Interim notes on Environmental Measurements

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Introduction

We used six environmental sensors with on-board data-logging capability. Made by Lascar Electronics, the battery powered EL-USB-2 measures temperature, relative humidity and dew point, storing the data for subsequent retrieval via usb link to a PC. Details are available at:
<*http://www.lascarelectronics.com/temperaturedatalogger.php?datalogger=102*>

An eighteen hour soak test was performed with all six sensors placed in a common environment. Sampling rate for this was 1 measurement per hour. Discrepancy between them was assessed using the RMS average of differences from each measurement made by sensor one. For temperature, discrepancy was less than 0.8°C. For relative humidity, the discrepancy was less than 1.3 on the %RH scale. For dew point, the discrepancy was less than 0.5°C.

Figure 1: Air temperature and humidity sensor mounted within the lancet

Five of these sensors were mounted on the interior of the Savile Chapel east window, mounted approximately 50mm away from the glass surface. For each sensor a radiation shield was provided to minimise heating by direct solar radiation without obstructing the vertical flow of air past the sensing head. Sensors were placed opposite the centre of the leaded panel, supported on

10mm cross section horizontal timber laths fixed to the stone mullions (see Figure 1 above). Three were disposed on the central lancet at the top, middle and bottom of the window, two were disposed midway up the leftmost and the rightmost lancets. The sixth sensor was fixed outside the central lancet, midway up, fixed to the protective external guard grills.

Data collection began at midday on Monday 1st March 2010, sampling every six hours. This note covers the period from 1st March to 28th June, approximately 500 days.

External air temperature measurements:

As expected, the external sensor showed both diurnal and seasonal variation. Midnight temperature was on average 7°C colder than the previous midday temperature. This is visible in Figure 2 which displays the external temperature as measured.

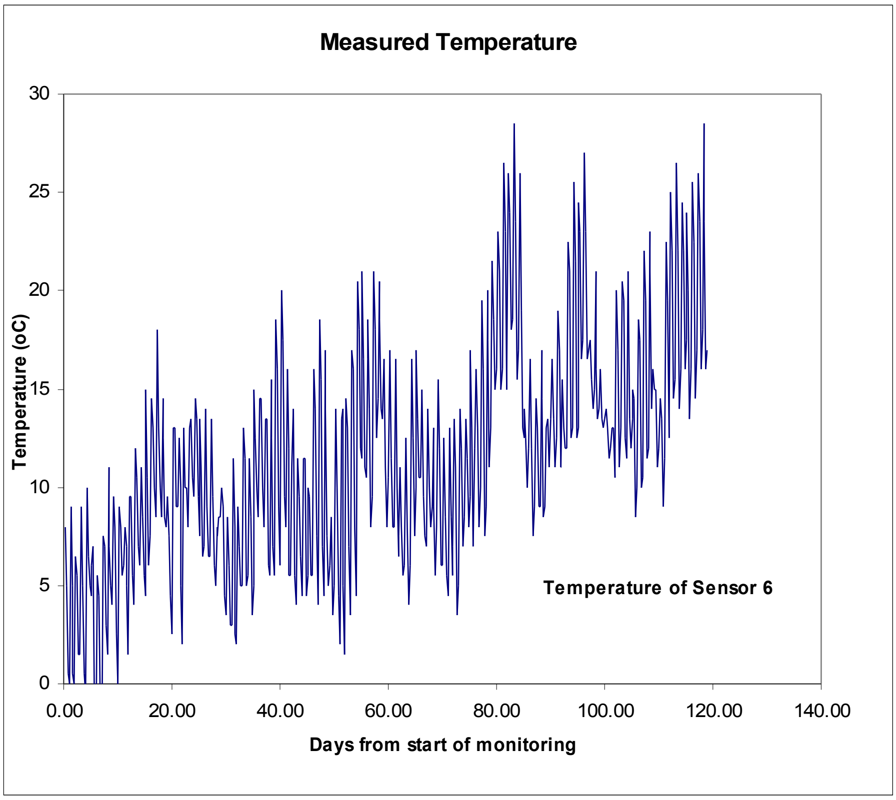

Figure 2: Air temperature measured outside the central lancet

In Figure 3 the daily average temperatures are plotted (each point representing the average of the midday temperature and the three preceding values). The seasonal trend as winter gives way to spring is clearly visible.

