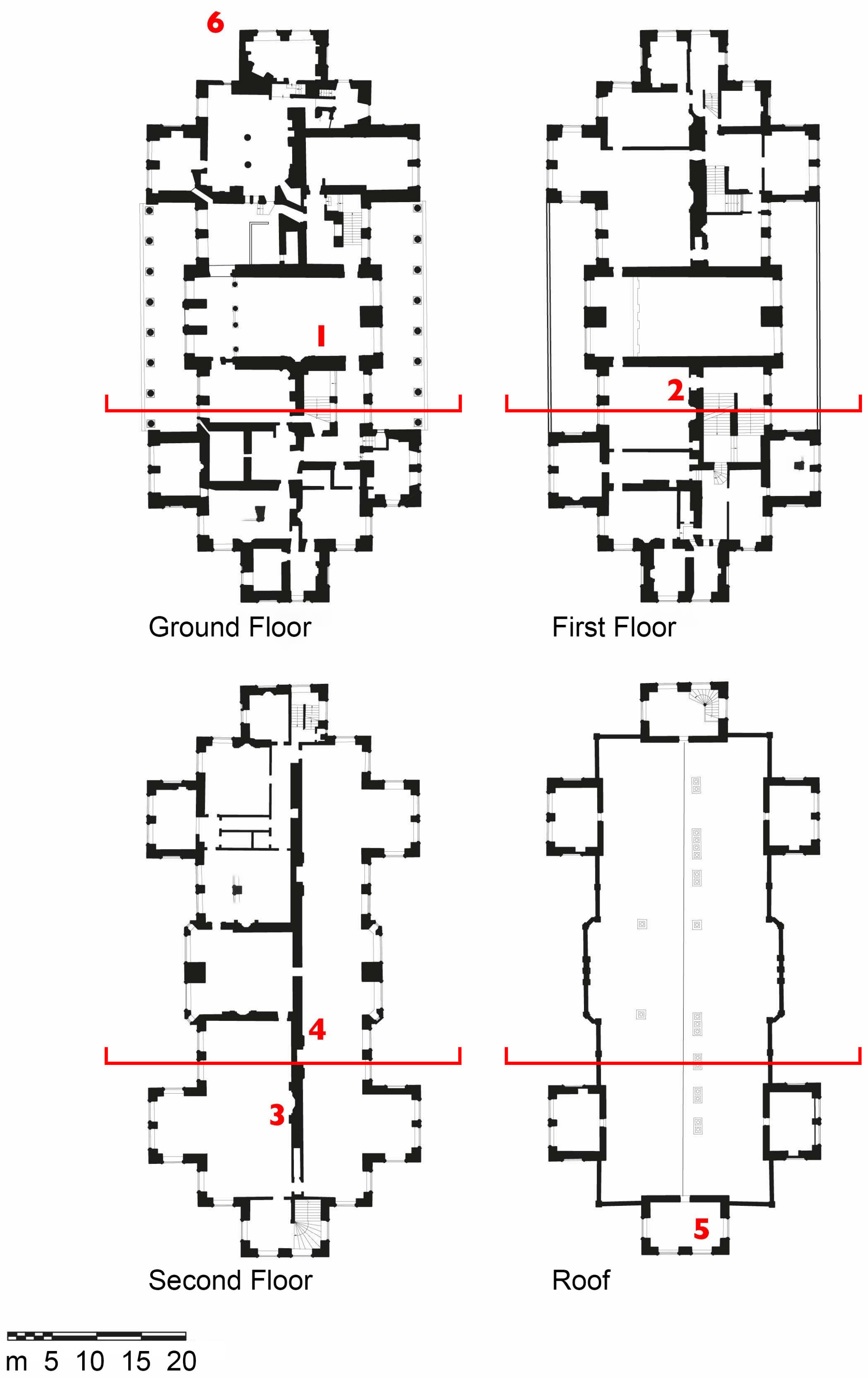

Figure 6 Monitoring Points (indicated in red numerals). Authors. Plan drawings by Luke Kon.

The context of each location is illustrated at Figure 7 (a-f) and each specific site is shown in the images at Figure 8. With the exception of locations 5 and 6, the loggers were positioned 7-10m from external walls, at a height of approx. 1.8m from the floor (representing air temperature at head height for a standing subject). Location 5 is surrounded by external walls on all sides. A location on the southern wall close to the floor was chosen for shading. Location 6 is a shaded external reference. Positions near radiators, all on external walls, were avoided.

Figure 7 Monitoring locations. Author 1.

Figure 8 Data-logger locations. Author 1.

Supplementary Meteorological Data

The external reference point, Location 6, has provided the essential data on air temperature and RH on site throughout the monitoring period. To provide a broader background to this we obtained a complete meteorological data set from the Meteorological Office for the weather station at Nottingham Watnall. This is located approximately 15 miles south of Hardwick. The coordinates of Hardwick are 53° 10'N, 1° 18'W, altitude 168 m. Watnall is 53° 00'N, 1° 15'W, altitude 118 m. The data consist of:

Daily Maximum Temperature: °C

Daily Minimum Temperature : °C

Daily Mean Temperature: °C

Daily Total Rainfall: mm.

Daily Total Sunshine: hrs.

Although there are small differences between the data for Hardwick and Watnall, these provide additional background to the Hardwick monitoring by, for example, indicating whether a day was sunny or cloudy or whether there was precipitation in the locality.

Hardwick Hall Temperature and RH Graphs

Figure 9 shows the temperature at all locations throughout the entire monitoring period.[26] The data shows that conditions at Hardwick broadly followed weather patterns across the country, with an unusually warm and dry summer in 2018 (average temperatures in July were 2.2°C above the 1981-2010 range) giving way to a relatively mild autumn. With the exception of a cold spell at the end of January / beginning of February the winter was dry and mild compared to the 1981-2010 average. A sunny February (sunshine hours 144% of average) gave way to a rainy March (rainfall 140% of average). This was followed by a mild spring and a relatively cool start to summer, before temperatures peaked at the end of June and July, with a new UK temperature record set on the 25th July.[27]

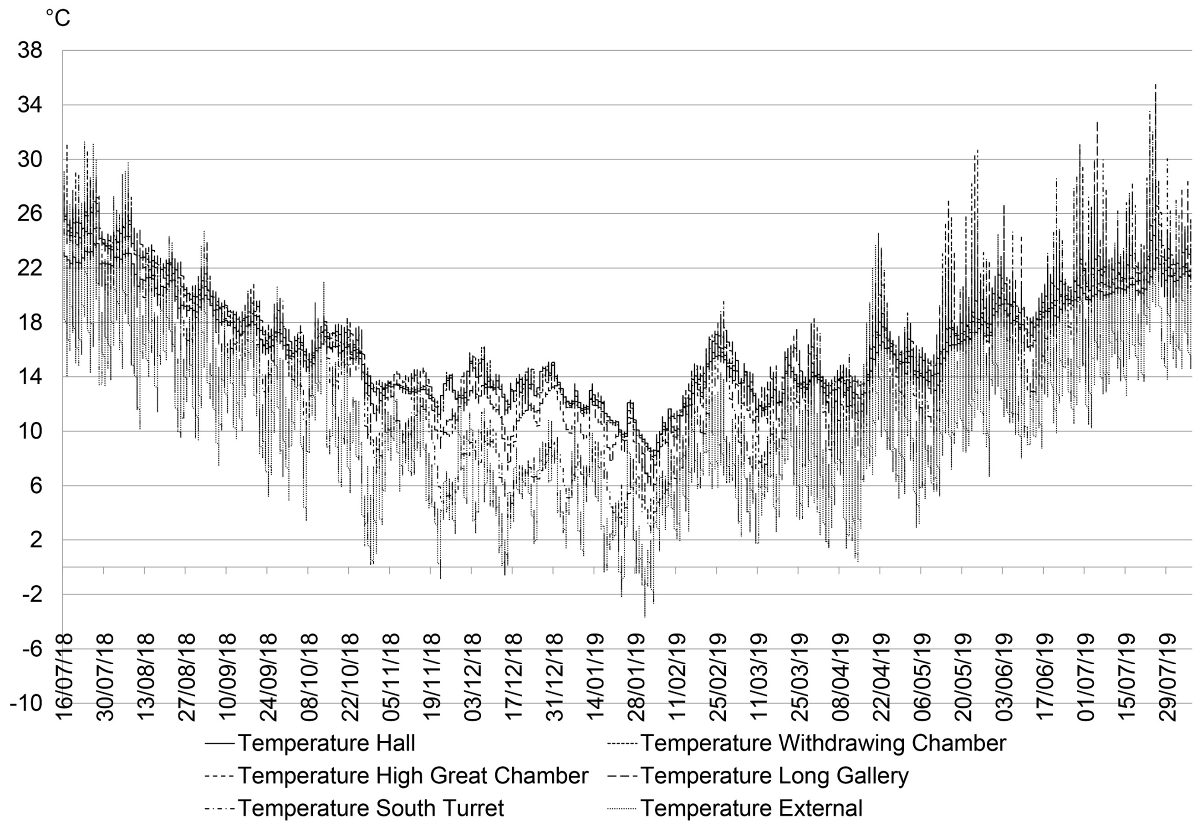

Figure 9 Temperatures, 16th July 2018 - 6th August 2019.

Coldest and Hottest Months

January 2019

The January graph, Figure 10, shows that the external temperature varied throughout the month with alternating cold and mild periods.

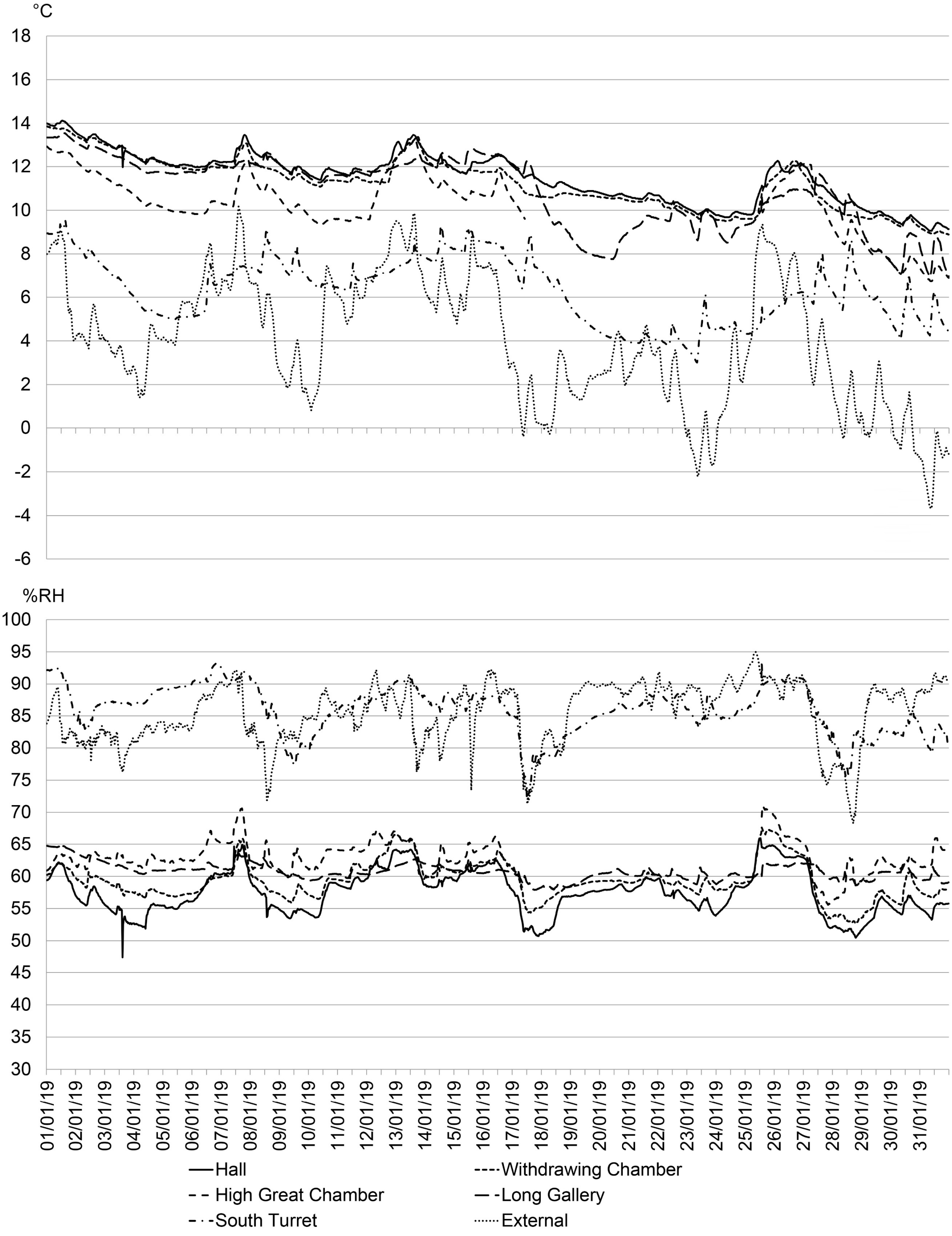

Figure 10 Temperatures (above), RH (below), January 2019.

