Assessment report
'Museum Our Lord in the Attic'

Part II – Assessments

A collaborative project of
The Getty Conservation Institute
The Netherlands Institute for Cultural Heritage
Museum Ons' Lieve Heer op Solder ('Our Lord in the Attic')

7 Indoor climate research

7.1 Introduction

From January 1st 2005 up to January 2006, climate data have been collected by the ICN with collaboration of the Technical University Eindhoven (TU/E) in the historic house museum 'Our Lord in the Attic'. Relative humidity (RH) and temperature (T) data have been collected using Hanwell sensors placed at different locations throughout the building: in five locations in the Church (at three different heights: in the center of Church, on top of the organ and behind the altar); in the Sael Room; Canal Room and Entrance Room. Issues related to the exchange of air between rooms will also be addressed, using the results of the air exchange rate measurements by the TU/E.

Special attention is given to the impact of specific events involving large group gatherings in the building on indoor climate. An attempt is made to establish the maximum allowable climatic change indoors (based on current literature and practical experience, taking into consideration the type of collection), which information will be used to estimate the maximum dwelling time and maximum group size in the Church. It should be noted here that these estimates are in terms of impact in indoor climate, not on other issues such as wear and tear and visitor appreciation and safety.

In addition an attempt was made to recreate historic indoor climatic conditions in the house, which were modeled using available historic outdoor climate data and the general knowledge of building properties and methods of heating in the past, will be discussed.

Shin Maekawa (GCI), Vincent Beltran (GCI) and Bart Ankersmit (ICN) analyzed the climate data.

Before discussing the indoor climate, a brief history is presented of the heating for human comfort and indoor climate adjustments in this building.

7.2 History of heating in the building

The building is built in such a way that has limited insulation properties. The walls are relatively thin, there are large windows and the roof structure is fairly open. The outdoor climate has therefore an almost immediate affect on the indoor climate. In summer, the sun rapidly heats up the building on the front (SE facing facade) and the roof, and the top floors become quite warm. In winter, without heating, the temperatures would have normally dropped to uncomfortable levels. In the old days, church heating for human comfort occurred with wooden stoves, containing an earthenware container for glowing peat. Peat was stored on the first gallery, behind the altar. Heating in the rest of the house was traditionally with peat, wood or coal fires and stoves.

In 1938 it is recorded that central heating was installed in the building. Where exactly (recorded are 'Regentenzaal', 'bibliotheek' – then Canal Room and 'voorzaal') and what it may have looked like remains unclear. It is mentioned that the generated heat was comfortable throughout the building. [1]
The heating at the bottom of the fixed benches for dignitaries in the church may date back to this period.

Heating at the base of the fixed church benches (photo: TU/E)

From 1953-1960 the museum was restored and the entire building was fitted with central heating. The museum is nowadays heated by means of 2 gas stoves and a central heating system. There are no installation drawings. The gas stoves are located on the ground floor in the antechamber and on the 2nd floor in the Canal Room. Fumes/smoke are extracted by chimneys.

[1] Source:
Blokhuis, Marco (editor) *Vroomheid op de Oudezijds: drie Nicolaaskerken in Amsterdam.* Amsterdam: De Bataafsche Leeuw/Stichting Museum Amstelkring, 1988.

Gas stove in antechamber (photo: TU/E)

Gas stove in Canal Room (photo TU/E)

The following information was extracted from an advisory report by the Technical University of Eindhoven. [2]

The boiler of the central heater (Rehema type Gas 3C, closed system, nominal capacity 138 kW, dating from 1991) is located in the basement of the second house on the Heintje Hoekssteeg. It provides warm water for the radiators in he museum and for the building at nr. 26 (offices and storage spaces).

The boiler (photo TU/E)

The air supply is located in the door of the basement. Smoke/fumes are extracted through chimneys in the building leading to the roof. The basement space has a gas detection system.

The boiler is regulated in an on/off manner, triggered by weather changes. The regulator is fixed in the switchboard cupboard located in the basement. The regulator's settings are [10]:

Correct day temp.	: 0.5 K
Night correction	: 4 K
Stoke line	: outside temp -5°C --> water supply temp 80°C
	outside temp 15°C --> water supply temp 50°C

A temperature sensor is fixed outside to the wall in order to trigger the regulator: a low outside temperature will result in a high temperature of the water in the boiler.