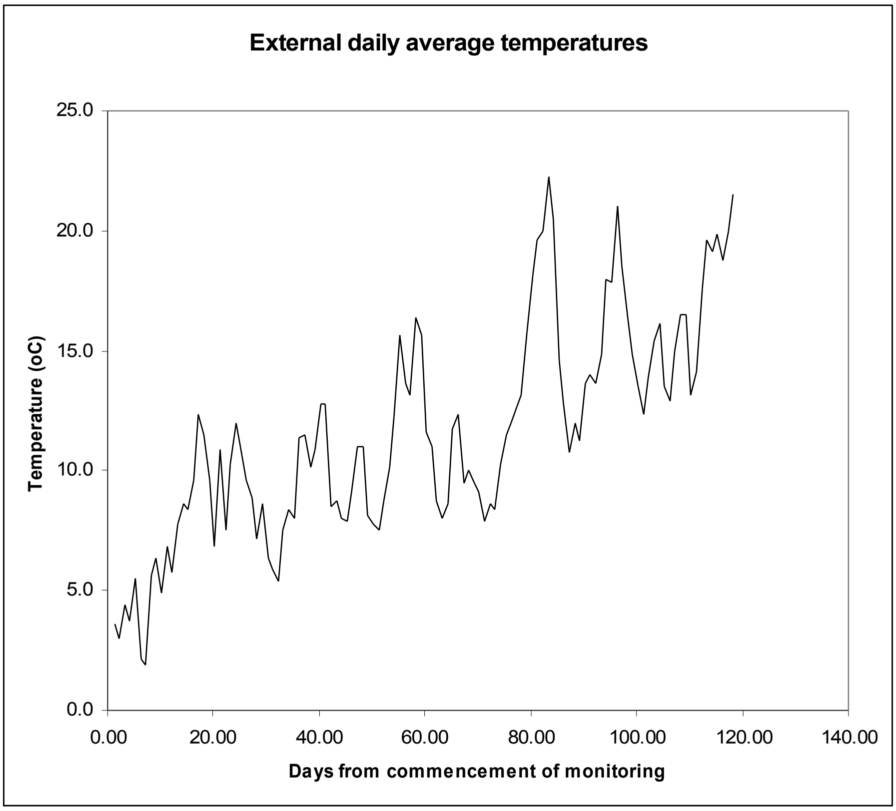

Figure 3: Daily average external air temperatures

Interior air temperature measurements:

Sensor #2 was positioned centrally between the mullions of the left hand lancet, half way up its height. Its measured temperatures are plotted in Figure 4. Not surprisingly, comparison with Figure 2 shows the general effect of the heating within the church, with temperatures on the left hand (winter) side of the graph having a more or less constant trend around 15°C. Measurements taken by Sensor #1 on the right hand lancet show a very similar result, revealing no significant differences between temperature conditions affecting the left and right lancets. So from these measurements there is no evidence of any large-scale horizontal air movement pattern which might affect conditions at the glass surfaces. The natural assumption therefore is that any difference between air temperatures outside and within the building would lead to predominantly vertical convective air flow adjacent to the lancet glazing and collimated by the very substantial masonry mullions.