The graph shows the effect of the building in modifying the external climate in more detail. The temperatures in the Hall and Withdrawing Chamber follow a similar line and are consistently the warmest spaces in the house. The Long Gallery follows a similar line, but there is a period between 18th and 22nd January when temperatures fall below these other spaces. Of the spaces in the body of the house, the High Great Chamber is colder than the others by between 1 and 2°C. The South Turret at roof level is the coldest of all the monitored spaces. The graph at Figure 11 shows these data in more detail, for the period of 18th January to 3rd February.

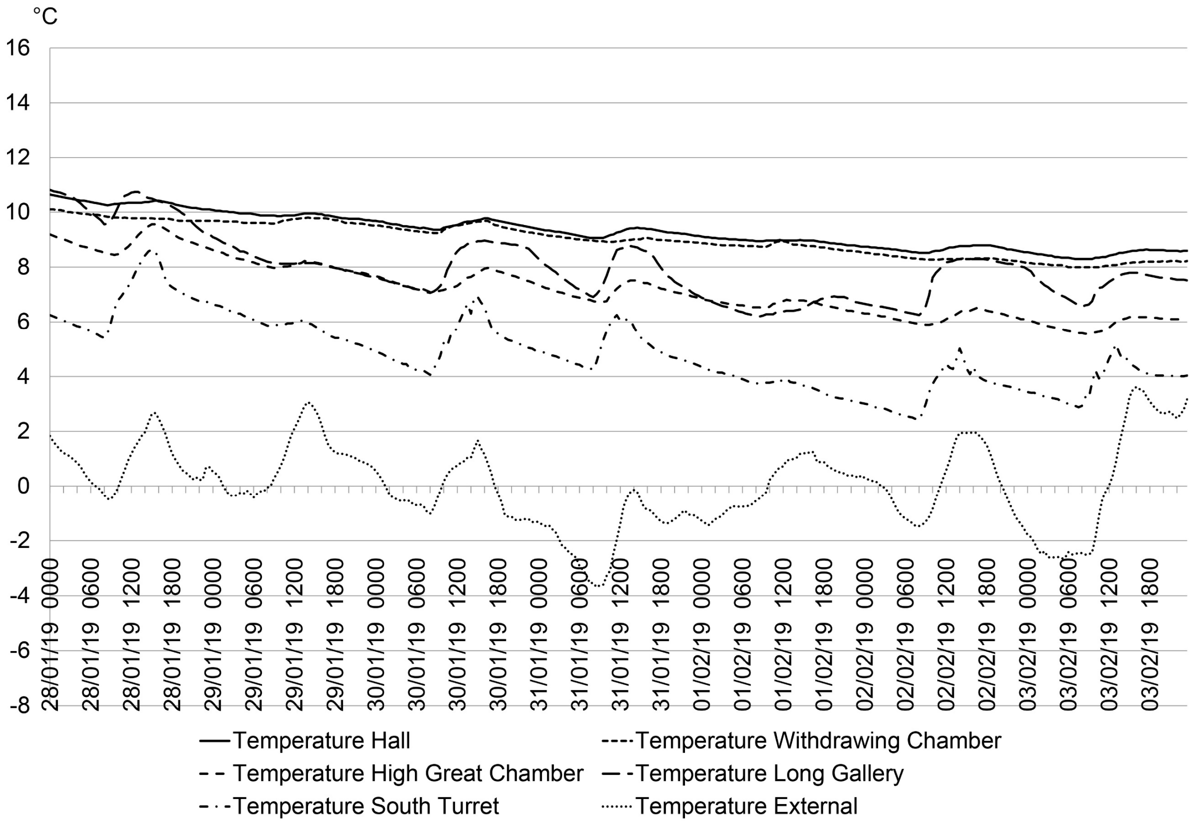

Figure 11 Temperatures, 28th January – 3rd February 2019.

In seeking to explain these results we can note that the Hall and Withdrawing Chamber have relatively small areas of external wall and, hence, low surface area and glazing to volume ratios. The Hall, at ground floor, (Figure 7a) is the only space in the house that runs across the plan from west to east. The Withdrawing Chamber (Figure 7b) at the first floor, has only one external wall and, hence, low external surface to volume ratio. It is lit by a pair of west-facing, nine-light windows. These conditions minimise the interaction between the external and internal environments. The High Great Chamber (Figure 7c) occupies the south west corner of the second floor. This floor has the highest floor-to-ceiling height in the house. The space has eight windows each 4 lights high by 3 lights wide. One window is in the south wall and three face to the west. The bay window has four windows, one each to south and north and two face to the west. In comparison with the Hall and Withdrawing Chamber, this space has a higher ratio of external wall and of glazing to volume. This makes it more brightly lit in keeping with its purpose and also explains the slightly lower temperatures measured on winter days. The Long Gallery (Figure 7d) occupies the entire 61m length of the east front at the second floor. It is lit by a great array of 16 windows, of which two are large bay windows. The windows are all four lights in height.

One window is located in the north end wall of the Gallery with one in the opposite wall at the south end. The bay windows each have two east-facing windows and one south-facing. Their north sides have 'blind' windows in which masonry inner walls stand behind the external glazing. The second floor plan shows that the spine wall that runs the entire length of the plan is offset towards the east. The extensive glazing in the gallery, combined with the relative narrowness of the space, significantly increases the ratio of glazing to volume – the highest in the monitored spaces.

The rectangular South Turret (Figure 7e) is the most exposed space in the study. Located at roof level at the south end of the house, it is exposed on all four sides. It responds to this exposure by having a solid, unglazed wall on the north face and is highly glazed to the east, south and west. The short east and west sides have single tall windows, 3 lights high by 3 lights wide and the south face has a pair of these windows. Unlike the other turret Banqueting Houses the South Turret has no fireplace. This suggests that it was consciously designed to benefit from the warmth of the sun. The data show that, as would be expected, the temperatures in the Turret are generally between 4°C and 5°C below those in the spaces on the lower floors, although there are days when the space enjoys short 'peaks' as it responds to solar heat gains. Generally, it is warmer within the Turret than outdoors, although there is a small number of days when the temperature falls below. Data for the coldest day in the monitoring period, 31st January 2019 (Figure 12) show in detail the general performance of the building.

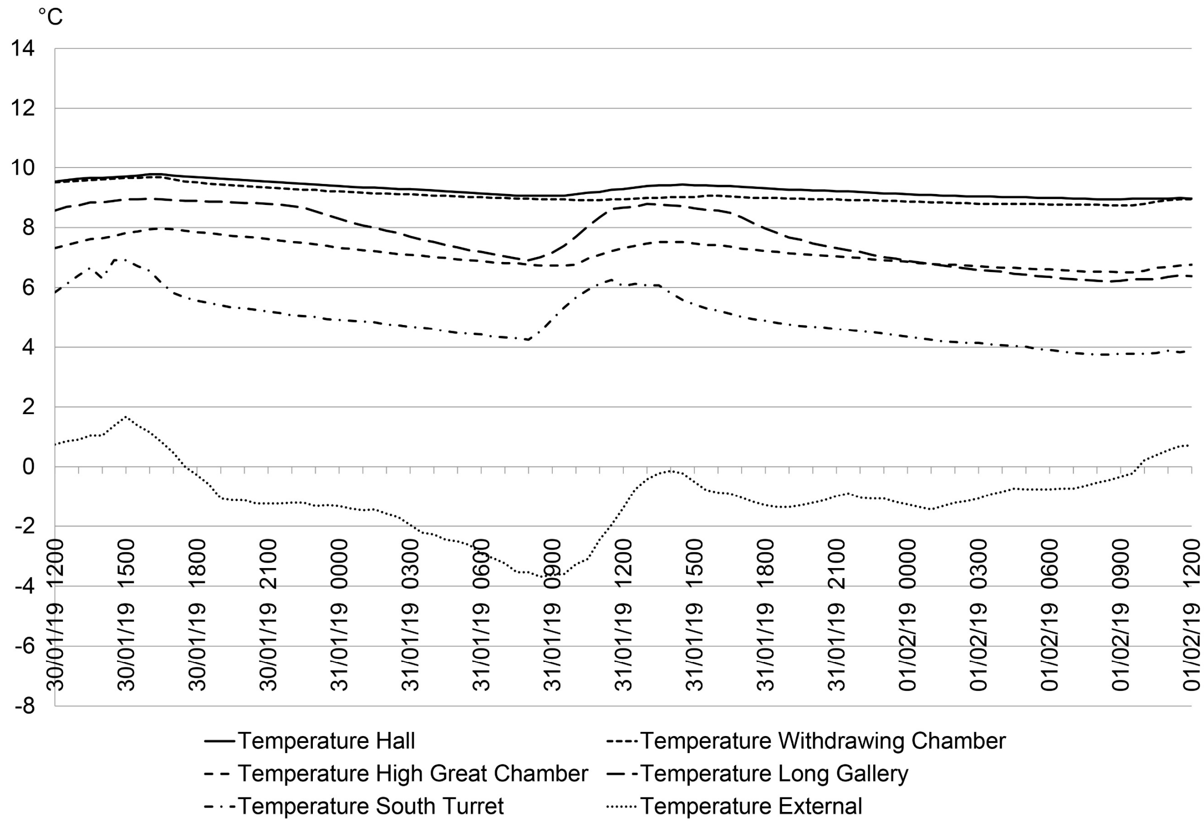

Figure 12 Temperatures, coldest day, 31st January 2019.

The RH data for January 2019 (Figure 10) clearly show the effect of the building enclosure on humidity inside the house. Throughout this period the external RH was in the range 70% - 90% and the RH in the South Turret closely follows these values. The data for the principal monitored internal spaces are significantly below the external values, being in the range 50% - 65%, with a small number of 'peaks' of 70%. These values closely follow the external RH, with the 'peaks' coinciding with high external values. In the individual spaces, the RH data follow those for internal temperature in the sense that the Hall and Withdrawing Chamber are generally lower than those for the High Great Chamber and the Long Gallery, with the former having the highest values. RH in the unheated South Turret is closely connected to the external values, which suggests that RH in the spaces within the body of the house are influenced by the operation of the heating (humidity control) system.

Present-day effect of heating system

If the temperature and humidity in the Long Gallery are compared, it is interesting to note that the drop in external RH around the 17-19 Jan and 28-29 Jan does not register as in the Hall and Withdrawing Chamber. This coincides with a drop in temperature of around 2°C below these other spaces. As noted above, the heating system is set to operate when the internal RH rises above 60%. We can assume that in these periods the heating in the Long Gallery was turned off, explaining the stability of RH just below 60% and the drop in temperature compared with the Hall and Withdrawing Chamber, where the heating was still active.

Looking in detail at the RH data for the single day, 28th January 2019 (Figure 13), a similar picture is seen. External RH ranges from 70% - 90% and this is quite closely followed in the South Turret, where the range is 70% - 80%. In the principal spaces RH is controlled in the range 50% - 60%, with the exception of a short-lived rise between 11.30 – 17.00 hrs. when RH was above 60% in the High Great Chamber, with a peak of 62.91% at 1300 hrs. The consistency of internal RH throughout the 24 hour period suggests that the heating system might have been in operation, but the temperature data show that these spaces were in the range 8.5°C - 10.8°C throughout the period, indicating that the heating effect was fairly minimal. This supposition is supported by the small size of the radiators in comparison to the volumes of the spaces in which they are situated.