[2] TU/E report (Ing. E. Neuhaus, Dr.ir. H.L. Schellen: M*useum Amstelkring te Amsterdam Adviesrapport binnenklimaat* (March 2006))

A room thermostat is fixed inside the Church (third floor) to the south facing wall, which is set at 23°C. The installation engineer believes that this thermostat is no longer connected to the system. This implies that the boiler is regulated by weather changes only – final adjustments in the building are made locally by means of thermostatic radiator knobs.

A 2nd room-thermostat is fixed near the entrance on the Heintje Hoeksteeg. According to the installation engineer, this thermostat will send a signal to central security when the indoor temperature drops below 16°C. Procedure is that security will then call in the engineer.

7.3 Indoor climate adjustments

At present, moveable humidifiers and dehumidifiers are placed in several locations within the museum to create a more stable indoor relative humidity for the collections (also refer to 7.4.5). Their location is more or less permanent. Only in special instances, such as an exhibition, are they moved. It is unclear when exactly they were introduced, but it is assumed that their acquisition coincided with the Dutch Deltaplan (early 1990's), which made special subsidies available. Their location can be found on the maps in the appendix.

Humidifier and dehumidifier in the Sael. (photo: TU/E)

The following information on the equipment was extracted from an advisory report by the Technical University of Eindhoven. [3]

The humidifiers (Defensor P14, cold evaporation type) are equipped with active carbon filters that filter the air and remove pollutants. Their setting is 50% RH. Their capacity is set in winter at level III and in summer at level I.

Capacity levels	I	II	III
Humidification capacity [l/h]	0.5	0.7	0.9
Air movement [m^3/h]	180	280	360

Water reservoir 2 x 10 liters
Energy max. 55 W

Some of the reservoirs of the humidifiers were punctured and on a few occasions some water is spilled when refilling the humidifiers. They are refilled approximately 3 times per week for 9 months of the year.

The dehumidifiers are set at 50%; they are of the cooling dehumidifier type.

Details at room condition	10°C/80%	20°C/80%
Dehumidification capacity [l/h]	0.125	0.250
Energy usage [W/h]	275	330

Water reservoir 8 liters

In the summer of 2006, which was the hottest on record, mobile fans were placed throughout the building to increase ventilation and create a cooling sensation for the public. Visitors were also given a personal paper fan.

[3] Sources:
Museum Amstelkring advisory report TU/E concept March 2006.

7.4 Analysis of the current indoor climate

7.4.1 Canal Room

The Canal Room is located on the second floor of the building, between the reception on the ground floor and the church on the 3rd floor (refer to floor plan in the Appendix). It has only one entrance on the northwest side of the room. The four half-height windows facing the canal are oriented southeast, which receive full morning sun. It has a 27.6 m^2 floor area and a ceiling at 2.9 m (volume of 80 m^3). A small alcove (approximately 1,8 x 1 x 1,3 m) with a cupboard or box bed is located in the northwest wall. The room was recently restored and the walls are now covered with textiles. Both ceiling and floor are made from wood.

The Canal Room (photos: ICN)

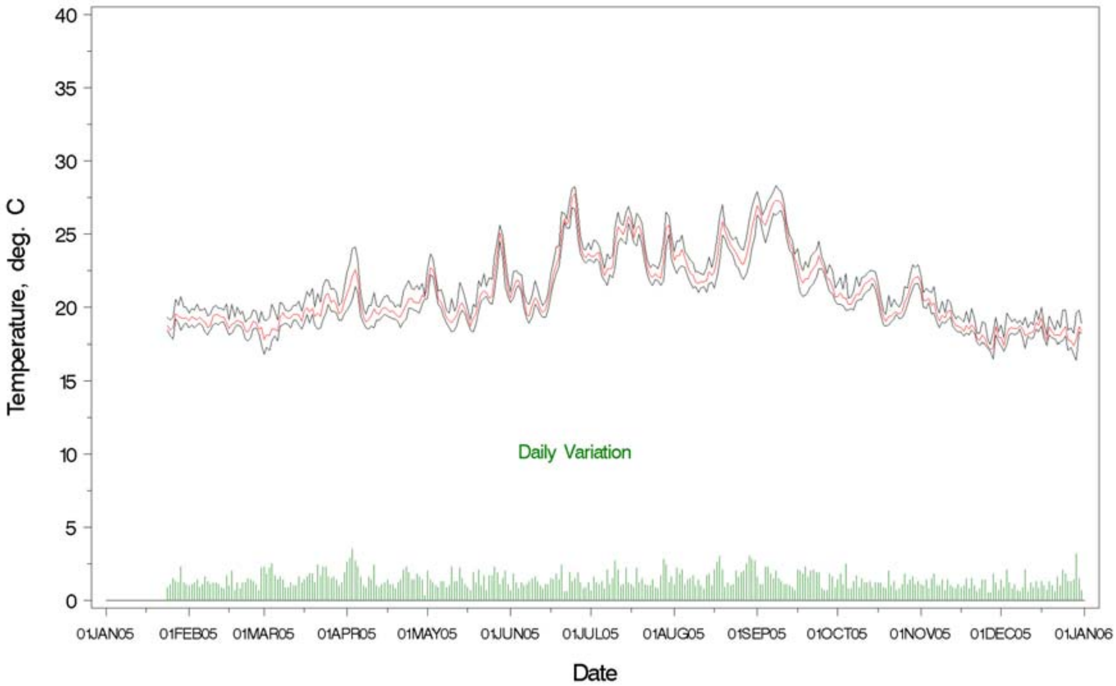
The Canal Room is a historic interior with a few objects: several paintings (on canvas and on panel), several pieces of furniture (including a painted cabinet), a ceramic vase and some metallic lamps. The cupboard bed is made up with bed linens.