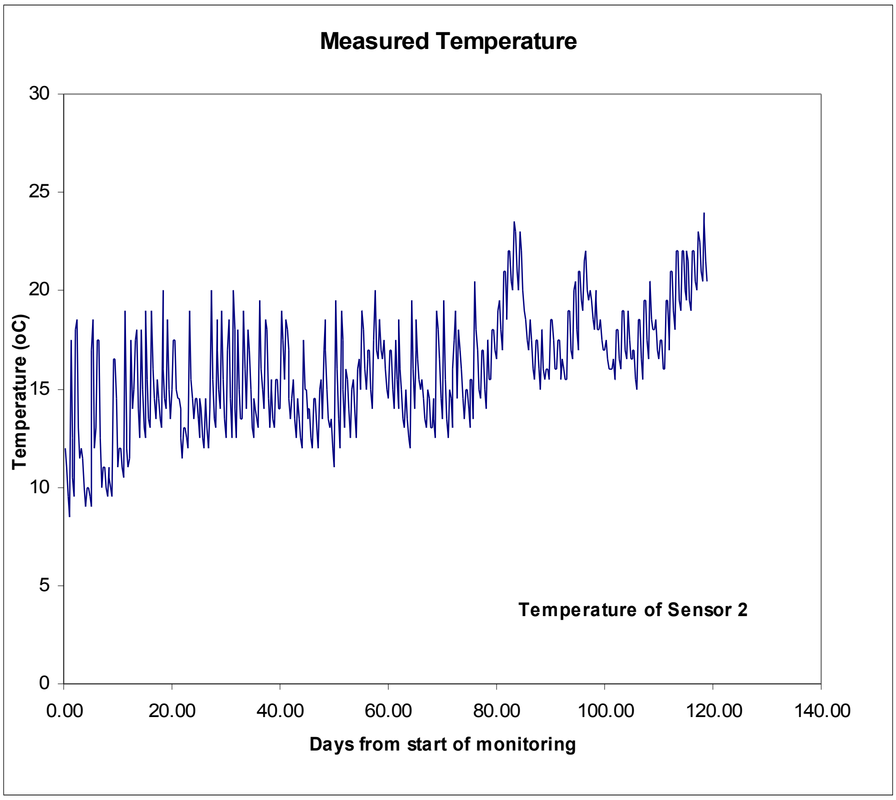

Figure 4: Interior air temperatures measured mid way up the left hand lancet window

The picture given by the sensors mounted in the central lancet is very different, at least on the winter half of the plot. All three sensors show significant temperature excursions with peaks around 10°C higher than the maximum temperatures recorded for that period in the left hand and right hand lancets. The cause of this is clearly the modern central heating radiator positioned just behind the altar, on the wall below the central three lancets of the east window.

Figure 5 Photograph of the modern central heating radiator positioned on the east wall below the window

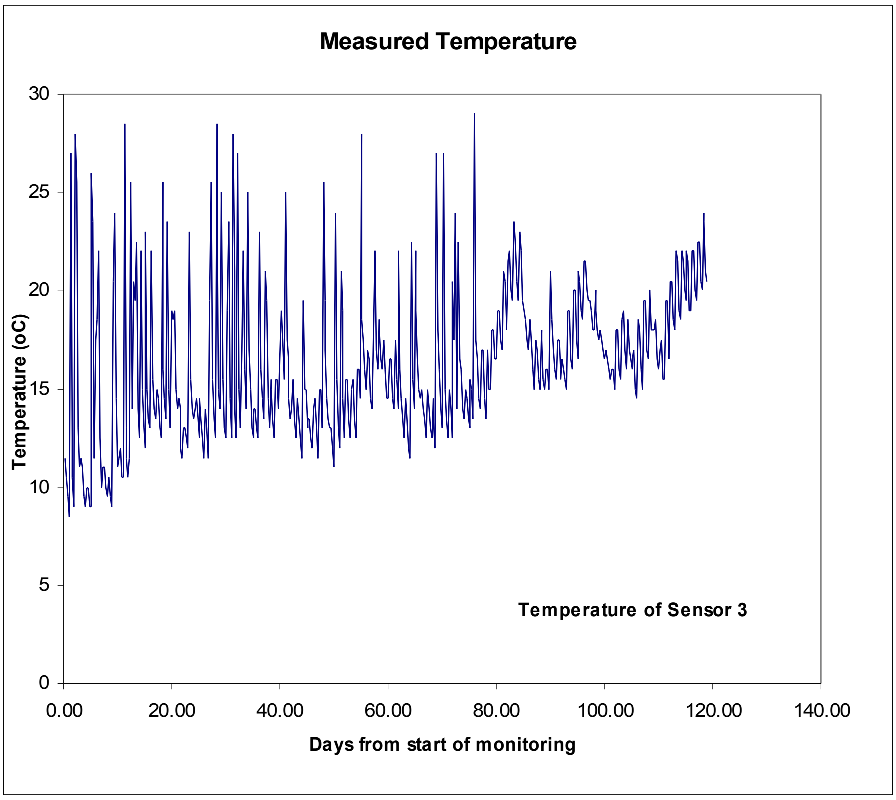

Figure 6: Interior air temperatures measured mid way up the central lancet window