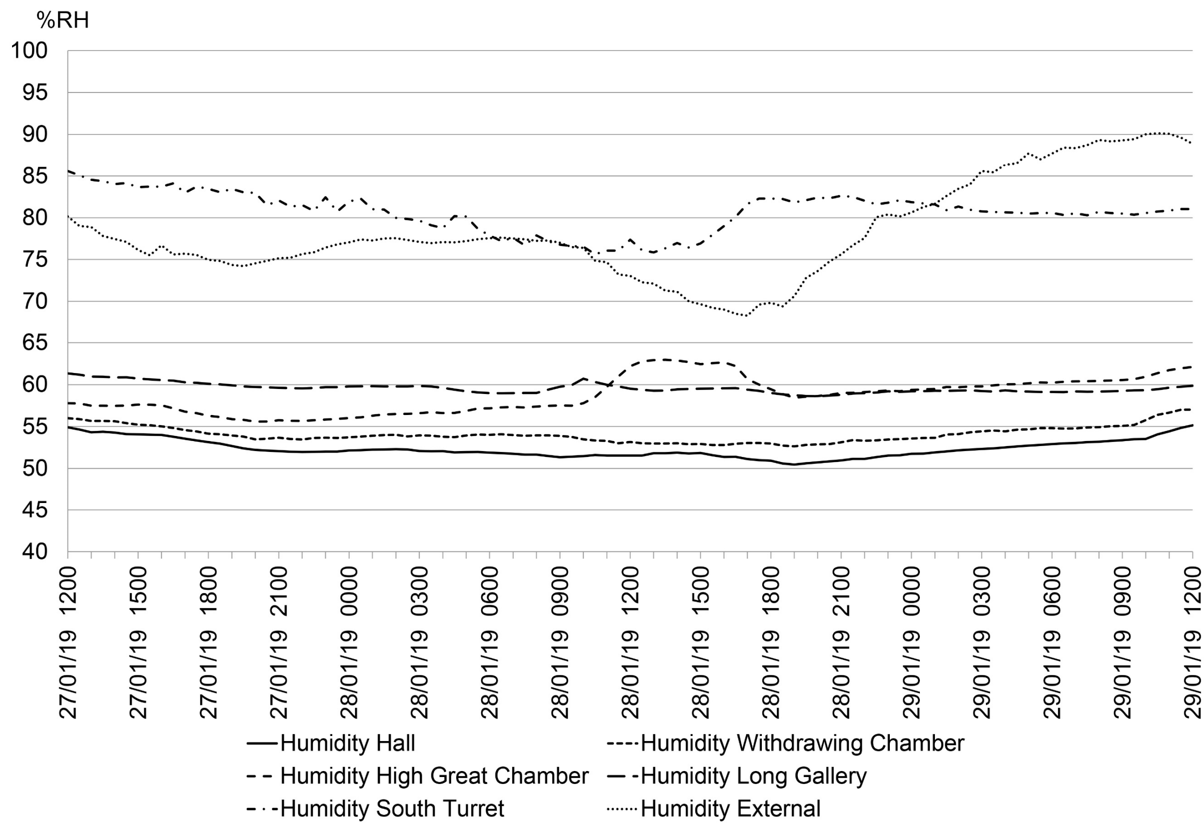

Figure 13 RH, 28th January 2019.

July 2019

The July graph (Figure 14) shows that this was a warm month, with a very hot period between 23rd and 26th , when the temperature each day exceeded 30°C. The lowest nighttime temperatures were generally in the mid-teens °C and the diurnal temperature range was of the order of 12°C. For example, the data for 15th July show the lowest temperature of 12.56°C occurred at 02.30 and the highest of 24.75°C occurred at 15.00.

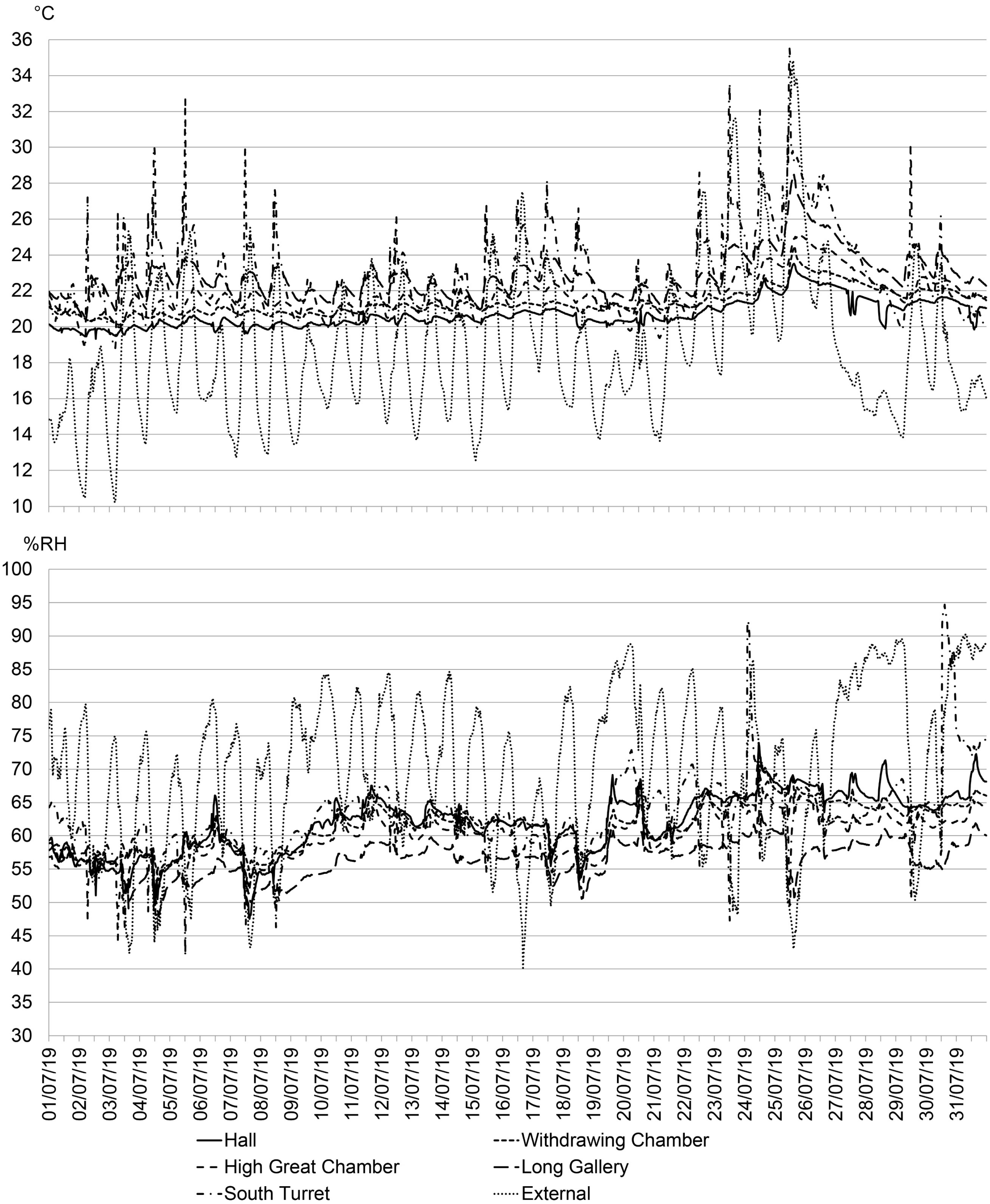

Figure 14 Temperatures (above), RH (below), July 2019.

As with the winter data, the graph shows the extent to which the building modifies the external temperature. Again, the Hall and Withdrawing Chamber are the most thermally stable spaces, with the temperature for most of the month within the range of 19°C to 21°C, with only small diurnal variation, and only exceeding 24°C on the hottest day of 25th July, when the external temperature reached 34.84°C, at 14.00 (Figure 15). The High Great Chamber temperatures follow those in these spaces and are typically between 1°C and 2°C higher, whereas the Long Gallery is some 4°C warmer than these less exposed spaces, but still considerably cooler than the outdoor temperature. The South Turret is the warmest of these spaces and experiences temperatures that are, for short periods, higher than external. These peaks are probably the consequence of the sensor's location in the turret being exposed to direct sunlight. The data for 25th July 2019 (Figure 16) show a peak of 35.50°C at 11.30 in the turret with the highest external temperature of 34.83°C occurring at 14.00. This suggests that the sensor was in direct sunlight from the high, late morning sun.

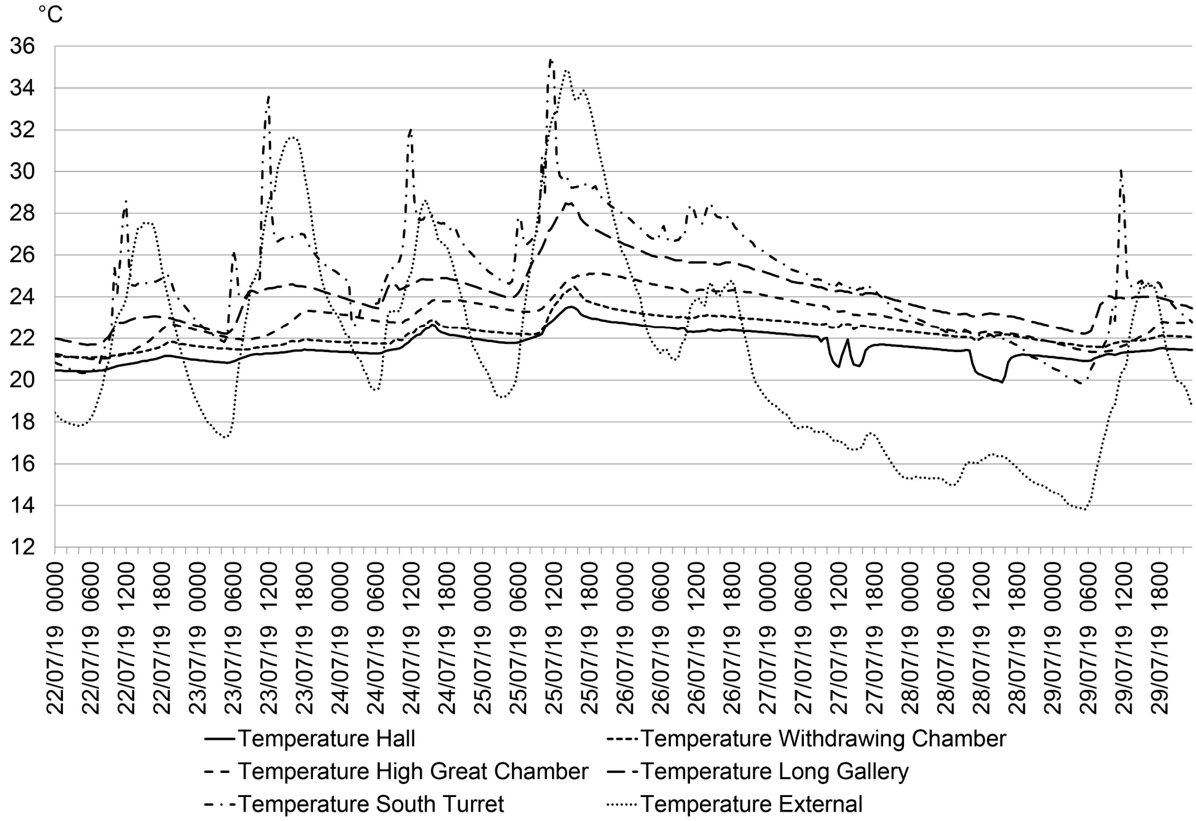

Figure 15 Temperatures, 22nd – 29th July 2019.

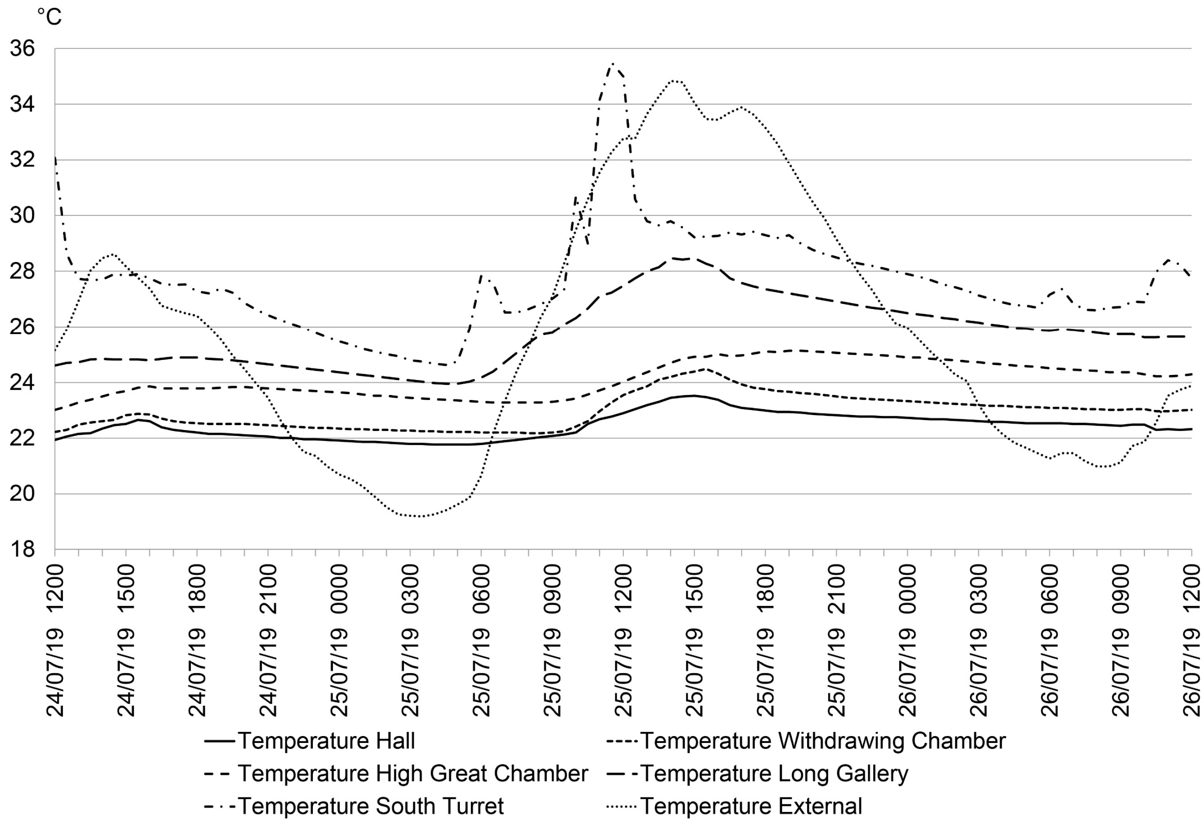

Figure 16 Temperatures, hottest day, 25th July 2019.

