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An assessment of moisture induced damage in Blickling Hall in Norfolk, England, via environmental monitoring

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Abstract
In the last few decades, extreme weather events mostly characterized by more intense and frequent precipitation and wind incidents have risen, and current climatic projections strongly suggest that this trend will keep its pace in the future. These climatic conditions pose additional hygrothermal loading onto the built environment, which may lead to moisture induced deterioration and even strength reduction in masonry. Despite their already long service lives, this impact may in time become problematic for historic buildings, which, by nature of their design and construction, interact with moisture and climate to a far greater degree than modern buildings. The PARNASSUS project was set up with the aim of identifying and quantifying the impact of environment on historic buildings in the face of a changing climate. As part of this project, an extensive environmental monitoring campaign was carried out between 2012 and 2014 at Blicking Hall, a National Trust property in Norfolk, England, with the aim of providing further insight into the building's overall performance under hygrothermal loading. Environmental monitoring work targeted not only indoor and outdoor conditions, but provided information about the temperature and relative humidity profiles across the walls by means of in-wall probes. Wind and rain gauges helped quantify other environmental parameters. This paper presents the findings from this environmental monitoring work, with specific emphasis on the basement suffering from sustained saturation in vapour phase and resulting biological growth, as well as the Long Gallery, where Blickling's valuable library is kept.

Keywords: Environmental monitoring, Moisture-induced damage, Wind-driven rain, Mould, Condensation

Background

Despite high local variations and associated uncertainties, current trends show that significant changes are taking place in the global climate [1]. UK is among the European countries suffering most from this impact in various ways [2]. It is expected that seasonal temperatures, and precipitation and wind patterns will dramatically change in the course of coming decades, which will bring along more frequent and intense extreme weather events. The total amount of rainfall is expected to increase in winter [3, 4] and, to a lesser extent, in spring and autumn, but this increase does not always accompany an increase in the number of wet days, which may result in more intense rainfall events that might, in turn, trigger both urban and riverine flooding [5]. These observations are in broad agreement with the conclusions drawn by Jones and Reid [6] with regard to expected heavy precipitation events in the UK. It is a well-established fact that the resulting moisture loading, both cyclical and sustained loading, have a wide variety of implications ranging from issues such as mould formation or other biodeterioration, to those that may in time jeopardize the material and structural integrity of built environment such as material erosion, and loss of strength and stiffness (e.g. [7–11]).

Blickling Hall is one of the most famous Jacobean mansions, dating from the early seventeenth century and known for its outstanding architectural features [12]. The building has a double courtyard plan, with a great hall

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in between [13]. It is a Grade I listed property located in a registered park of total area 340 ha, near Aylsham in Norfolk, England [14]. Blickling Hall was given to the National Trust in 1940 under the terms of the 1937 Country Houses Scheme [15]. The locality is under constant threat of flooding of the River Bure basin, the most famous one being the big 1912 Norwich flood. More recently, Blickling has been affected by pluvial flooding, in September 2001, August 2004, June 2007, September 2008 and August 2014. Furthermore, the building is known to have high exposure to wind-driven rain and freezing conditions during winter [16].

The building is generally in a good state of preservation, however the lower elevations, especially the basement area is clearly affected by sustained high levels of moisture due to saturated soil below the basement window level, leading to biological growth and salt crystallization. Maurice Adams, as early as 1894, describes the continually saturated basement walls due to non-functional drains from a faulty culvert extending on the sides of the building on almost the same level as the basement, and mentions that it even often partly fills up the basement with sewer-contaminated water and that "the walls were green with damp". Adams in 1894 [17] gives a full account of the replacement of the hugely deteriorated culvert with a pipe system, and although there is no mention of that in this paper, the tanking that is currently present within the basement is thought to have been built towards the end of the nineteenth century, perhaps also by Adams himself. In the early 2000s more interventions took place to further improve the drainage issues of this space, which included cleaning and repairing the historic brick rainwater culvert which extends around the perimeter of the mansion and to address surface water management and run off issues in the upper front meadows inundating the front forecourt of the house. Following these maintenance improvements there has been little to no occurrences of major flooding in the basements or within the dry moat.