Results from the Sensor #4 at the top of the lancet were very similar indeed; those from Sensor #5 were qualitatively similar but the upward temperature excursions were not quite so marked.

These consistent results point towards a heated air stream rising from the radiator, moving towards the glass surface once the air rises above the level of the substantial stone windowsill. In normal heating and ventilating practice this effect is deliberately exploited to counteract the tendency in cold weather for a convective downflow to be produced by the cold glass creating uncomfortably cold draughts at floor level.

Modern glass is satisfactorily resistant to attack by moist air, so the rising hot air creates no damage to the glass itself. However it is important to recognise that at Thornhill we are faced with a glass composition which is clearly highly susceptible to moisture vapour. For chemical reactions involving water a rise of 10°C is usually associated with a doubling of the rate of attack. Therefore the accepted practice for radiator placement below windows is most emphatically not appropriate at Thornhill. **I recommend that in the interests of conserving the historic east window this particular radiator be removed completely.**

External Relative Humidity:

As with the temperatures, the sensors logged RH each day at six hour intervals, beginning at around midday. Over the period of the measurements, the average external RH was 68% with a standard deviation of 15% on the RH scale. This very large variability is clearly shown in the data plot:

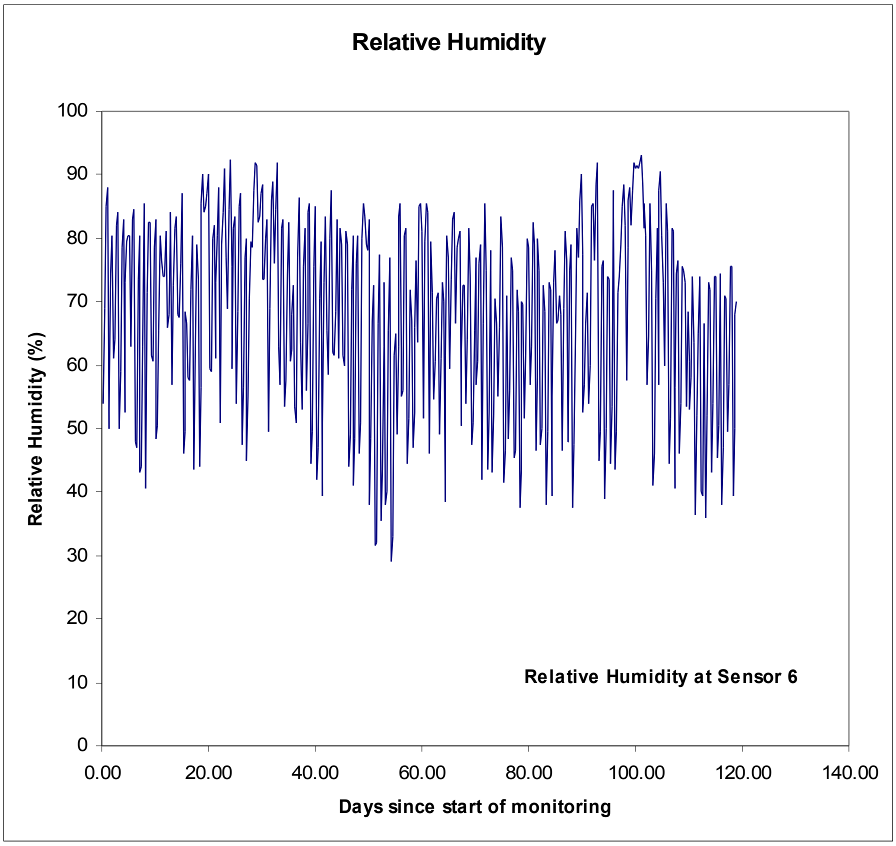

Figure 7: External Relative Humidity measurements

Clearly the diurnal variability of RH is important. Readings taken at midnight and early in the morning are on average 10% above (on the RH scale) the twenty-four hour average figure, the mid-day figure is on average 14% below and the evening measurement is on average 7% below the twenty-four hour average.