The external RH in July 2019 (Figure 14) varies widely between lows of 40% to highs of 90%, with wide diurnal variation. This is principally a function of the diurnal temperature variations that occur in summer, in comparison with the lower variations of the winter months. The moisture capacity of air increases at higher temperatures. RH inside the house is in a much narrower range, typically between 50% and 65%, with the South Turret being the most variable, at both low and high values, with two peaks above 90% on 24th and 30th July. The first of these occurred between 02.00 - 03.30 and the second between 12.30 - 17.30. Of the principal apartments, the Long Gallery has consistently the lowest RH, almost always below 60%. The other apartments are a little higher, but lie in the range 55% - 65%. In the latter part of the month, 20-31 July, the internal RH in these apartments is slightly higher than the earlier days, with occasional peaks just above 70%. These coincide with the hot period noted above, when the external temperature exceeded 30°C on a number of days.

The graph for 18th July (Figure 17) shows the stability of RH within the house, in the range 50% - 60%, including in the South Turret, against the wider variation, 50% - 80% of the external value.

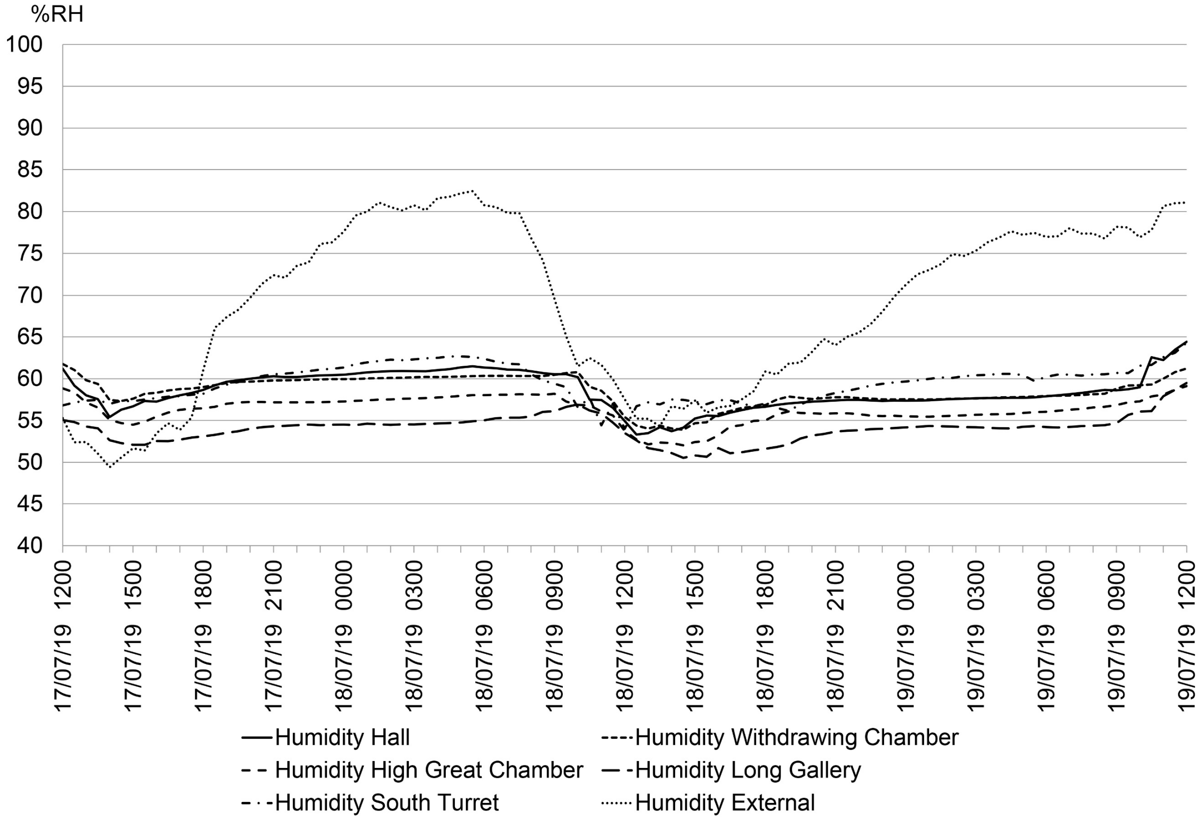

Figure 17 RH, 18th July 2019.

As in the analysis of the winter temperatures the July temperature data shows the extent to which the form and construction of the house are effective in modifying the external temperatures to achieve thermal comfort within. In relation to modern comfort theory and standards the principal spaces at Hardwick fall within the ‘comfort zone’ for domestic uses.

Solstices and Equinoxes

The data for the Autumn Equinox (Figure 18, Table 1) shows the thermal stability of the internal environment of the house, with all the monitored rooms enjoying temperatures in the range 16°C – 18C. The South Turret is cooler, in the range 12° - 14°C, but is also quite stable.

Table 1 Autumn Equinox.

Factor	Time	Hardwick	Watnall
Sunrise	06.10	7.62°C	-
Low temperature	06.30	7.59°C	7.8°C
High temperature	16.00	14.17°C	14.6°C
Sunset	18.20	11.79°C	-
Sunshine			5.8 hours

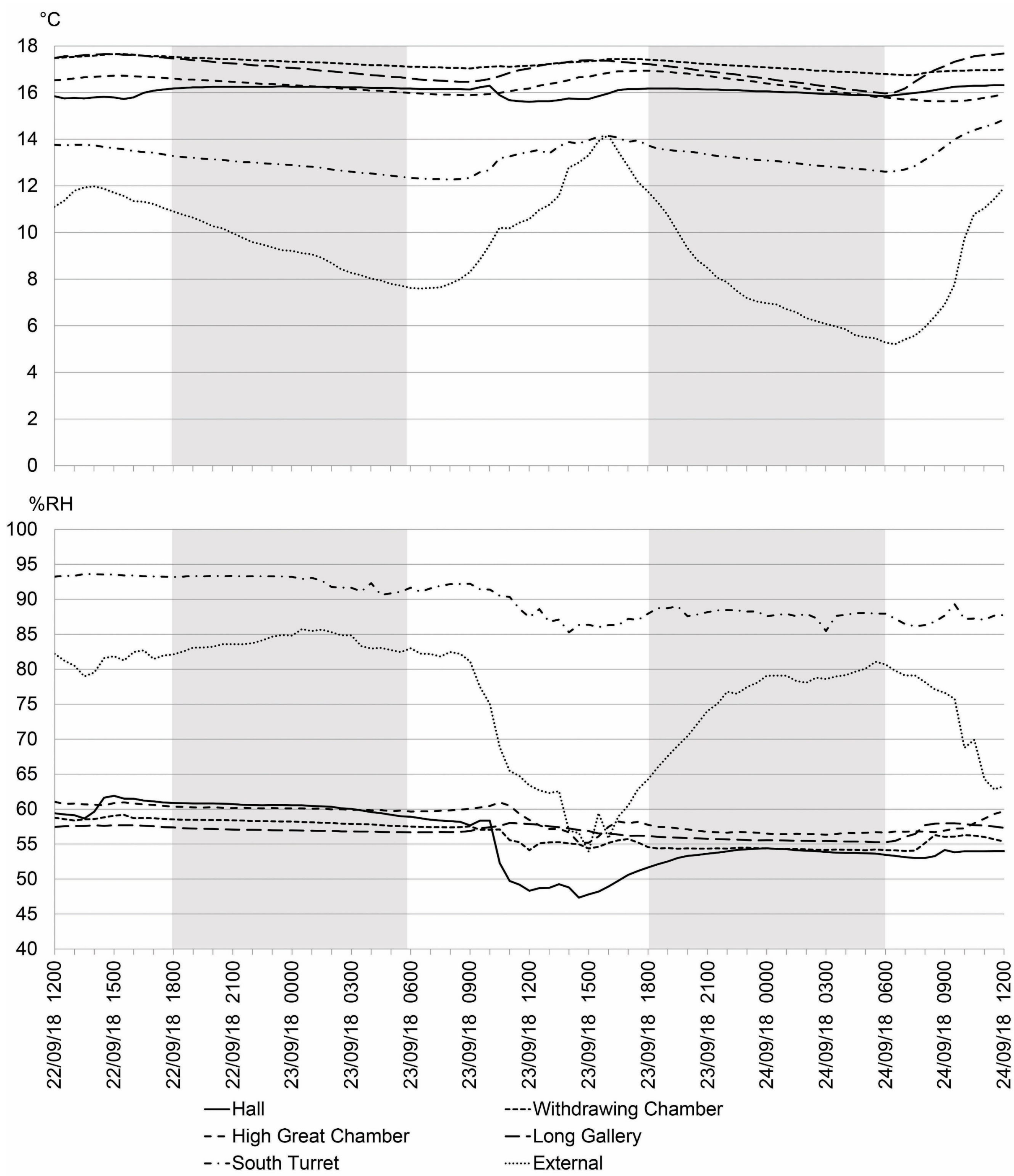

Figure 18 Temperatures (above), RH (below), Autumn Equinox. Shading on the graph indicates nighttime.

As at the Autumn Equinox, at the Winter Solstice (Figure 19, Table 2) the internal temperatures of the house are quite stable in the range 11°- 14°C, with the exception of the South Turret, where the temperature is slightly above the external value, remaining close to 7°C through the 24 hour period.

Table 2 Winter Solstice.

Factor	Time	Hardwick	Watnall
Sunrise	08.20	6.00°C	-
Low temperature	07.30	5.95°C	5.4°C
High temperature	14.00	7.22°C	8.9°C
Sunset	15.50	6.81°C	-
Sunshine			0 hours
Rainfall			2mm

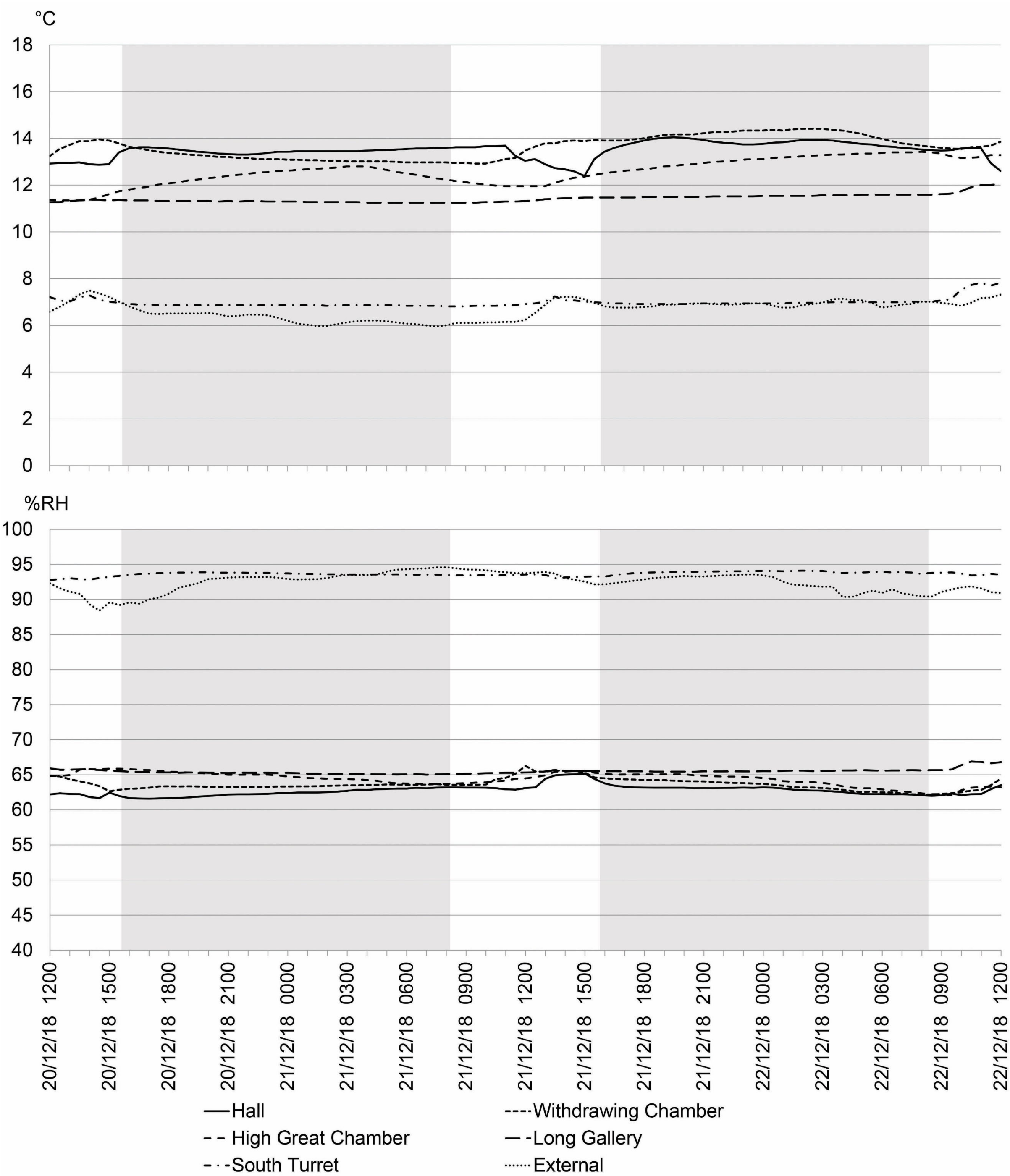

Figure 19 Temperatures (above), RH (below), Winter Solstice.