On its eastern side the Hall contains one of the most significant libraries in the National Trust, filled with Sir Richard Ellys's books [13]. Ellys's library was installed in 1745 in the Long Gallery [18], one of the finest rooms at Blickling with its elaborately decorated Jacobean plaster ceiling, has been the principle focus for content conservation for some years within the house. The library is known to suffer on and off from mould growth on leather and vellum book bindings, notably at the back of the books, where temperature may be lower due to radiant heat loss from the external walls. In the 1980s, the presses were altered by extending the depth of the shelves so that ventilation holes could be drilled at the back of the shelves to facilitate ventilation behind the book stack and mitigate mould growth. However, occasional mould growth still occurs. Another significant issue within the library is deathwatch beetle infestation, of the textblock of books and wooden structural elements, especially at the North end of the library. This may be related to poor environmental conditions inside the library at this time, as well as past water ingress, such as flooding caused by failure of rainwater goods that was discovered in 1999. Water-soaked or decayed timber is vulnerable to insect attack [19–21]. Since these events, the National Trust has made considerable effort to prevent water ingress through repair and maintenance of the building fabric and rainwater goods. In the Long Gallery itself heating is used to prevent high humidity conditions that can encourage mould growth and insect infestation, aiming to keep indoor relative humidity level below about 60%. The North East Turret is also subject to death watch beetle infestation, due to a long history of water ingress affecting its timbers. For all these reasons, with the aim of identifying and quantifying the environmental exposure, Blickling Hall was monitored between August 2012 and October 2014 using an extensive monitoring system, which is described in detail below. This paper summarizes the findings of this monitoring study and discusses the susceptibility of the building envelope to moisture-induced damage.

Environmental monitoring

The environmental monitoring work in Blickling Hall started in October 2012 and continued up to October 2014. A number of parameters were monitored on a half-hourly basis by an extensive environmental monitoring system, designed and installed on the building, with an online, real-time logging capability via a website. The monitoring system was composed of the following components: wind speed and direction gauge, a horizontal rainfall (HRF) gauge, three wall mounted wind-driven rain (WDR) gauges designed and manufactured as part of this study, in-wall temperature and relative humidity probes and thermocouples for surface temperature measurements. The locations and details of all these sensors can be seen in Fig. 1 and Table 1, respectively.

Separately, a set of standalone temperature and relative humidity sensors (EL-USB-2) were placed in various places across the building (in the basement for in-wall indoor values, in the gallery for in-wall values and underneath a moat in the garden for outdoor values) to monitor the temperature and relative humidity (measurement ranges: 0–100% RH±, −35 to +80 °C T ± 0.5 °C), again on a half-hourly basis. These standalone sensors were chosen from the thinnest products available commercially (around 2 cm thickness) to ensure limited impact on historic fabric, and disruption to mortar