Visitors have access to this room - normal visitation levels are less than 5 people, with high extremes of 15-20 visitors in the room at any one time. The room has a thermostatically controlled gas heater on the northeast wall, which is believed to be set at 20 ^{o}C during the winter. It is unclear if the windows are ever used for ventilation. It is expected that both floor and ceiling allow some air movement through the planks.
The curtains are replicas and have mainly a decorative function.
There is no local (de)humidifier present in this room.

The RH/T sensor was placed inside the alcove above the bed on a 1,8 m height from the floor of the room.

Annual Variation Statistics Variable	Canal Room T (°C)	Canal Room RH (%)	Canal Room W[4] (g/kg)
Mean	20.84	49.55	7.75
Maximum	28.30	75.20	15.99
Minimum	15.30	29.30	3.61
Standard deviation[5]	2.47	6.95	2.04

Daily Variation Statistics Variable	Canal Room T (°C)	Canal Room RH (%)
Mean	1.39	7.00
Maximum	3.50	20.80
Minimum	0.20	1.10
Standard deviation	0.55	3.09



The minimum, maximum and average of daily temperature and relative humidity in 2005 in the Canal Room. The green lines present the daily variation.

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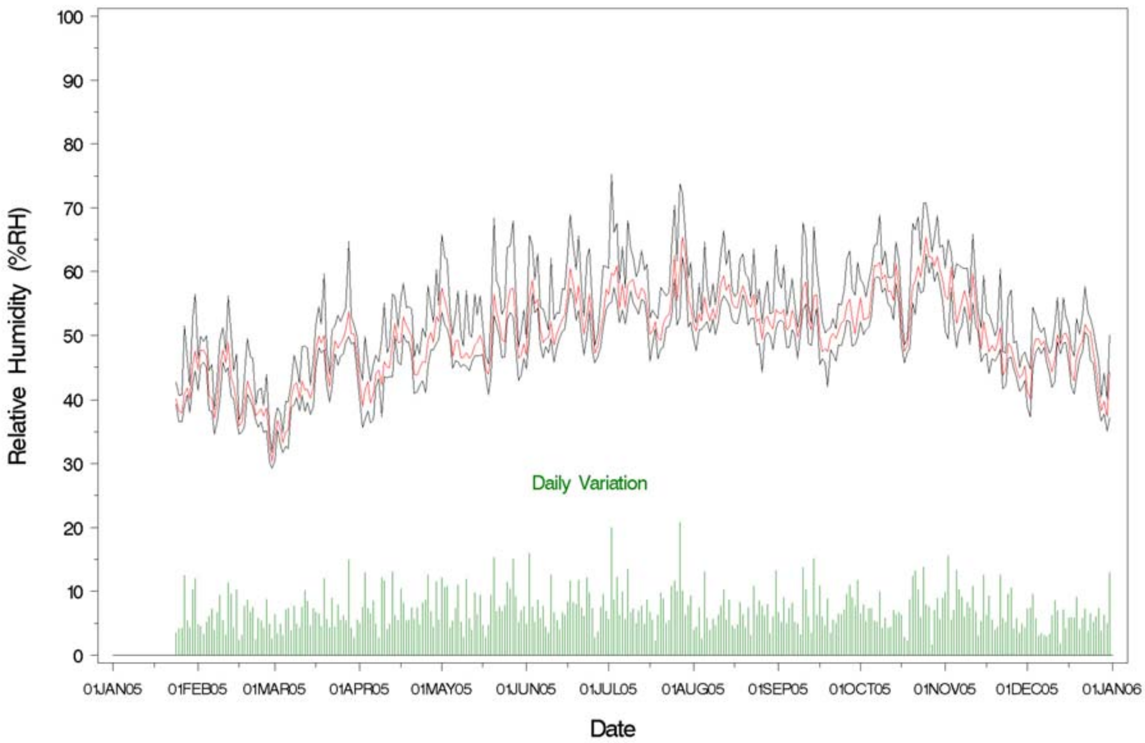
[4] W = humidity ratio (gram of water per kg of air).