The Vernal Equinox (Figure 20, Table 3) was characterised by a wide diurnal range in external temperature. However, the temperatures in the house are quite stable. The Long Gallery and the High Great Chamber are the warmest rooms with peaks of 15.75°C at 15.00 and 15.89°C at 18.00 (i.e. sunset). The other principal apartments follow this general pattern with their highest temperatures coinciding with the external temperature peak in the afternoon. The temperatures in the South Turret, interestingly, show little evidence of solar gain, with a peak of 12.53°C at 14.00 hrs.

Table 3 Vernal Equinox.

Factor	Time	Hardwick	Watnall
Sunrise	06.10	7.42°C	-
Low temperature	06.00	7.42°C	7.2°C
High temperature	15.00	14.91°C	16.7°C
Sunset	18.20	13.42°C	-
Sunshine			9.1 hours

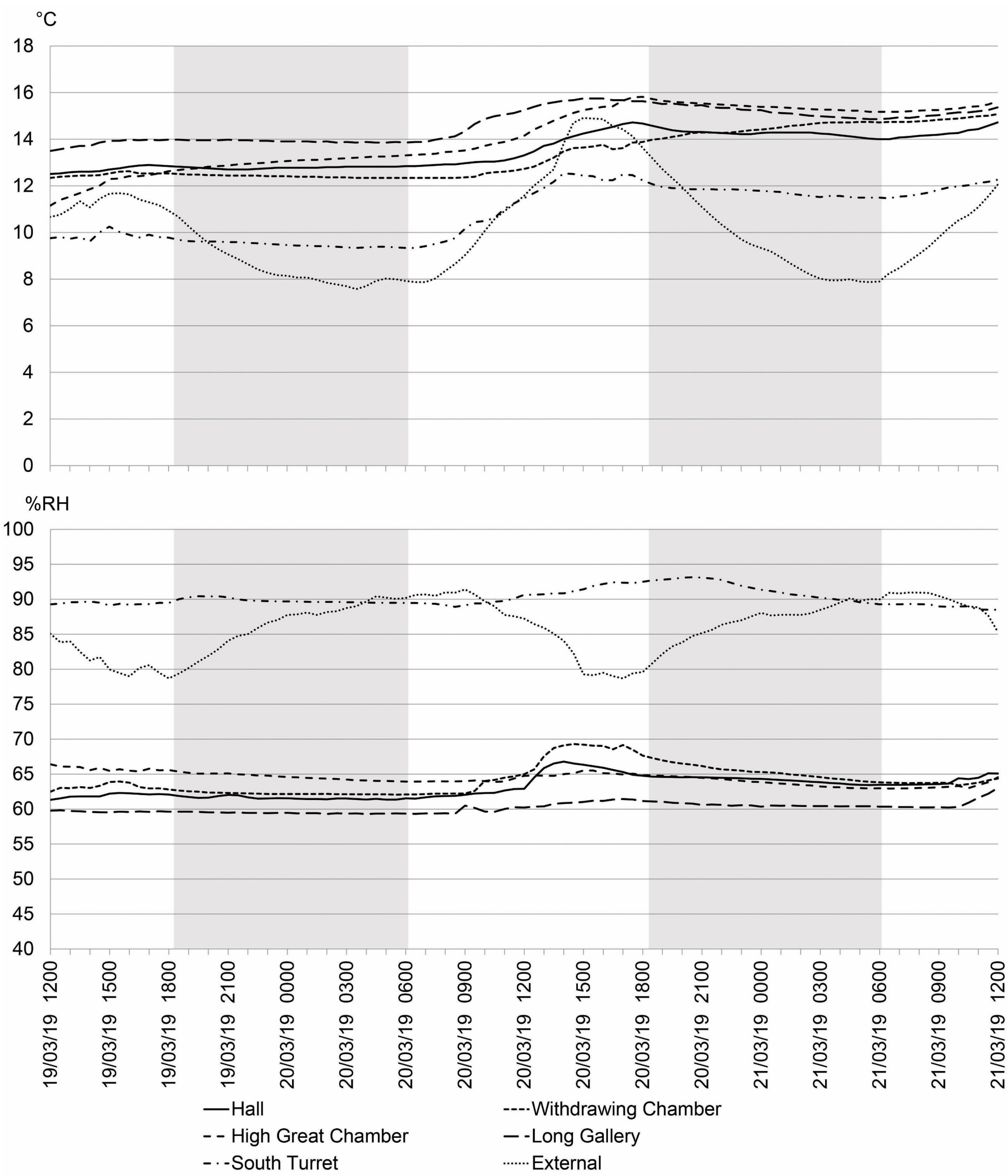

Figure 20 Temperatures (above), RH (below), Vernal Equinox.

The longest day of the year was warm, but not hot, and sunny at Hardwick (Figure 21, Table 4). The South Turret is the warmest space on this day. This confirms the suggestion that its design is consciously contrived to benefit from summer sunshine. The data show three extreme peaks in this space, all probably the result of the sensor being directly in sunlight. The temperature at other times of the day, when the sensor was shaded, varied between 18.98°C at 08.30 hrs., 22.08°C at 12.30 and 21.58°C at 19.00. The data also show that the

Turret remained warm after sunset, with a temperature at midnight of 19.18°C. We can infer that on this warm, sunny Midsummer the Turret would provide an agreeable location for Solstice celebrations.

Table 4 Summer Solstice.

Factor	Time	Hardwick	Watnall
Sunrise	03.40	9.96°C	-
Low temperature	03.00	9.88°C	9.7°C
High temperature	14.00	20.13°C	22.4°C
Sunset	20.40	16.15°C	-
Sunshine			9.5 hours

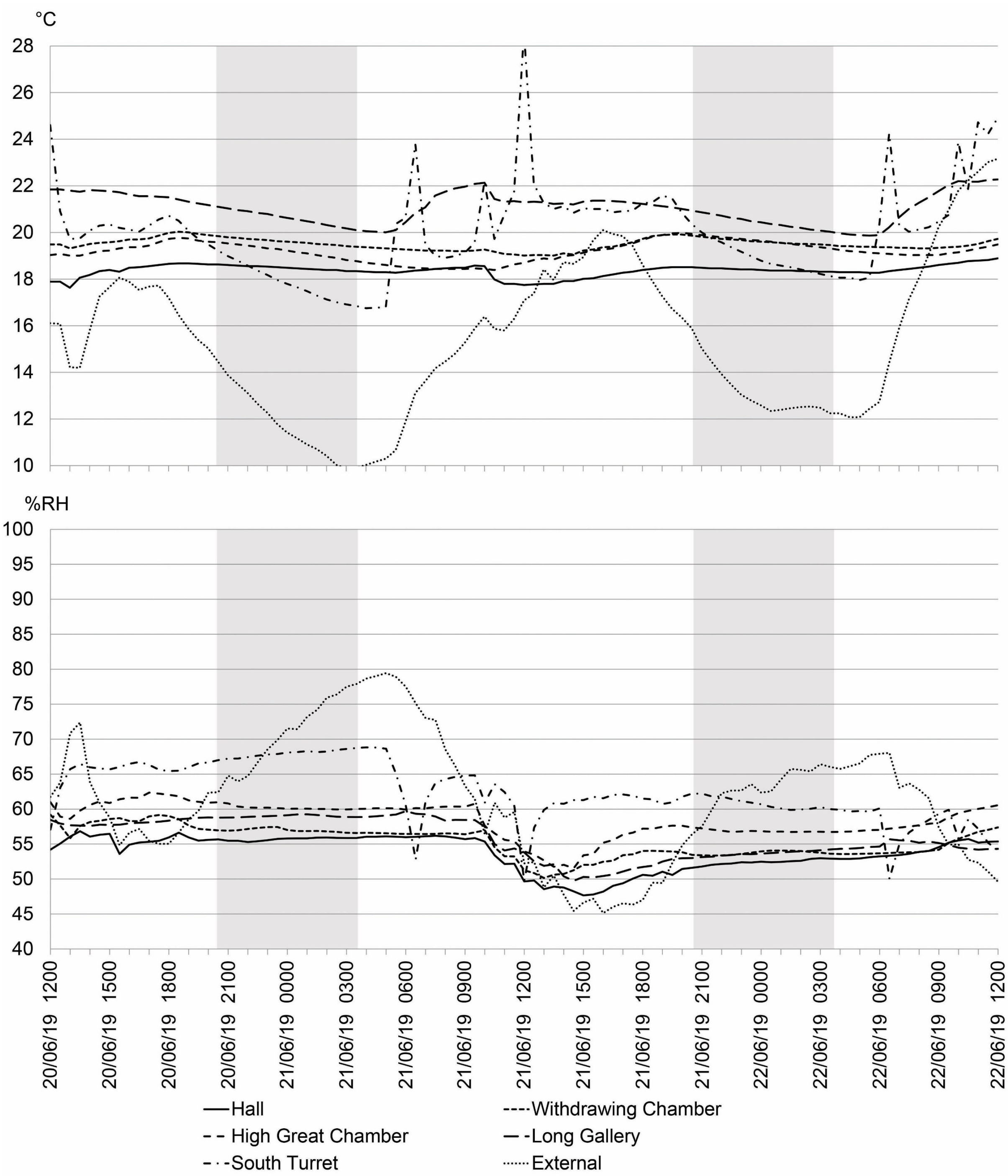

Figure 21 Temperatures (above), RH (below), Summer Solstice.

Temperatures in the other apartments of the house were relatively stable and comfortable (Table 5). Considering these in turn, the Hall temperature is remarkably stable, with less than one degree variation throughout the day. The slight 'peak' at 09.30 is probably due to morning sun striking the east-facing windows. The Withdrawing Chamber is slightly warmer, but similarly stable. Here it is worth noting that the 'peak' temperature occurred at 19.30 as would be expected in this west-facing room. The High Great Chamber, with its location at the south-west corner of the house, shows slightly greater variation in temperature than these more protected spaces. It is coolest, 18.75°C at sunrise, and reaches its maximum at 19.30 when the temperature was 19.96°C. This, again, is to be expected in a room with a large expanse of west-facing glazing. Orientation is clearly influential in the results for the Long Gallery. This is the warmest of the spaces, above 20°C through the daylight hours, and has the greatest temperature range. The maximum, 22.08°C occurs at 09.30 and shows the effect of the east-facing orientation.

Table 5 Hardwick Hall temperatures, Summer Solstice.

Location	Sunrise temperature	High temperature	Sunset temperature
External	9.96°C	20.13°C (14.00)	16.15°C
Hall	18.34°C	18.58°C (09.30)	18.51°C
Withdrawing Chamber	19.40°	19.91°C (19.30)	19.90°C
High Great Chamber	18.75°C	19.96°C (19.30)	19.95°C
Long Gallery	20.10°C	22.08°C (09.30)	20.60°C

Figure 18 shows the disparity, noted above, in RH as recorded in the South Turret in comparison with the measurements for the principal spaces of the house. The Turret levels are consistently above those of the exterior throughout the day, ranging between 85% - 95%, whereas the external values fall significantly at the middle of the day, as the external temperature rises to around 14°C. In all the other spaces RH remains relatively constant in the range 50% - 60%, with the exception of the Hall, where it falls in the middle of the day in concert with the external value. This is possibly the result of the entrance door being opened to admit visitors to the house. The temperatures in these spaces were in the range 16° - 18°C throughout the entire 24 hours.

At the Winter Solstice the internal humidity was in the range 60% - 65% in all the principal apartments, when the external measurement was consistently in the range 90% - 95% (Figure 19). The internal temperatures were equally consistent, in the range 11°C - 14°C.

Figure 20, once again, shows that the RH in the principal apartments was in the range 60% - 65%, with the exception of the Withdrawing Chamber, which reached just below 70% for two hours in the early afternoon. The external readings show variation between 80% - 90%, with the highest values in the morning and the lowest in the afternoon, coinciding with the rise in the Withdrawing Chamber.

At midsummer the RH measurements show more variation than at the other dates of the solar calendar (Figure 21). The range in the building, including the South Turret, is between 46% - 60%, with the lower values occurring from mid-morning until early evening. This is against the background of external RH measurements that range between 40% - 80%, with highest shortly after sunrise and the lowest in the afternoon. As noted above, this was a pleasantly warm, but not hot day. From the temperature and RH data, we may infer that the building's heating system was not in operation to control humidity in these conditions. The data, therefore, represent the thermal environment of Hardwick in its present, 'modern' state, as it results from the interaction of its form and fabric with the external environment.