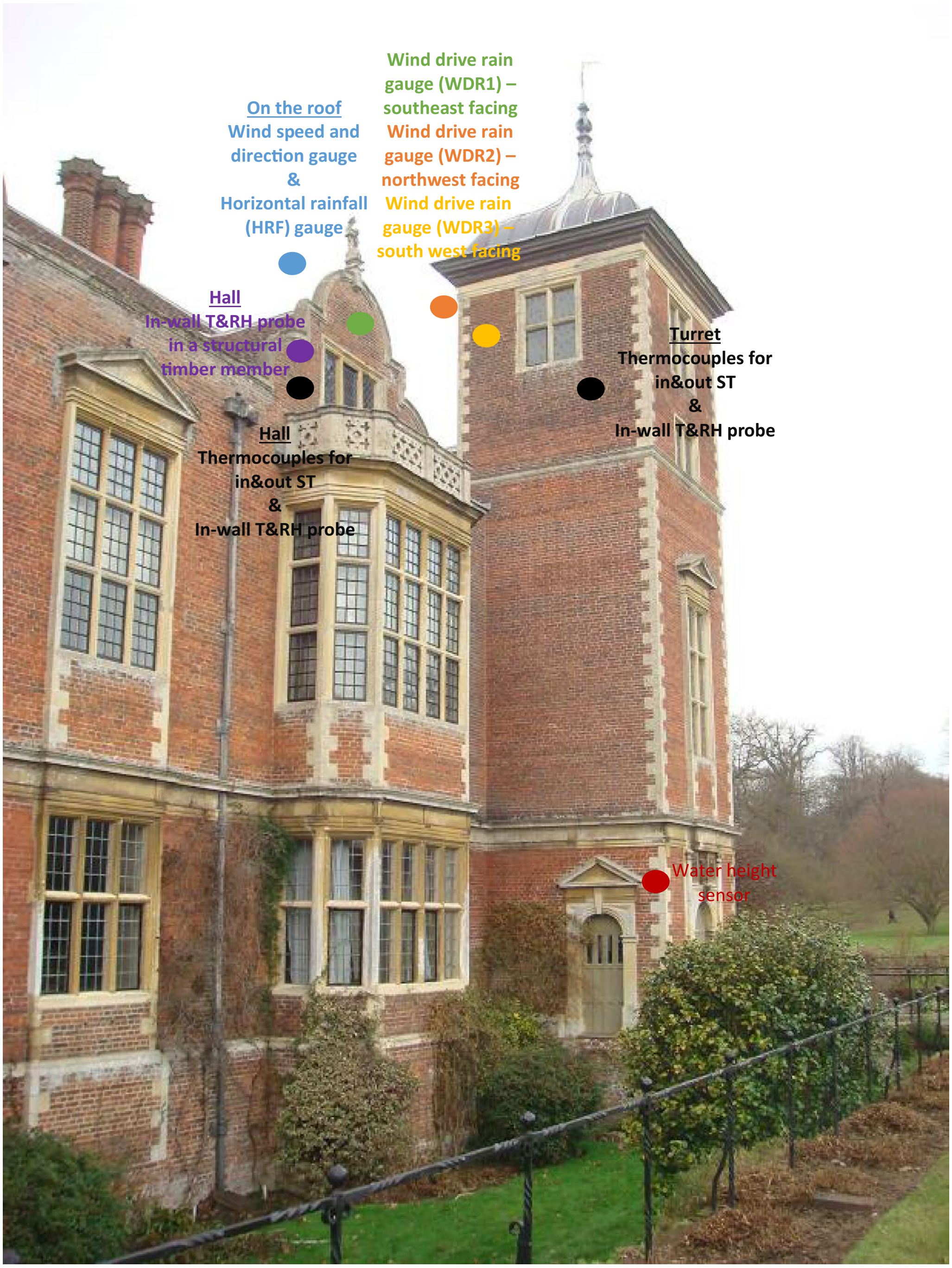

Fig. 1 Blickling Hall environmental monitoring system located on the north eastern corner

joints. Existing cracks or other defects on the walls were exploited for their placement in order to minimize intervention. In addition, the National Trust's outdoor and gallery indoors monitoring data were used in this paper.

The obtained results are discussed in the following sections in relation to the likelihood of most common moisture-induced damaging mechanisms in various sections of Blickling Hall.

Impact of temperature and relative humidity variations

The measurements taken from the *basement* (both in-wall and indoors) by means of standalone sensors (Fig. 2)

Table 1 Sensors used in the monitoring of Blickling Hall and their specifications (credits: [7])

Instrument	Notes
Wind gauge	Speed and direction range: 0–60 m/s and 0–359°
	Speed and direction accuracy: ±2% and ± 3°
	Speed and direction resolution: 0.01 m/s and 1°
	Wind direction range: 0–359° (no dead band)
	Wind direction accuracy: ±3° @12 m/s
	Wind direction resolution: 1°
Horizontal rainfall (HRF) gauge	Tipping bucket rain gauge with resolution of 1 pulse equal to 0.1 mm
Wind-driven rain gauges	
Outdoor temperature and RH sensor	−50 to +100 °C for temperature; accuracy ±0.1 °C
	0–100% for RH; accuracy ±0.8%
In-wall temperature and relative humidity probes	−40 to +100 °C for temperature; accuracy ±0.1 °C
	0–100% for RH; accuracy ±0.8%
Indoor temperature and RH sensor	−40 °C to +120 °C for temperature; accuracy ± 0.5 °C
	0–100% for RH; accuracy ±1.5%
Thermocouples	Maximum operating temperature of +350 °C, shielded against solar radiation
Water height sensor	Optimum range: 20.3 cm to 4.0 m
	Maximum range: 6.1 m
	Resolution: 0.344 mm

show that the basement walls are subject to prolonged saturation in vapour phase (100% RH) and therefore highly likely to contain liquid water. During the monitoring period, the in-wall sensors were taken out of the wall a number of times to download the data and change the battery. Once they were replaced in the measurement location they returned to a constant reading of 100% RH within one week. The study of the basement of the Blickling Hall by Baker et al. [22] with the aim of collecting data to validate a hygrothermal model also confirmed that drying does not take place where the wall surface is in contact with ground moisture. The walls under examination here were continuously at 100% RH during the entire monitoring period. Figure 2 also shows that the indoor and outdoor temperature and relative humidity peaks and troughs almost coincide. This is indicative of a rather rapid thermal response and a low inertia to hygrothermal fluctuations. Some other brick masonry buildings monitored as part of this study, whose results were reported elsewhere, appeared to have a slower response and thus higher inertia to temperature and humidity fluctuations across their walls [7, 8]. This indicates the importance of a full hygrothermal characterization for an accurate appraisal of the environmental performance of different building materials. While a rapid thermal response might have negative implications in terms of, for instance, energy performance of a building envelope, it can be beneficial in some circumstances, for instance reducing condensation risk in spring because the cold building fabric will warm more quickly as ambient temperature and air moisture contents rise. Similar to the in-wall conditions, the basement indoors is also extremely humid with relative humidity values not dropping below 85%. The maximum daily humidity and temperature fluctuations are 10% and 3 °C, respectively, pointing to very stable indoor conditions.