Taking the twenty-four hour average reading as a way of filtering out this diurnal variability, we find that there is still considerable variation of RH day to day. Figure 8 (below) shows these data. Any seasonal trend is small compared with the more random variability day to day. Weather conditions during the latter part of this measuring period were remarkably sunny and rainfall was sufficiently low to cause concern over water supplies: many reservoirs were depleted. Even so, the RH values measured at Thornhill remained high.

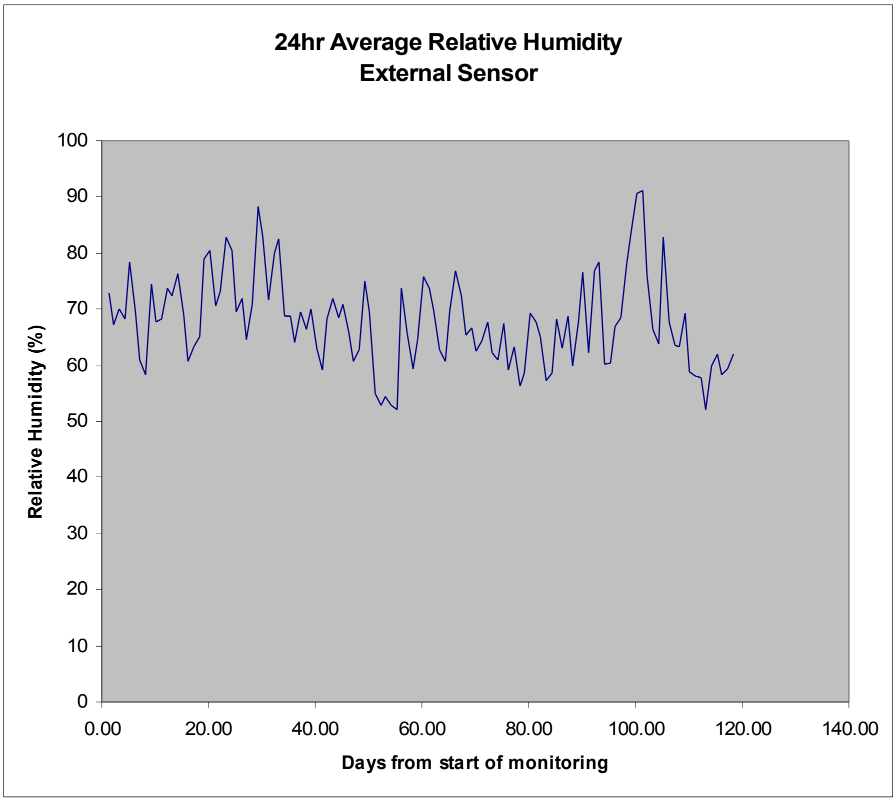

Figure 8: External Relative Humidity measurements - average values for each day

Interior Relative Humidity:

Relative Humidity measured mid way up the left hand lancet showed less extreme variability. The overall average RH value was 62% and the standard deviation was 5% on the RH scale. As Figure 9 below makes clear, there does not appear to be a dominant seasonal variability - indeed in the period when external weather conditions were surprisingly dry the readings peaked briefly at around 70% RH.

Whatever the reasons, this consistently high RH is known to be hazardous for vulnerable glass compositions. There is a parallel between this glass and the glass vessels in many museum collections, dating from a similar period and know as “façon de Venise”. Moisture attack has been studied over the last fifty years, and early measurements by Prof R Brill of the Corning Museum of Glass strongly suggested that conservation was best served by a constant RH of around 42% and by the maintenance of as constant a temperature as possible. On average, the Thornhill window conditions are such as to encourage continuing attack on the glass by water vapour in the atmosphere.