Estimating the impact of solar gain on thermal conditions in the High Great Chamber on the Spring Equinox

In order to model the effect of a solar gains on the internal microclimate of Hardwick Hall, monitored air temperature data from the spring equinox has been used to calculate the Mean Radiant Temperature experienced by guests sitting down to supper on a sunny afternoon in the High Great Chamber, between the hours of 3 and 7 pm (Figure 22). Operative temperatures are then calculated as a product of the modelled Mean Radiant Temperature and monitored air temperatures.

Figure 22 P. F Robinson, *The High Great Chamber, Hardwick Hall* (engraving), New Vitruvius Britannicus (1835). Note the pattern of reflected light on the ceiling, depicting sunset. This is a visual conceit of the artist, who has projected shadows from a point on the horizon line to the left of the image. Private Collection, Bridgeman Images.

The solar and window geometry is calculated from an average of two subjects in different positions (Figure 23). One subject is exposed to west-facing windows measuring 5.6m in height and 5.3m in width, at an average distance of 7.9m. The other subject is exposed to west-facing windows measuring 7.0m in width, at an average distance of 10.3m. This gives an average window width of 6.15m in line of sight from the position of a subject at an average distance of 9.1m (Table 6).

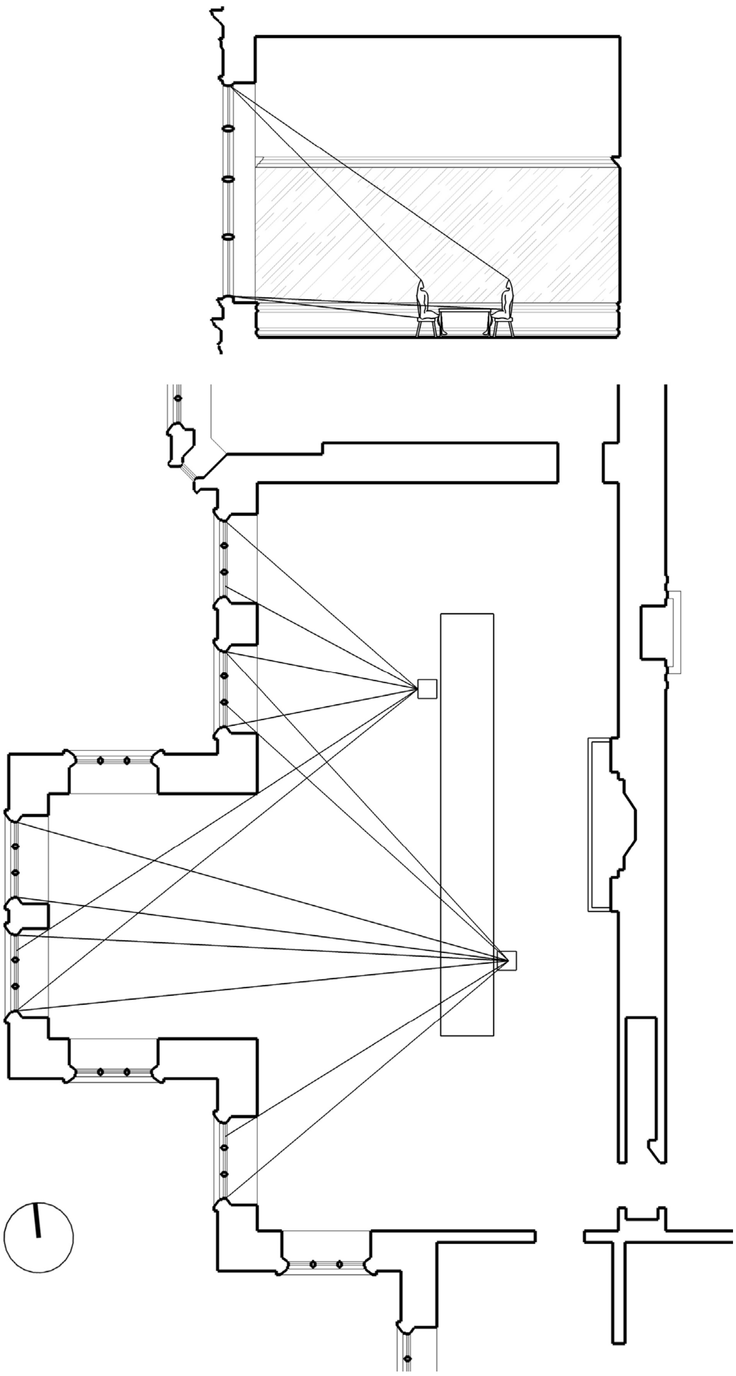

Figure 23 High Great Chamber. Section and plan illustrating exposure to windows of subjects seated at dining table. Author 1.

Table 6 High Great Chamber. Solar geometry.

Time pm 20/03/2019	Solar altitude (β)	Solar azimuth	Window height h (m)	Window width w (m)	Distance from window d (m)	Sky Vault View Fraction f_{svv}
15:00	27	229	5.60	6.15	9.10	0.02
15:30	23	236	5.60	6.15	9.10	0.02
16:00	19	242	5.60	6.15	9.10	0.02
16:30	15	249	5.60	6.15	9.10	0.02
17:00	11	255	5.60	6.15	9.10	0.02
17:30	7	261	5.60	6.15	9.10	0.02
18:00	2	268	5.60	6.15	9.10	0.02

The effective radiant flux, adjusted for the fraction of the body exposed to the sun (f_{bes})[28], is calculated by the following equation:

$ERF_{solar} = (0.5\ f_{eff}\ f_{svv}\ (I_{diff} + I_{TH}\ R_{floor}) + f_{eff}\ f_p\ f_{bes}\ I_{dir})\ T_{sol}\ (a_{SW}/a_{LW})$ [29]

Total outdoor irradiance (I_{TH}) is a product of direct beam solar radiation (I_{dir}) and diffuse sky irradiance (I_{diff}), which vary according to solar altitude β. The fraction of the sky vault in view of the subject (f_{svv}) is a property of the width (w) and height (h) of the window, and the distance from the window to the subject (d): $f_{svv} = (\tan^{-1}(w/2d)\ \tan^{-1}(h/2d)) / 16{,}200$

The energy flux absorbed by the body will vary according to long and short-wave absorptivity (a_{LW} and a_{SW}), estimated to be 0.95 and 0.7 respectively. The value for the effective radiation fraction for a body (f_{eff}) is 0.725 for a standing pose. The radiant flux reflected onto the subject from the floor will vary with the reflectance of the floor (R_{floor}), estimated to be 0.5. The projected area factor of a body facing the sun (f_p) varies with solar altitude and azimuth, but is estimated to be 0.3 for a subject facing the sun with solar altitude <45°.[30]

The fraction of the body exposed to the sun (f_{bes}) will be affected by the placement of furniture and shading from the window reveals (varying with solar azimuth). The solar azimuth is perpendicular to the glazing of the High Great Chamber at approximately 5.30pm. At this point f_{bes} is estimated to be 0.6 (accounting for shading from the table/chair). Before and after this time, f_{bes} is reduced to account for the sun striking the window reveals.

Mean radiant temperature (MRT) is then calculated from the effective radiant flux by the equation: $MRT = (q_{eff} / f_{eff} h_r) + T_a$

The radiant heat transfer coefficient (h_r) is 4.7W/m^2.[31] The air temperature (T_a) is the monitored air temperature.

Air movement will also affect thermal comfort. Draughts caused by windows can lead to non-uniform air velocity fields, particularly affecting the lower body. To assess the potential impact of draughts in the High Great Chamber, the maximum velocity close to the floor at a distance > 2.0 m from a window of height H was calculated by the equation:

$v_{max} = 0.028 \sqrt{(\Delta\theta \cdot H)}$

where $\Delta\theta$ is the temperature difference between the window surface and the room air temperature.[32]

The maximum velocity increased with $\Delta\theta$ from 0.03m/s at 3pm to 0.1m/s at 7pm, as external temperatures fell. While draughts may be augmented by air leakage from the windows or other spaces, it was considered unlikely to exceed a threshold of 0.1m/s when averaged across a subject's body. The operative temperature can therefore be approximated by the equation:

$T_o = (T_a + MRT) / 2$ [33]

An example calculation is presented in Appendix A. The results of the calculations are presented below (Table 7).

Table 7 High Great Chamber. Mean radiant and operative temperatures.

Time pm 20/03/2019	Solar transmittance adjusted for angle of sun incident on glass T_{sol}	Fraction of body exposed to sun f_{bes}	Direct beam solar radiation I_{dir} (W/m2)	Horizontal diffuse sky irradiance I_{diff} (W/m2)	Total outdoor horizontal irradiance I_T (W/m2)	Floor reflectance R_f	Effective radiant field/flux W/m2	Air temperature T_a (°C)	MRT (°C)	Mean operative temperature T_o (°C)
15:00	0.70	0.35	704	54	374	0.50	28.07	15.25	23.48	19.37
15:30	0.72	0.40	646	43	295	0.50	30.21	15.32	24.18	19.75
16:00	0.74	0.45	577	32	220	0.50	31.11	15.39	24.52	19.96
16:30	0.76	0.50	495	22	150	0.50	30.42	15.41	24.34	19.88
17:00	0.78	0.55	400	13	89	0.50	27.70	15.65	23.78	19.72
17:30	0.80	0.60	291	6	42	0.50	22.50	15.80	22.40	19.10
18:00	0.80	0.55	133	1	5	0.50	9.19	15.82	18.52	17.17
18:30	0.80	0.00	27	0	0	0.50	0.00	15.72	15.72	15.72

With external air temperatures falling gradually from 12.44°C to 11.95°C, this shows internal air temperatures rising gradually from 15.25°C to 15.82°C, as might be expected with the sun moving to the west. Mean radiant temperatures remain in a pleasant range of 23-25°C until 5pm, dropping to 22.43°C at 5.30pm, before dropping rapidly as the sun sets. This results in a mean operative temperature of 19°C to 20°C all afternoon, without any additional heating by means of the fireplace. According to Hubbard, following supper 'guests would adjourn to the Withdrawing Chamber, or the Long Gallery, so the High Great Chamber could be cleared, for music perhaps, or a play.'[34] During this interval candlesticks could be brought in to light the space, and in winter the fireplace might be stoked at the same time.

Quantifying the warming effect of a fire in the Long Gallery on the Winter Solstice

Winter warmth was provided by the 35 fireplaces in Hardwick Hall that are embedded in the substantial structural walls, in particular in the great spine wall. Their presence is expressed in the line of chimneys that rise high above the ridge of the roof. The full 61m length of the spine wall is revealed in the Long Gallery. An interior view by the landscape painter David Cox illustrates the atmosphere and quality of light in this room (Figure 24). The warm glow of the sun is depicted shining on the floor of the southernmost bay. We can surmise from the azimuth of the sun (south south-east) that the time is late morning, and light suggests a solar altitude close to the autumnal or vernal equinox (37° at midday). The subject matter (a morning dog walk) emphasises the promenade function of the space.

Figure 24 David Cox, *The Long Gallery, Hardwick Hall, Derbyshire* (1811).

Two large fireplaces are located just inward of the two window bays formed by the east facing towers, dividing the gallery into three and forming two pockets of warmth when lit.

In order to recreate an accurate impression of this room from an environmental perspective, the warming effect of one of the fireplaces has been estimated from measurements conducted by Margaret Fishenden, at the University of Manchester, of the heat radiated by a large 'old fashioned' fireplace measuring 270mm deep and 710mm wide.[35] This compares favourably with the fireplaces at Hardwick.

Fishenden's experiment took place in 'a large rectangular room approx. 18 x 9m, with a chimney flue 14m high. For comparison, the Long Gallery at Hardwick is approx. 7m wide at the fireplace, and the flue is also 14m high. The fire was lit with 15lbs. of coal and ½ lb. of wood, with an additional 7 ½ lbs. added every hour for 12 hours. The heat absorbed by a radiometer was measured in BTUs/sq ft/hr every few minutes at 81 points forming a hemisphere of radius 870mm, centred on the fire itself.[36]

While the primary heating effect of a fireplace is achieved through the transfer of radiant energy, there is also an associated heating of the air via convection. Fishenden recorded that before a fireplace was lit the temperature in the room was on average 4°F (2.2K) warmer than the air entering the room, and after 6 hours of burning it was 9.3°F (5.2K) warmer.[37]

In order to model the effect of a fire lit in the Long Gallery, monitored air temperature data from the winter solstice has been used together with Fishenden's data to calculate the Mean Radiant Temperature at a distance of 3m from the fireplace, lit at midday. Air temperature has been adjusted based on Fishenden's experiments, rising in increments of 0.5K every hour until 6 hours after the fire is lit, after which it drops in increments of 0.5K. Operative temperatures are calculated as a product of the modelled Mean Radiant Temperature and adjusted air temperatures (Table 8).

Table 8 Long Gallery. Mean radiant and operative temperatures.