The *Long Gallery* where the library of Blickling Hall is kept is one of the highlights of the entire property. This study therefore included the *in-wall* monitoring of the Long Gallery. The results show that the gallery in-wall temperatures fluctuate between 5.5 and 25 °C with an average of 14.4 °C, while the relative humidity values vary between 66.5 and 77% with an average of 72%. The fact that the in-wall relative humidity values are all lower than 77% is quite positive from a biodeterioration point of view and an indication that the building fabric is coping well with the local climate. The rarity of wind incidents with speeds higher than 2 m/s are considered to contribute to the relatively low in-wall relative humidity values (discussed more in depth in "In-wall moisture enrichment due to rain penetration" section). When the daily maximum variations are examined, one sees that the maximum daily difference in the relative humidity values is in the range of 12%, whilst this is negligible for temperature values. The likely implications of these high relative humidity values combined with temperatures at the high end is further discussed in "Mould formation and other moisture induced bio-deterioration" section. Also, it is noteworthy that even when the outdoor temperature values fall below the freezing point, the in-wall

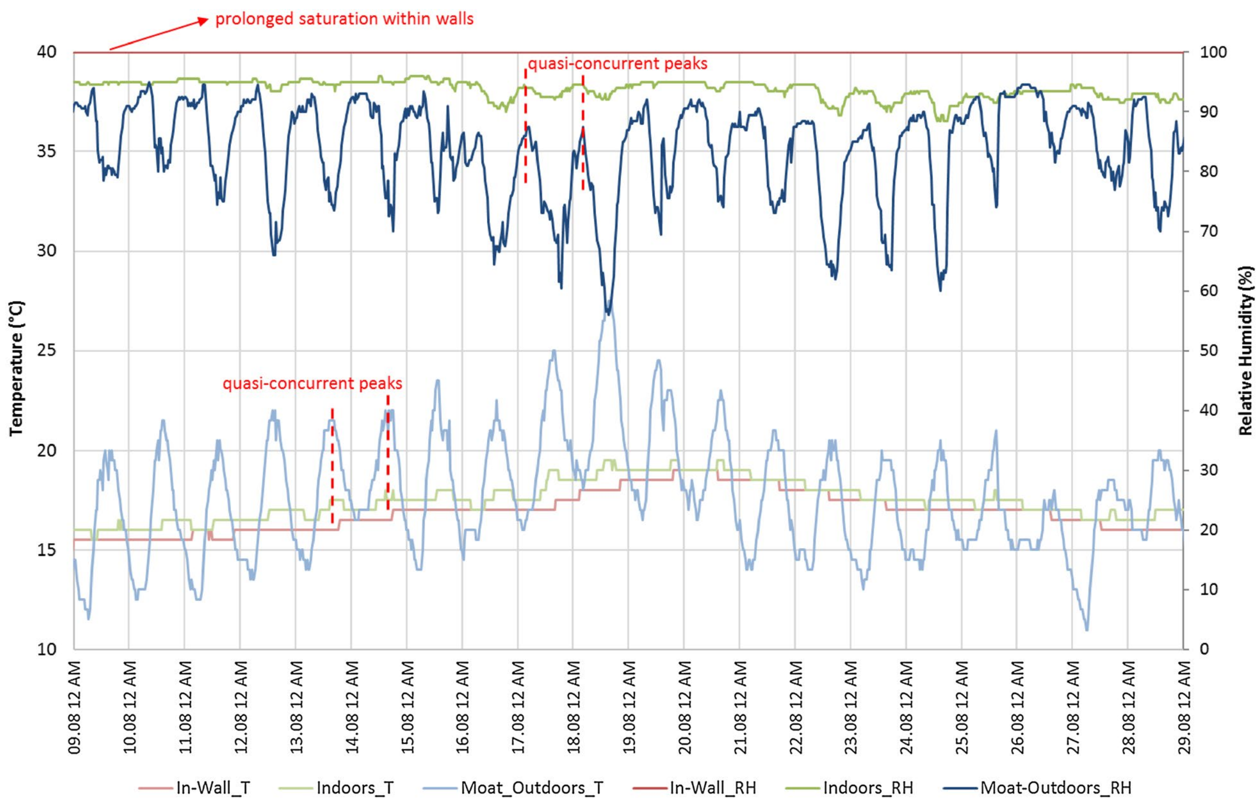

Fig. 2 T and RH values obtained from the basement between 09 and 29 August 2012

temperatures stay above 0 °C. In fact, the minimum in-wall temperature is 5.5 °C. Therefore, cyclic freeze and thaw is not a relevant phenomenon for this part of the estate.