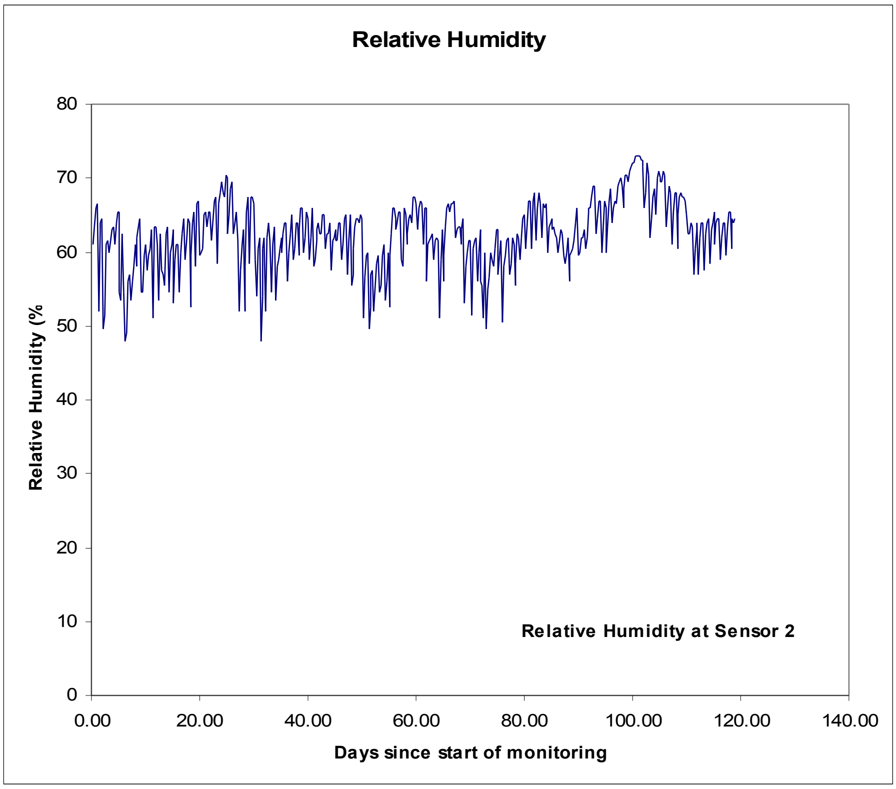

Figure 9: Interior Relative Humidity measurements taken mid way up the left hand lancet