Time pm 21/12/2018	Radiant flux q" (BTU/h.ft2) at 0.87m	Radiant flux q" (W/m2) at 0.87m	Radiant heat release rate Q_r (W)	Distance R (m)	q" (W/m2) at 3m	Effective radiant flux q_{eff} (W/m2)	Air temperature T_a (°C)	Adjusted air temperature T_a (°C) (Fishenden)	MRT (°C)	Mean operative temperature T_o (°C)
12:00	95	299.69	2875.19	3	25.42	7.37	11.39	11.89	14.06	12.98
13:00	448	1413.26	13558.78	3	119.89	34.77	11.44	12.44	22.65	17.54
14:00	822	2593.07	24877.94	3	219.98	63.79	11.47	12.97	31.69	22.33
15:00	837	2640.39	25331.92	3	223.99	64.96	11.47	13.47	32.53	23.00
16:00	785	2476.35	23758.13	3	210.07	60.92	11.47	13.97	31.85	22.91
17:00	690	2176.67	20882.94	3	184.65	53.55	11.49	14.49	30.21	22.35
18:00	694	2189.29	21004.00	3	185.72	53.86	11.49	14.49	30.30	22.40
19:00	326	1028.40	9866.43	3	87.24	25.30	11.49	13.99	21.42	17.70
20:00	79	249.21	2390.95	3	21.14	6.13	11.49	13.49	15.29	14.39
21:00	44	138.80	1331.67	3	11.77	3.41	11.52	13.02	14.02	13.52
22:00	4	12.62	121.06	3	1.07	0.31	11.52	12.52	12.61	12.56

The point source model of radiant flux[38] is the simplest method for estimating radiant heat flux from a flame.[39] It assumes that the point source is located at the centre of the fire, and radiant heat flux is inversely proportional to the distance from this point.[40] Fishenden's measurements of absorbed heat (radiant flux from point source of radiation, q") at 34.4 inches / 0.87m (radial distance, R) have been converted from imperial, BTU/h.ft^2, to metric, W/m^2.K. The radiant heat release rate of the fire is estimated by the equation: $Q_r = q'' \, 4 \pi R^2$

The radiant flux at 3m distance can then be calculated by rearranging this equation as follows: $q'' = Q_r / 4 \pi R^2$

The effective radiant flux, q_{eff}, adjusted for the fraction of the body surface area facing the fire (f) is given by the equation: $q_{eff} = q'' / f$ where f = 0.29.[41]

Mean radiant temperature (MRT) is then calculated from the effective radiant flux by the equation: $MRT = (q_{eff} / f_{eff} h_r) + T_a$

The value for the effective radiation fraction for a body (f_{eff}) is 0.725 for a standing pose, and the radiant heat transfer coefficient (h_r) is 4.7W/m^2.[42] The air temperature (T_a) is the monitored temperature modified according to Fishenden's experiments.

To check the potential impact of draughts in the Long Gallery, the maximum velocity close to the floor was calculated as in the High Great Chamber. This ranged from 0.07-0.09m/s. This draught may be accelerated by upwards convection near the fireplace, however it was considered that any additional thermal effect would be negligible compared with the increase in MRT near the fire. The operative temperature can therefore also be approximated by the equation: $T_o = (T_a + MRT) / 2$

An example calculation is presented in Appendix B.

Based on Adaptive Comfort Temperatures[43] calculated from the external air temperature, low and high comfort temperatures have been calculated together with corresponding distances from the fireplace, to ascertain how a notional comfort zone centred on the fireplace changes over time (Table 9). The data suggests that a relatively consistent comfort zone is formed, averaging 2-3.5m and centred 3-4m from the fireplace, from 2-7pm. The fireplace will offer the greatest warmth, and the widest comfort zone at approximately 5pm (Figure 25). It is likely however that the fireplaces in Hardwick would have been permanently lit during winter, with adjustments made by stoking with more or less fuel as required.

Table 9 Long Gallery. Comfort zone centred on fireplace.

Time pm 21/12/2018	Outdoor temperature (°C)	Adaptive comfort temperature (°C)	Low (°C)	High (°C)	Comfort zone near (m)	Comfort zone far (m)	Comfort zone centre (m)	Comfort zone range (m)
12:00	6.86	19.93	16.43	23.43	0.92	1.47	1.19	0.56
13:00	7.22	20.04	16.54	23.54	2.03	3.35	2.67	1.36
14:00	7.12	20.01	16.51	23.51	2.83	4.88	3.81	2.15
15:00	6.81	19.91	16.41	23.41	2.94	5.40	4.10	2.60
16:00	6.76	19.90	16.40	23.40	2.92	5.75	4.25	3.01
17:00	6.79	19.90	16.40	23.40	2.82	6.08	4.34	3.48
18:00	6.89	19.94	16.44	23.44	2.82	6.05	4.33	3.44
19:00	6.91	19.94	16.44	23.44	1.88	3.69	2.73	1.92
20:00	6.94	19.95	16.45	23.45	0.90	1.65	1.26	0.79
21:00	6.89	19.94	16.44	23.44	0.66	1.15	0.89	0.51
22:00	6.91	19.94	16.44	23.44	0.19	0.32	0.26	0.13

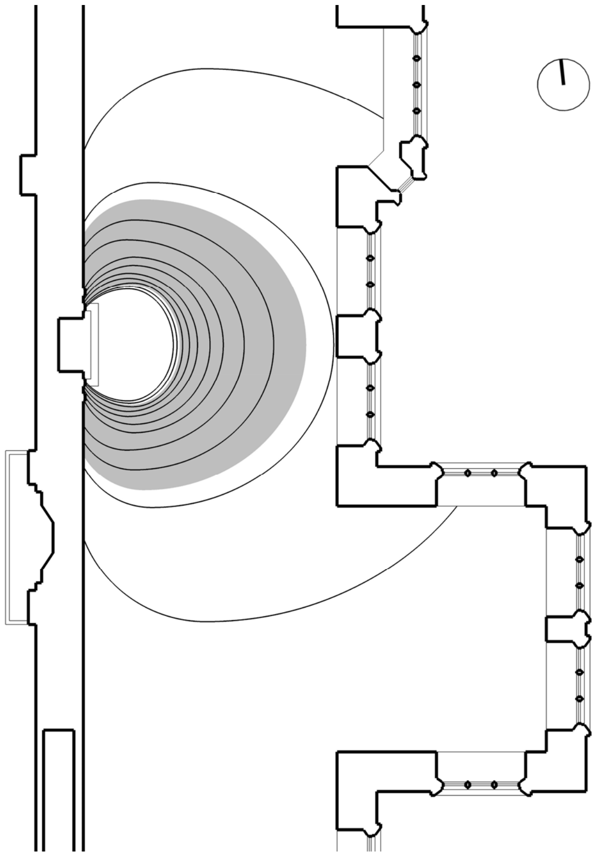

Figure 25 Long Gallery, plan. Isotherms in 1K intervals from 15°C to 25°C near the fireplace, at 5pm on 21/12/2018. Comfort zone shaded in grey. Author 1.

Another common cause of discomfort is radiant asymmetry, causing significant temperature nonuniformities on different parts of the body. Fanger et al. demonstrated experimentally that when exposed to a radiant temperature asymmetry of 35.1°C from a vertical surface (MRT: 30.5°C; T_a: 16.7°C), 12.5% of subjects reported some discomfort after 30 minutes. This is roughly analogous to the effect of the fire in the Long Gallery in our model at 5pm (R: 3m; MRT: 30.21°C; T_a: 14.49°C), and while it does not meet present-day criteria (with a discomfort limit of 5% of subjects), nevertheless shows that conditions would have been quite comfortable by the standards of the time.[44]

Limitations

The primary purpose of our research has not been to analyse the present-day performance of the building, but to develop a deeper understanding of the environmental experience of Hardwick Hall at the time of its construction. The monitoring described here supports our interpretation of life at the time, and has allowed us to better describe how the fireplaces and the orientation of key rooms played a crucial role in the inhabitation of the building. The calculations demonstrate that key spaces in the Hall could provide a pleasant thermal environment for inhabitants of the Hall to adapt to – but they do not represent accurate simulations of the performance of the building in the sixteenth century. Such an exercise is precluded by the absence of quantifiable meteorological data for the period. The application of CFD to historic environments is a relatively new field of research, beset by problems including the accurate modelling of the physical properties of the building envelope and materials, particularly interaction with surfaces, and the requirement for experimental validation using spatially distributed data.[45] Nonetheless future CFD analysis may provide further descriptive detail, on the impact of draughts from the windows for example, or the insulative role of the tapestries that lined many of the internal walls.

Conclusion

The thermal monitoring described in this paper reveals how environmental conditions inside Hardwick Hall change seasonally and diurnally, and informs our understanding of how the house was inhabited when first constructed at the end of the sixteenth century, at the height of the Little Ice Age. While 2018-19 was an unusually warm year in historic terms, enough data was collected to demonstrate, for example, how conditions inside the house responded to periods of sub-zero temperatures at the end of January / beginning of February, and a heat wave at the height of summer. What this reveals is a surprising degree of thermal stability given the amount of glazing of the exterior of the building, a characteristic influenced by the thermal mass, volume of space, and above all the orientation of the house, with the long elevations facing east and west rather than due south.

Taken together, the thermal monitoring and our calculations of solar gains show how these factors informed the disposition of key rooms of the house, accommodating the day-to-day routine of the occupants, as well as seasonal events such as feasts and festivals. The High Great Chamber, for example, was ideally situated for supper feasts to benefit from solar gains due to the afternoon sun, which, for the majority of the year, would have provided adequately comfortable thermal conditions on sunny days without the need for additional heating from the fire. Similarly, the Long Gallery benefitted from solar gains from the east in the morning, and would have been ideally suited for informal gatherings and exercise.

As constructed the house would have been far from airtight by modern standards. In summer additional ventilation would be possible by opening lights in the leaded windows, which required constant maintenance, as evidenced by the presence of Richard Snidall, glazier, on the permanent staff.[46] In hot weather, however, a more effective strategy would be to retain the cool air from the nighttime, aided by the stabilising thermal effect of the massive spine wall.

On overcast days and in winter, our calculations, based on Fishenden's experiments, show that the 35 open fireplaces were effective at providing smaller zones of comfort in the larger rooms of the Hall, warming smaller apartments such as Bess's Withdrawing Chamber sufficiently to maintain them at comfortable levels for permanent inhabitation. The fireplaces would have provided localised pools of warmth to retreat to in the long months of winter. The central spine wall would act as a building-scale heat sink, storing heat from the fireplaces and solar radiation during the day, and reradiating it at night.

The 1601 Inventory refers to three 'skreynes' in the Withdrawing Chamber.[47] Thornton suggests that one of these, 'a travice like a skreyne covered with violet Couloured Cloth layed about with black lace', may have been employed to partition off a part of the room near the fire to provide a warmer enclosure.[48] It is likely that one or both of the other screens may have been positioned to offer protection from the radiant heat of the fire. We can assume that over the winter months this fire would have been maintained close to 24 hours a day. Together with the darnix curtains, it is likely that these arrangements would have been quite comfortable, even cosy, at nighttime.

In the Long Gallery, the Inventories describe 'a Cloth for the skreyne of Crimson velvet with a brode parchment lace of golde throughout the middest & rownde about and with a golde frenge about lyned with Crimson taffetie sarcenet.' The other furnishings and cushions, together with contemporary accounts from the period, imply that this space was frequently used by the household during the day.[49]

The details of life we have recovered through the combination of climatic observation and documentary evidence from the period reveal how life in the Elizabethan age was both defined and circumscribed by the changing weather and climate. This is particularly evident in Hardwick Hall, the design of which accommodated the most beneficial aspects of its climate while offering protection from extremes, selecting particular aspects, principally the path of the sun, and utilising them to create settings for the most appropriate activities, whether dining, exercising, or resting.

The sophistication of this fine-tuning of architecture and climate offers profound lessons for the present.

Declaration of interests

The authors have no relevant financial or non-financial competing interests to report.

Acknowledgements

The authors wish to thank the National Trust for allowing access to Hardwick for the purposes of this research. We should like to express our gratitude to Dr Nigel Wright and Dr Lucie Morris at the house for their assistance on our research visits.

Appendix A: Spring Equinox, 3pm – calculation of solar gain

The sky vault view fraction (f_{svv}) is calculated as follows:

$f_{svv} = (\tan^{-1} (6.15/18.2) \tan^{-1} (5.6/18.2)) / 16{,}200 = 0.02$

Direct beam solar radiation (I_{dir}) values are based on a standard cloudless atmosphere.[50] At 3pm on the Spring Equinox, (a solar altitude β of 27 degrees), I_{dir} is estimated at 704W/m^2.

Horizontal diffuse sky irradiance is calculated by the equation:

$I_{diff} = 0.17\ I_{dir} \sin\beta = 54$W/m^2.[51]

Total outdoor irradiance on a horizontal surface (I_{TH}) is calculated by the equation:

$I_{TH} = I_{dir} \sin\beta + I_{diff} = 374$W/m^2.

At 3pm the fraction of the body exposed to the sun (f_{bes}) is estimated at 0.35. Solar transmittance through the glass (T_{sol}) is estimated at 0.7.