[5] Standard deviation: A statistic that indicates the amount of variability in a group of scores. When scores are normally distributed (i.e., when they are part of a bell-shaped, "normal" curve), about two-thirds of the scores (i.e. 68%) are within one SD above and below the average (mean) score, and about 95% of scores are within 2 SDs of the mean. In almost any shaped distribution, all scores will be within 5 SDs of the mean score.

Annual Temperature

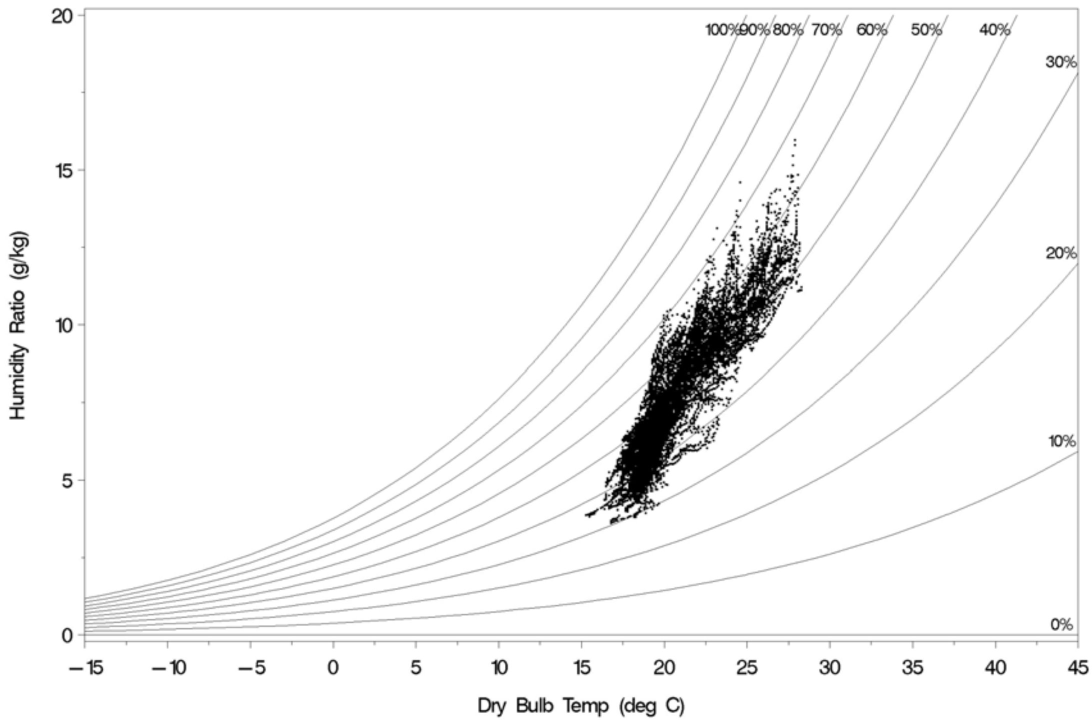
Temperature varies from 15.3 °C on the 23rd January to 28.3 °C on the 8th of September. Temperature is more stable during the winter (November to April), with a typical daily fluctuation of about 2 °C. From spring to fall daily fluctuations remain the same, however temperature varies from day to day (with a maximum of 5 °C).



The minimum, maximum and average of daily relative humidity in 2005 in Canal Room. The green lines present the daily variation.

Annual Relative Humidity

Over the year the room is dry in winter and humid in summer, with the RH ranging from 29.3% on the 28th of February to 75.2% on the 2nd of July. Therefore a typical annual RH cycle of 45% is expected. Daily fluctuations vary from day to day between 3% and 20%. Three levels of fluctuations can be distinguished: 3-5% as a lower limit on many days, approximately 10% on regular basis and approximately 20% fluctuations on two occasions during summer.