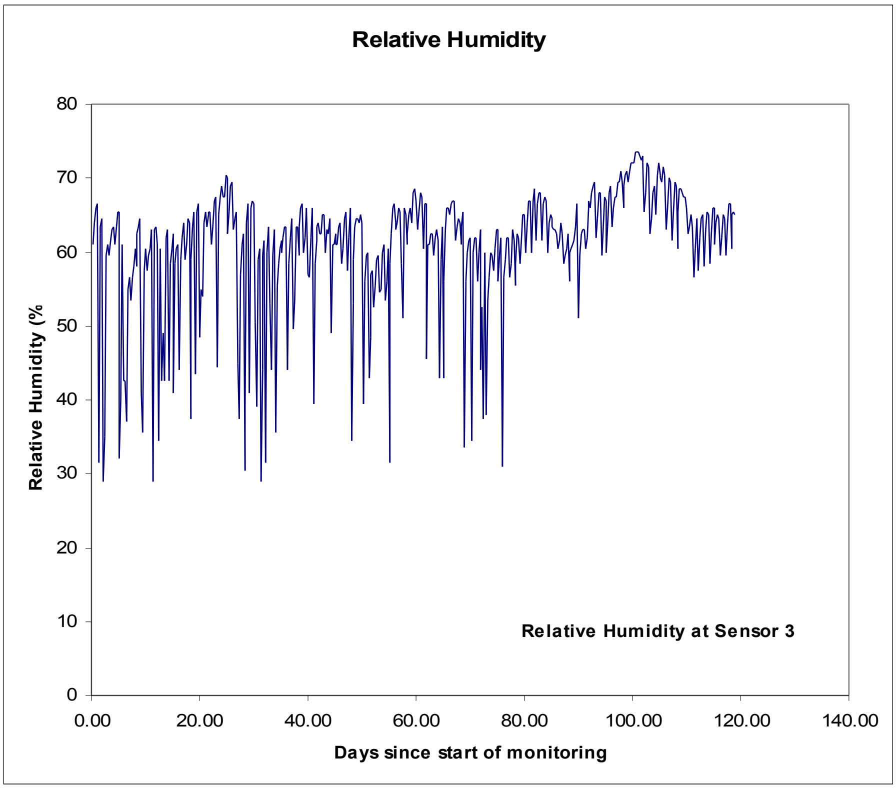

Figure 10: Interior Relative Humidity measurements taken mid way up the central lancet

The readings reported by sensor 3, mid way up the central lancet, are very different. Figure 10 records severe downward excursions of RH during the first part of the measurement period. On a significant number of occasions the RH value dropped below 40%, sometimes going as low as 30%.

Museum experience associates these low RH values with surface cracks appearing on vulnerable glass artifacts, sometimes progressing as far as severe spalling of the surface with fragments of glass becoming detached from the surface.

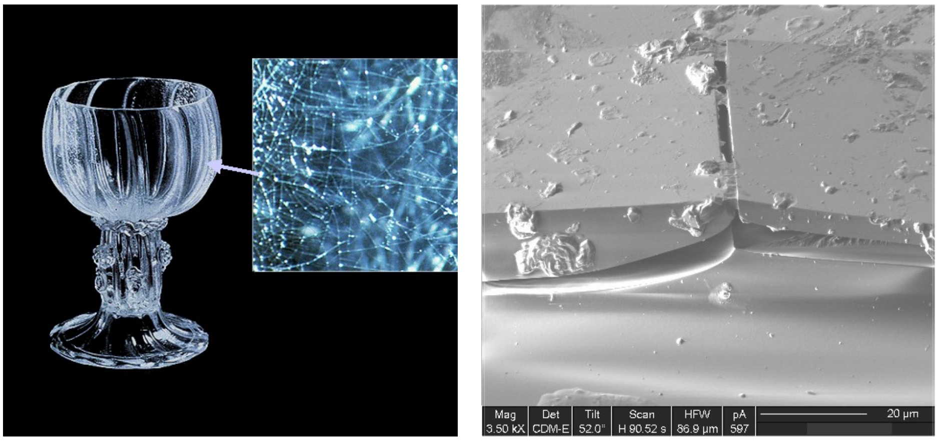

Figure 11: A Ravenscroft goblet exhibiting a network of surface cracks, and a micrograph of glass which has started spalling after exposure to water vapour (illustrations courtesy of Sarah Fearn)

The mechanism is thought to involve the initial formation of a surface layer of glass in which sodium had been replaced by water - this often referred to as the "gel layer". When the RH gets too low, this gel layer starts to lose water to the surrounding dry atmosphere; it tries to shrink, but is held in place by the glass beneath, so cracks start to appear and grow. In the museum context, it is said that these vulnerable objects suffered severe deterioration when brought into the centrally heated environment of the modern gallery.

In the Thornhill context, it must be said that all five lancets of the window exhibit severe moisture attack on the vulnerable panes, and that this attack had progressed as far as the spalling of glass flakes off the original surface. Although the gross effect of the central heating radiator is evident only in the centre lancet, the heating system may well have played a part in accelerating the deterioration over the whole window. Clearly from the data, when the central heating is switched on, the temperature near the glass goes up by circa 10°C and the RH goes down below 40% - conditions which are likely to increase very significantly the risk of cracking and spalling.

The question of Condensation:

The sensors use on-board computing capability to calculate dew point from the measured temperature and Relative Humidity values, and store these calculated values for output. So if we can estimate the glass surface temperatures then we can form a view about the likelihood of condensation taking place.

From the measurements made at Thornhill, we can estimate the glass surface temperatures provided that we can calculate the heat transfer coefficient from air to glass surface. An empirical equation for this is available.