$ERF_{solar} = (0.5\ f_{eff}\ f_{svv}\ (I_{diff} + I_{TH}\ R_{floor}) + f_{eff}\ f_p\ f_{bes}\ I_{dir})\ T_{sol}\ (a_{SW}/a_{LW})$

$ERF_{solar} = (0.5 \times 0.35 \times 0.0197\ (54 + 374 \times 0.5) + 0.725 \times 0.3 \times 0.35 \times 704) \times 0.7\ (0.7 / 0.95)$

$= 28.07$W/m^2

At 3pm the air temperature (T_a) is 15.25°C.

$MRT = (q_{eff} / f_{eff}\, h_r) + T_a$

$MRT = (28.07 / 0.725 \times 4.7) + 15.25 = 23.48°C$

$T_o = (15.25 + 23.48) / 2 = 19.37°C$

Appendix B: Winter Solstice, 1pm – calculation of radiant heat gain from fire

At 1pm the radiant heat release rate of the fire is 13558.78W and the adjusted air temperature (T_a) is 12.44°C.

$q'' = Q_r / 4 \pi R^2 = 13558.78 / 4 \times 3.14 \times 3^2 = 119.89 W/m^2$

$q_{eff} = 119.89 / 0.29 = 34.77 W/m^2$

$MRT = (34.77 / 0.725 \times 4.7) + 12.44 = 22.65°C.$

$T_o = (12.44 + 22.65) / 2 = 17.54°C.$

Notes and references

[1] This attribution is argued by Mark Girouard in *Robert Smythson and the Elizabethan Country House*, New Haven & London, Yale University Press, 1983.

[2] These dates are from the 'Hardwick Building Accounts' as published in David N. Durant and Philip Riden, *The Building of Hardwick Hall, Part 2: The New Hall, 1591-98*, Chesterfield, Derbyshire Record Society, Vol. IX, 1984.

[3] 30 of the windows, largely facing north, are 'blind', with externally visible glazing backed with masonry lining.

[4] Dean Hawkes and Ranald Lawrence, 'Studies of the Environment of the Elizabethan House: Hardwick Hall', n.d.

[5] Constructional information from David N. Durant and Philip Riden, *The Building of Hardwick Hall, Part 2: The New Hall, 1591 – 98*, op cit.

[6] May Cassar, *Environmental Management Performance Standards: Guidelines for Historic Buildings* (Swindon: English Heritage, 2009).

[7] Charlotte Adams et al., 'Building with History: Exploring the Relationship between Heritage and Energy in Institutionally Managed Buildings', *The Historic Environment: Policy & Practice* 5, no. 2 (1 July 2014): 167–81.

[8] Cassar, *Environmental Management Performance Standards: Guidelines for Historic Buildings*.

[9] May Cassar and Joel Taylor, 'A Cross-Disciplinary Approach to the Use of Archives as Evidence of Past Indoor Environments in Historic Buildings', *Journal of the Society of Archivists*, 4 August 2010.

[10] Gunhild Eriksdotter and Mattias Legnér, 'Indoor Climate and Thermal Comfort from a Long-Term Perspective', *Home Cultures* 12, no. 1 (1 March 2015): 29–53.

[11] See for example, Todd Willmert, 'Heating Methods and Their Impact on Soane's Work: Lincoln's Inn Fields and Dulwich Picture Gallery', *Journal of the Society of Architectural Historians* 52, no. 1 (1 March 1993): 26–58.

[12] De Heptarchia Mystica (1581-85), written by Queen Elizabeth's astrologer John Dee, was a guide to summoning angels from the seven planetary spheres. Dee observed Tycho's supernova of 1572, which shone so bright as to be visible during the day. Richard Dunn, 'John Dee and Astrology in Elizabethan England', in *John Dee: Interdisciplinary Studies in English Renaissance Thought*, ed. Stephen Clucas (Springer Science & Business Media, 2006), 85–94.

[13] See W.E. Knowles Middleton, *Invention of the Meteorological Instruments*, Baltimore, Johns Hopkins University Press, 1969.

[14] Authoritative sources include J.M. Grove, *The Little Ice Age*, London, Methuen, 1988; Brian M. Fagan, *The Little Ice Age – how climate made history 1300 – 1850*, 2000, and H.H. Lamb, *Climate History and the Modern World*, 2nd edition, London, Routledge, 1995.

[15] Mike Hulme, 'Climate', in *The Cambridge Guide to the worlds of Shakespeare*, Vol. 1, Cambridge, Cambridge University Press, 2015.

[16] H. H. Lamb, 'The Early Medieval Warm Epoch and Its Sequel', *Palaeogeography, Palaeoclimatology, Palaeoecology* 1 (1 January 1965): 13–37, https://doi.org/10.1016/0031-0182(65)90004-0; Brian Fagan, *The Little Ice Age: How Climate Made History 1300-1850* (New York: Basic Books, 2001), 94.

[17] John Harold Brazell, *London Weather* (H.M. Stationery Office, 1968), 150.

[18] John Walter, Roger Schofield, and Andrew B. Appleby, *Famine, Disease and the Social Order in Early Modern Society* (Cambridge University Press, 1991), 143.

[19] The physics of combustion made little impact on fireplace design until the eighteenth century, when many fireplaces were altered by reducing the clear opening both of the chimney and the fireplace itself to increase efficiency. Mark Girouard, *Life in the English Country House: A Social and Architectural History*, New Ed edition (New Haven: Yale University Press, 1993), 263.

[20] Lindsay Boynton, ed., *The Hardwick Inventories of 1601* (London: The Furniture History Society, 1971); see also Dean Hawkes, 'The Environment of the Elizabethan House: Hardwick Hall', in *Further Studies in the History of Construction: The Proceedings of the Third Annual Conference of the Construction History Society*, ed. James Campbell, Nicholas Bill, and Yiting Pan (Cambridge: Construction History Society, 2016).

[21] The house and its grounds are open to the public throughout the year. In 2018 it received 285,379 visitors.

[22] Durant notes red curtains over the 'two huge windows' in Bess's bedchamber. Durant, *Bess of Hardwick*, 1977; The Inventories note curtains of darnix. Boynton, *The Hardwick Inventories of 1601*.

[23] David Dungworth, 'The Value of Historic Window Glass', *The Historic Environment: Policy & Practice* 2, no. 1 (1 June 2011): 44.

[24] It is estimated that sheer blinds and heavy curtains will reduce heat loss in winter by 1-5% and 14% respectively. Keith Nicol, 'The Thermal Effectiveness of Various Types of Window Coverings', *Energy and Buildings* 9, no. 3 (1 August 1986): 231–37; Paul Baker, 'Thermal Performance of Traditional Windows' (Historic Scotland, 2008).

[25] ISO 7726, Ergonomics of the thermal environment – Instruments for measuring physical quantities (ISO 7726:1998), 1998.

[26] There is a brief discontinuity in the data for the High Great Chamber (monitoring point 3) from 17th – 25th January because the HOBO logger lost power. This was rectified when the first set of data was collected on 25th January and the battery replaced.

[27] Met Office, 'UK Monthly Climate Summaries', accessed 10 June 2020, https://www.metoffice.gov.uk/research/climate/maps-and-data/summaries/index.

[28] i.e. unobstructed by furniture or fenestration.

[29] Edward Arens et al., 'Modeling the Comfort Effects of Short-Wave Solar Radiation Indoors', *Building and Environment* 88 (1 June 2015): 3–9. Derived from equations 6 and 7: $ERF_{solar} = (0.5\ f_{eff}\ f_{svv}\ [I_{diff} + I_{TH}\ R_{floor}] + A_p\ f_{bes}\ I_{dir} / A_D)\ T_{sol}\ (a_{SW}/a_{LW})$; $A_p = f_{eff}\ f_p\ A_D$.

[30] Povl Ole Fanger, *Thermal Comfort – Analysis and Applications in Environmental Engineering* (New York: McGraw-Hill Book Company, 1972).

[31] ASHRAE, *Fundamentals* (Atlanta, Georgia: American Society of Heating Refrigerating and Air-Conditioning Engineers, 1993).

[32] The temperature of the inner window surface (θ_{si}) is calculated by the equation: $\theta_{si} = \theta_i - (U\ [\theta_i - \theta_e]) / h_{si}$ where θ_i and θ_e are internal and external air temperatures, U is the U-value of the window and h_{si} is the heat transfer coefficient at the surface of the glass. These values

are estimated at 5.8W/m^{2}K and 7.7W/m^{2}K respectively. Andrius Jurelionis and Edmundas Isevičius, 'CFD Predictions of Indoor Air Movement Induced by Cold Window Surfaces', *Journal of Civil Engineering and Management* 14, no. 1 (31 March 2008): 29–38.

[33] ASHRAE, 'Standard 55: Thermal Environment Conditions for Human Occupancy' (ASHRAE, 2004).

[34] Kate Hubbard, *Devices and Desires: Bess of Hardwick and the Building of Elizabethan England* (Random House, 2018).

[35] Margaret White Fishenden and Air Pollution Advisory Board, *The Coal Fire* (Edinburgh: H. M. Stationery Office, 1920), 13.

[36] The coal for Fishenden's experiment had a calorific value of 14,600 BTU/lb. The historic woodlands of Derbyshire were largely composed of ash, with an approximate calorific value of 9,360BTU/lb. Coal and wood have similar densities of approx. 40-50 lb/ft^3. If we assume a large log weighing approx. 90lbs was to be burned, this would be roughly equivalent to 1.5 times the total weight of coal burned in Fishenden's experiment, compensating for the reduced calorific value. The reduced temperature at which the log burns is compensated for by the increased surface area.

[37] Fishenden employed a 180 x 360mm register grate installation for this experiment, in a room measuring 5 x 3.5m with a chimney flue 27.4m high. Measurements were taken with a mercury thermometer 1.5m from the floor and 2.5m from the fireplace, protected from radiation by metal foil. While the fireplaces in Hardwick are considerably larger, the volume of air to be heated is also greater. The average rise in air temperature from Fishenden's experiments have therefore been added to the monitored background air temperatures from our data. The impact of the uncertainty in the air temperature increase due to convection is relatively minor in comparison with the effect of radiative warming. Fishenden and Air Pollution Advisory Board, *The Coal Fire*, 17, 64.

[38] Dougal Drysdale, *An Introduction to Fire Dynamics*, 2nd ed. (Chichester: John Wiley & Sons, 1998).

[39] According to Modak, the point source model is accurate within 5% when R is greater than 2.5 times the diameter of the fire. A. T. Modak, 'Thermal Radiation from Pool Fires', *Combustion and Flame* 29 (1977): 177–92; see also Naeem Iqbal, Mark Henry Salley, and Sunil Weerakkody, 'Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration, and Flame Height', in *Fire Dynamics Tools (FDTs): Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program* (Washington DC: U.S. Nuclear Regulatory Commission Office of

Nuclear Reactor Regulation, 2004), https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/s1/.

[40] Lawrence Marchetti, 'Estimating Radiant Heat Flux from Fire to a Target Fuel', in *Fire Dynamics Series: Estimating Fire Flame Height and Radiant Heat Flux From Fire* (Fairfax, Virginia: PDH Online), accessed 27 March 2020, https://pdhonline.com/courses/m312/m312_new.htm.

[41] D. Du Bois and E. F. Du Bois, 'A Formula to Estimate the Approximate Surface Area If Height and Weight Be Known', *Archives of Internal Medicine* 17 (1916): 863–71.

[42] ASHRAE, *Fundamentals*.

[43] ASHRAE, 'Standard 55: Thermal Environment Conditions for Human Occupancy'.

[44] P. O. Fanger et al., 'Comfort Limits for Asymmetric Thermal Radiation', *Energy and Buildings* 8, no. 3 (1 August 1985): 225–36.

[45] Josep Grau-Bové et al., 'Fluid Simulations in Heritage Science', *Heritage Science* 7, no. 1 (13 March 2019); G. G. Akkurt et al., 'Dynamic Thermal and Hygrometric Simulation of Historical Buildings: Critical Factors and Possible Solutions', *Renewable and Sustainable Energy Reviews* 118 (1 February 2020).

[46] Hubbard, *Devices and Desires*.

[47] Boynton, *The Hardwick Inventories of 1601*.

[48] Peter Thornton, 'A Short Commentary on the Hardwick Hall Inventory of 1601', in *The Hardwick Hall Inventories of 1601*, ed. Lindsay Boynton (London: The Furniture History Society, 1971).

[49] Sir Henry Bronker, the Queen's commissioner, records an unannounced visit on 7th January 1603 as follows: 'I found the house without strange company, My Lady of Shrewsbury after she had my name, sent for me in her gallery where she was walking with the Lady Arbella and her son William Cavendish.' Durant, *Bess of Hardwick*, 205.

[50] F. A. Brooks, *An Introduction to Physical Microclimatology* (Davis: University of California, 1959).

[51] Edward Arens et al., 'Modeling the Comfort Effects of Short-Wave Solar Radiation Indoors', *Building and Environment* 88 (1 June 2015): 3–9.