In-wall moisture enrichment due to rain penetration

The distribution of wind speed and direction for the entire monitoring duration is shown in Fig. 3 (left). The prevailing wind direction shown here is consistent with prevailing wind direction reported for Eastern England [23]. Wind speed does not exceed 2 m/s 90% of the time and when it does it mostly affects the south-west facing wall of the hall, where the WDR gauge number 3 is located in fact, this gauge measured the lowest cumulative amount of wind-driven rain. This means that the wind is not always accompanied by rainfall. The total amount of rain (HRF) measured throughout the monitoring period is 1114.5 mm. The WDR amounts measured by the WDR gauges (Fig. 3 right), on the other hand are 132.2, 71.4 and 55.3 mm, respectively.

BS EN ISO 15927-3 [24] defines a weather incident that can moisten the wall as one that lasts at least one half-day with more than 4 mm of horizontal rainfall, with average wind speed >2 m/s and average wind direction within ±60° incident angle. For gauge number 3, some of the rain spells that best suit these criteria were found to be 27/10-07/11/2012 and 21/11-06/12/2012 (Fig. 4). As seen, the average RH values within the wall increase by some 3% following the heavy rains on 27–28 October, and then by another 2% following the end of October rains, and the wall becomes saturated in the vapour phase at mid-way through its section for at least another 2 months where a number of more minor precipitation events take place.

We also see that the inner and outer wall surface temperature peaks and troughs happen at the same time, suggesting low thermal inertia once again. The in-wall temperature values on the other hand are rather constant. We also see that the peaks in the in-wall RH values correspond to peaks in the outer surface temperatures, pointing out presence of free water within the building fabric.

As mentioned in "Impact of temperature and relative humidity variations" section, the gallery in-wall relative humidity values are always below 77%, which, compared to the in-wall RH values measured in the unheated turret attached to the North East corner of the Long Gallery, are quite low. On this particular wall, we do not observe

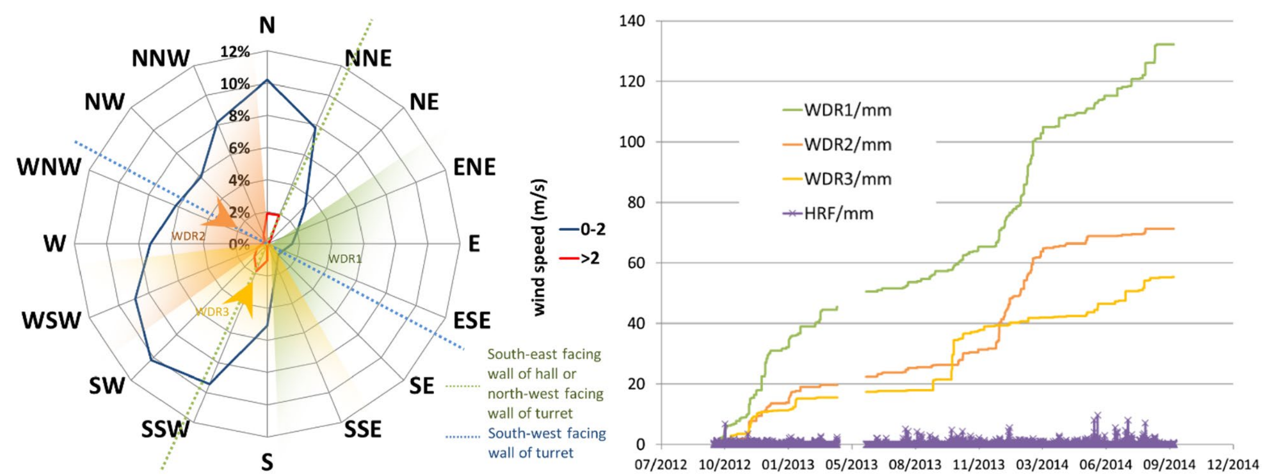

Fig. 3 Wind speed and direction (*left*) and wind-driven and horizontal rainfalls (*right*) on Blickling Hall for the entire monitoring period