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MEASUREMENT OF THE EXTERIOR CONVECTIVE FILM COEFFICIENT FOR WINDOWS IN LOW-RISE BUILDINGS

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$$h_{\infty} = \sqrt{[\,C_t(\Delta T)^{1/3}\,]^2 + [\,aV^b\,]^2}$$

Wind Direction	C_t	a	b	rms
Metric Units	$W/m^2 \cdot K^{4/3}$	$W/m^2 \cdot K \cdot (m/s)^b$	—	$W/m^2 \cdot K$
Windward	0.84±0.015	2.38±0.036	0.89±0.009	0.91
Leeward	0.84	2.86±0.098	0.617±0.017	0.76

Figure 12: Scheme for estimating film heat transfer coefficients between air and glass surfaces

Taking the free stream velocity of the air near the glass surface to be around two metres per second, the calculated value of heat transfer coefficient would be of order 5, whereas the heat transfer coefficient for conduction through the 2mm thick pane of glass would be of order 275. Effectively there is very little temperature difference between the internal and external surfaces of the glass pane, so the glass surface temperature can be taken to be the average of the internal and external air temperatures.

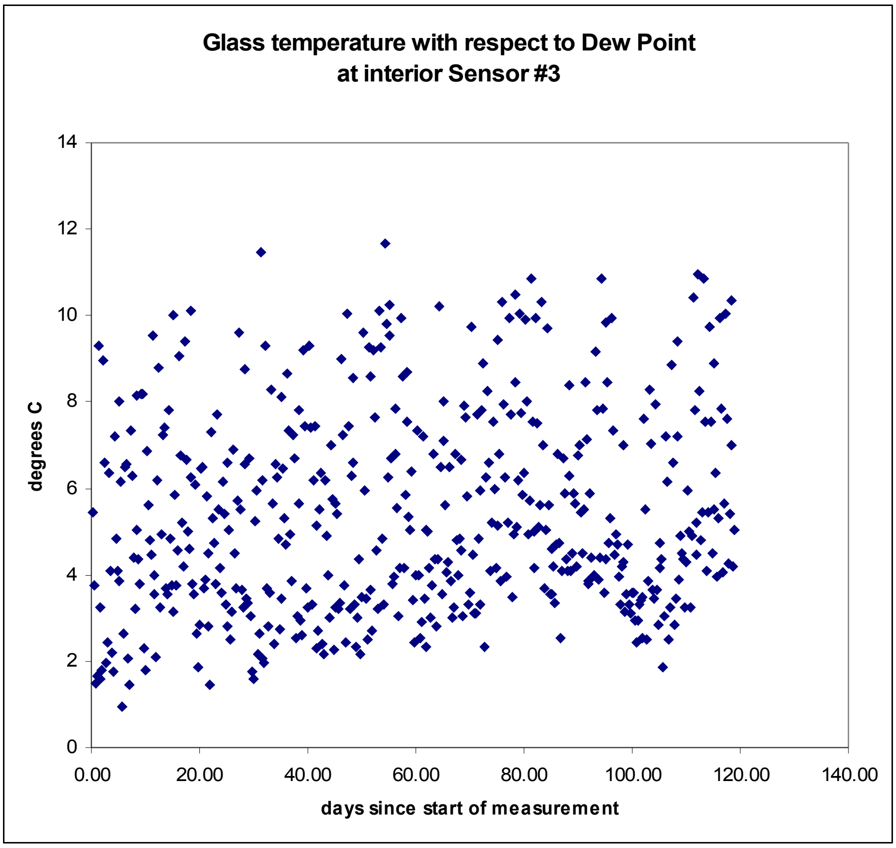

Figure 13: Estimated glass surface temperature with respect to the Dew Point of the interior air near the centre of the central lancet

The result of this exercise is recorded in Figure 13, which shows by how many degrees the calculated glass surface temperature exceeds the air stream Dew Point as reported by the sensor #3. It is clear that throughout the measurement period the glass temperature has consistently exceeded the Dew Point, so we conclude that moisture attack via condensation of liquid water on the glass surface is most unlikely.