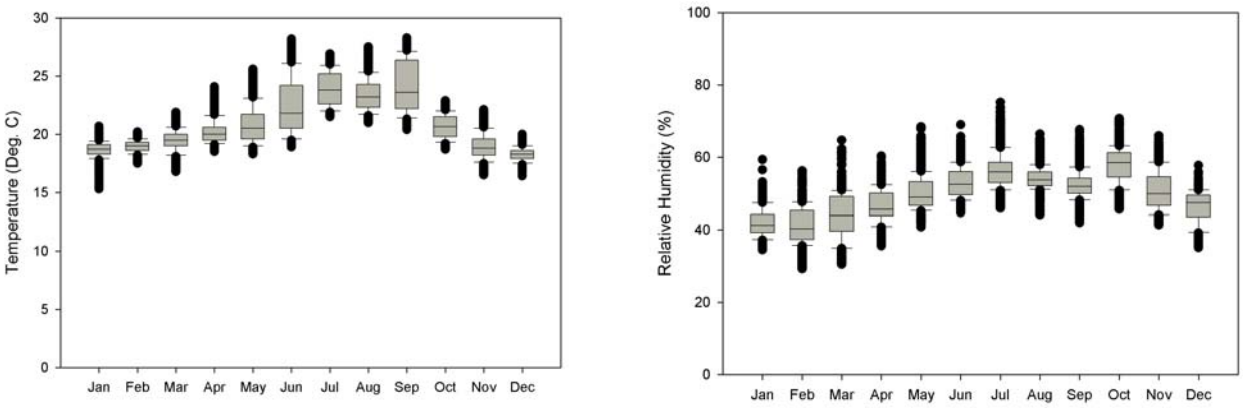


Canal Room climate data (2005) in psychometric chart

The psychometric chart shows the annual distribution of temperature, RH and humidity ratio in the canal Room. It can be readily seen that the humidity ratio varies, both in the low end of the temperature range (winter) as in summer.

Seasonal Temperature

From the box plots[6] it can be seen that the monthly average values range from 18 °C in December to 24 °C in July. Winter fluctuations are relatively small (typically 5 °C), possibly due to thermostatically controlled heating. During the summer variations are larger and range from 7 to 10 °C. In the month of June the largest variation of approximately 10 °C is observed. The temperature variations during summer are due to direct impact of the outdoor climate, including solar radiation.



Box plots of temperature (left) and relative humidity (right) in Canal Room (2005)

Seasonal RH

From the box plot it can also be seen that the monthly average values range from 40% in February to 58% in October. A striking aspect of the data within the 80% limit of the box plot is the similarity of the monthly RH variations throughout the year; between 25% and 32%. The exception being March where the heating system malfunctioned causing a higher variation. July shows a somewhat larger spread of outliers. During this month the temperature variation is relatively small. The spread of RH outliers is caused by the fluctuation of the humidity ratio outdoors.

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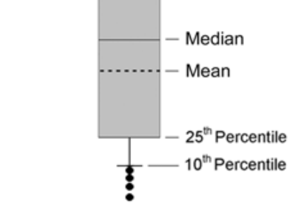
6 In the box plot the average value and the spread of data is presented. This spread is given as the % of data that fall within a certain T or RH range (y-axis). The grey box presents 50% of the data that fall within the given T or RH range, or 25% above and 25% under the median value. The dotted line presents 80% of data (40% above and 40% underneath the average). The data that are positioned outside the dotted line represent 20% of the data (10% above and 10% to low).



7.4.2 The Sael

The Sael is located in the middle of the building on the first floor, in between an office on the ground and the Church on the 3rd floor (refer to floor plan in the Appendix). It has only one entrance on the southeast side of the room. On floor level, the room is adjacent to a hallway on the southeast side (leading to the Canal Room) and on the northwest to a room used for temporary exhibitions. The room has a 35 m^2 floor and a ceiling at 5.4 m. Above the 3 m level from the floor, the southeast wall is connected to the chaplain's room (on 2nd floor) and the northwest wall to another room used for temporary exhibitions. Large windows facing the alley are oriented northeast. Opposite to the entrance is a large fireplace. The floor is of marble and the ceiling of painted wooden panels. The brick walls are covered with the original plaster.
The Sael is a historic interior with a number of paintings (mostly on canvas), several pieces of furniture (one built-in cupboard with authentic 18th Century wooden doors) and several metal objects.