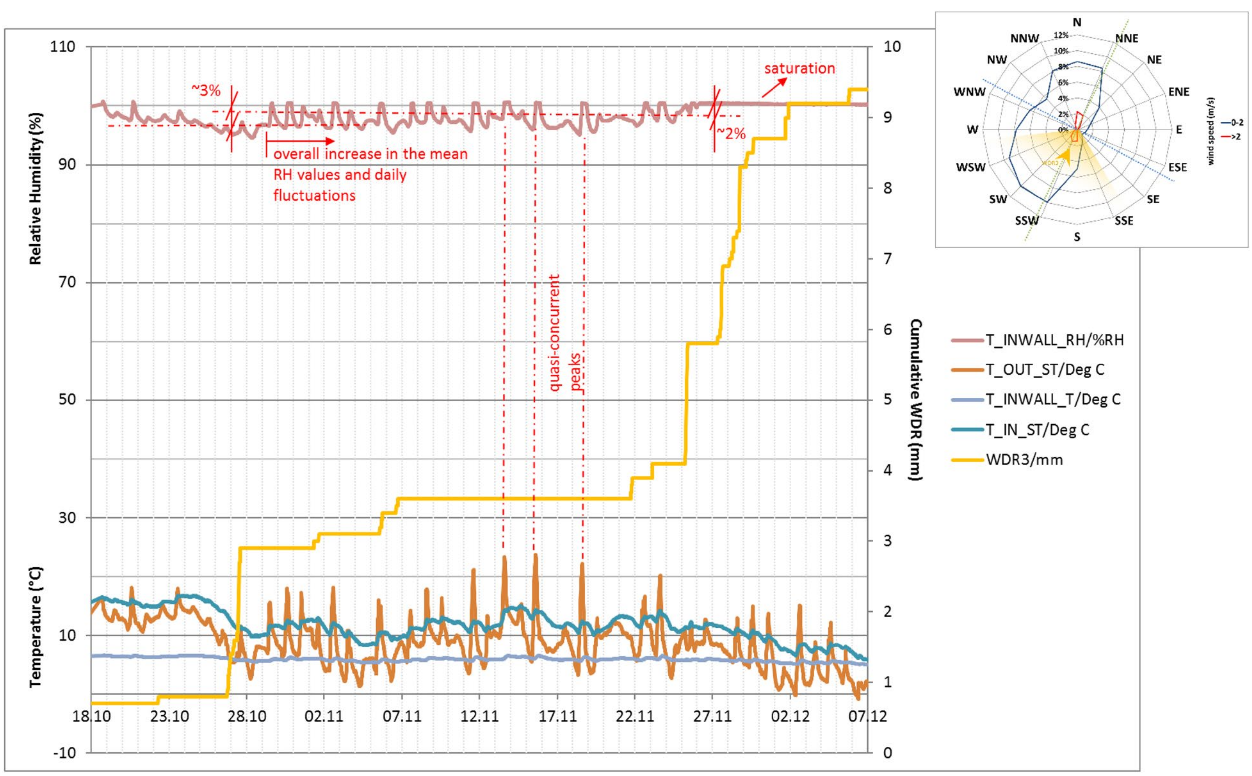

Fig. 4 Moisture enrichment within the turret walls (*top*) and distribution of wind speed and direction (*bottom*) between mid-October and early December 2012

a similar moisture enrichment phenomenon, even under heavy rain incidents that satisfies the half-day with more than 4 mm of horizontal rainfall criterion. This is considered to be due to the fact that the wall is not facing the prevalent wind direction and is not exposed to wind speeds higher than 2 m/s.

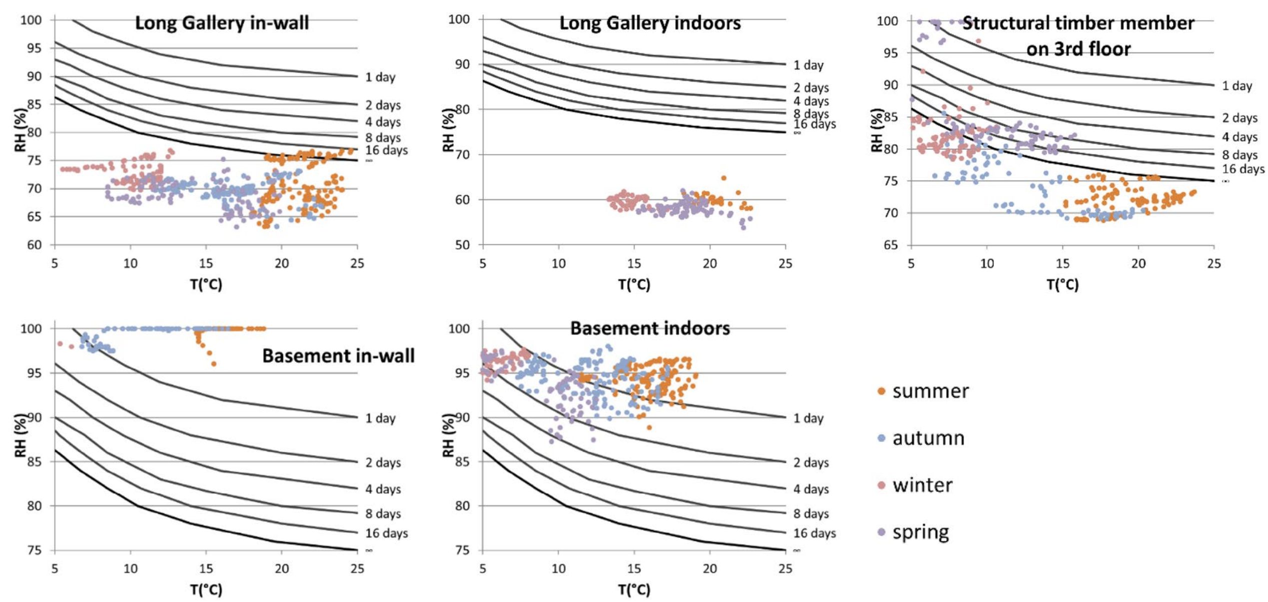

Fig. 5 Daily average T and RH values shown on generalised isopleths [33] of spore germination for different incubation duration values

Mould formation and other moisture induced bio-deterioration

Mould is known to occur in highly humid environments, including, notably, confined indoor spaces. In addition to surrounding environmental conditions, the type, surface texture and cleanliness of the substrate, as well as incubation duration and amount and type of available light are known to influence the likelihood of mould growth [25]. Despite the abundance of studies focusing on benchmarking of minimum temperature and humidity conditions that may result in an onset of mould formation on different building materials (e.g. [26–28]), different values were reported for the minimum RH values that govern and possibly trigger the onset of the mould growth, if no other information is available: 70% [29], 75% [28, 30], and 80% [31]. As the relative humidity increases, the temperature that should accompany it for an onset of mould growth decreases. However, the temperature interval optimal for the germination of most species is roughly 15–30 °C [25], which covers common temperature levels in controlled or uncontrolled indoor environments, but depending on the humidity conditions it can be as low as 10 °C, although that would significantly reduce the growing rate [32].

Although isopleths (or growth limit curves) defining the mould growth patterns based on temperature, humidity and incubation time are dependent on specifics of the substrate as well as the mould species, in order to assess the susceptibility of monitored spaces to mould formation the generic isopleths that Sedlbauer [33] developed for various building materials were used in this study (Fig. 5). Both brick masonry walls (after Abuku et al. [34]) and wood were accepted to be Substrate Category I (biologically recyclable building materials). Despite the generally low relative humidity levels within the gallery wall, the results show that high RH combined with relatively high temperature values occurring in summer may lead to mould formation if sustained for prolonged periods. Warm temperatures can also sustain or further increase the susceptibility for beetle infestation (see [35]). When the same exercise is repeated for the indoor conditions, on the other hand, it is seen that the temperature-humidity values remain way below the mould isotherms. Therefore, it can be concluded that the controlled environmental regime within the gallery is dry and warm enough to prevent mould formation on the building envelope, however this conclusion does not necessarily explain the microclimatic conditions that can occur behind the book stacks, close to the external walls, where the air is stagnant and water availability might at times be higher. Despite the moderate RH, mould growth on book bindings within the Long Gallery, is still observed from time to time. The basement, on the other hand, both indoors and in-wall, has a high risk of biological growth, which is compatible with the visual observations of this space.

As mentioned in "Environmental monitoring" section, a structural timber component embedded within an attic wall above the Long Gallery (purple dot in Fig. 1) was included within the monitoring programme. The same exercise using the monitoring results obtained here, shows that the timber element is quite vulnerable to mould growth, especially in winter and springtime. More concerning, is that the timber is likely to have as a consequence, high equilibrium moisture content enabling death watch beetle larvae to consume the wood. Death watch beetle attack has been observed in various timbers in Blickling, notably in the upper levels of the North East Turret. Fisher [20] states that the level of existing decay in the wood attacked by the deathwatch is another important factor—the more decayed the timber the more prone it is to be attacked. Also, fungi-infested timber is more suitable for the development of these insects.

Another important phenomenon that is known to be damaging and that may lead to mould formation is condensation. In order to evaluate this, the dew point values were calculated using the equation below given by BS EN 16242 [36].

$$DewPoint = \frac{243.12 * \ln\left[\left(\frac{RH}{100}\right) * 10^\wedge\left(\frac{7.65T}{243.12+T}\right)\right]}{17.62 * \ln\left[\left(\frac{RH}{100}\right) * 10^\wedge\left(\frac{7.65T}{243.12+T}\right)\right]}$$

The data obtained from the basement show that the in-wall temperature values are equal to or lower than the calculated dew point temperature for more than 70% of the time. Moreover, the data shows that most of these incidents take place in relatively warm months, i.e. from May to October. Therefore, one can conclude that interstitial condensation is a serious risk factor for the basement, especially in summer and autumn.

Another location that seems to suffer from occasional condensation is the North East Turret. An analysis of the temperature and relative humidity values show that the temperature values are lower than the dew point for almost a quarter of all readings. Here, on the other hand, the critical season seems to be the winter. The times of the year where condensation occurs in these two different parts of the building are completely different, which can be attributed to different phenomena triggering condensation: summer condensation is commonly seen in historic buildings with very thick walls [37], especially in underground structures such as crypts (see [38]) and caves, and is an indication of relatively warmer surface temperatures, humid air and still cold building envelopes. Winter condensation, on the other hand, is rather a result of cold air surrounding the relatively warm building fabric. The fact that the basement is partly below ground level keeps the building fabric at quite low temperatures regardless of the season, whereas the monitored portion of the turret is quite high up and located very closely to the portion of the building that is frequently in use, and therefore the walls are relatively warmer.

Summary and conclusions

This paper presents the results obtained from a long monitoring campaign on Blickling Hall, carried out between August 2012 and October 2014. The results show that the building envelope has a rather rapid thermal and hygric response. Moisture enrichment due to rain penetration is a critical issue and can be exacerbated by empty mortar joints or otherwise damaged pointing, and under heavier precipitation expected as a result of changes observed in climate. Additionally, it is seen that different parts of the building suffer from different environmental phenomena, with varying implications.

Based on the results obtained in this study, the following recommendations are proposed: the facades that are exposed to high winds, specifically north and south facing walls, are expected to absorb considerable moisture during wind-driven rain spells, and therefore it is critical to maintain the wind and water tightness of these facades in the current and increasingly wetter future climates. This result confirms the value of the National Trust regime of regular inspection and maintenance of rainwater goods such as gutters, hoppers and downpipes and ensuring that pointing and detailing is in good order.

Conservation heating should be used in parts of the building housing sensitive collections, to reduce the indoor relative humidity levels and thus eliminate susceptibility to mould growth and other biodeterioration. It was observed that death watch beetle infestations die back if the wood moisture content is consistently below 12% [39]. Work is ongoing, follow recommendations from the National Trust's building consultants, to remove severely infested timbers and create a drier environment for other timbers through dealing with water penetration and ensuring adequate ventilation and in some cases using active dehumidification. In the Long Gallery conservation heating to maintain RH below 60% is used to reduce wood moisture content of the book presses and other timber elements below the critical 12% threshold.

The basement walls are continually saturated in the vapour phase, and do not dry out even during relatively dry and warm outdoor conditions. On the other hand, most of the pressing drainage issues have been dealt with in the early 2000s and the conditions are currently quite stable. As the basement is expected to have some level of dampness because it is partly located underground; as a result, does not house vulnerable collections, a very dry building fabric is not required here; however, the conditions should be kept under close surveillance in order to make sure that conditions do not worsen as the outdoor climatic conditions get more problematic as expected in the light of current trends.

This study shows that the on-site monitoring is a powerful tool for an in-depth appraisal of the environmental loading that buildings are actually exposed to as well as of the hygrothermal performance of the building envelope. To this end, an ad hoc monitoring system that brings together measurement tools for not only indoor and outdoor but also the in-wall conditions, as well as wind and rain in the close vicinity of the building is needed. Environmental monitoring should be an integrated component of condition assessment and should inform activities towards the retrofitting and conservation of historic buildings.

Authors' contributions

YDA wrote the manuscript. YDA and DD made the data analysis. NB and CC provided information about the history of the hall, and outlined the past and present problems, as well as past interventions that were used to contextualise the monitoring work reported here. DD, NB and CC helped to draft the manuscript with thorough discussions. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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