The Sael and the wooden ceiling (showing a crack in the lower panel) (photo: ICN)

The Sael is part of the normal visitation route. The normal visitor occupation of the room is less than 5, with high extremes of 15-20 visitors in the room at one time. The room has a thermostatically controlled radiator under the windows, which is believed to be set at 20 °C in the winter months. A portable humidifier (type Defensor P14) and dehumidifier (Trion) are placed next to the fireplace on the northern corner of the room. The humidifier and dehumidifier are set to 50%. The windows are opened twice a day, in the morning to open the wooden shutters on the outside and in the afternoon to close them.

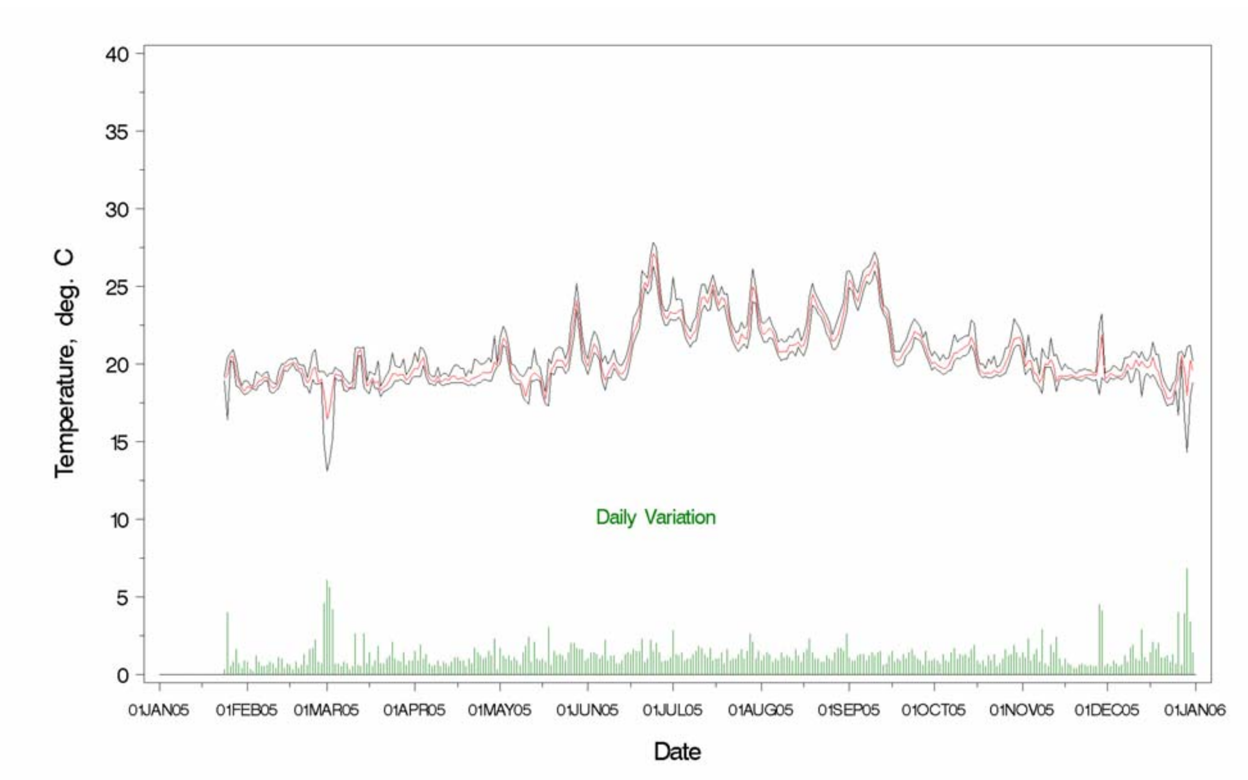
The RH/T sensor was placed next to the windows, on top of the doorframe of the wardrobe, in the east corner of the room on a height of approximately 2 m.

Annual Value Statistics			
Variable	Sael T (oC)	Sael RH (%)	Sael W (g/kg)
Mean	20.50	49.65	7.58
Maximum	27.80	69.80	14.35
Minimum	13.10	28.30	3.53
Standard deviation	2.02	8.12	1.97

Daily Variation Statistics		
Variable	Sael T (oC)	Sael RH (%)
Mean	1.27	6.46
Maximum	6.80	16.80
Minimum	0.20	1.20
Standard deviation	0.88	2.56

Annual Temperature

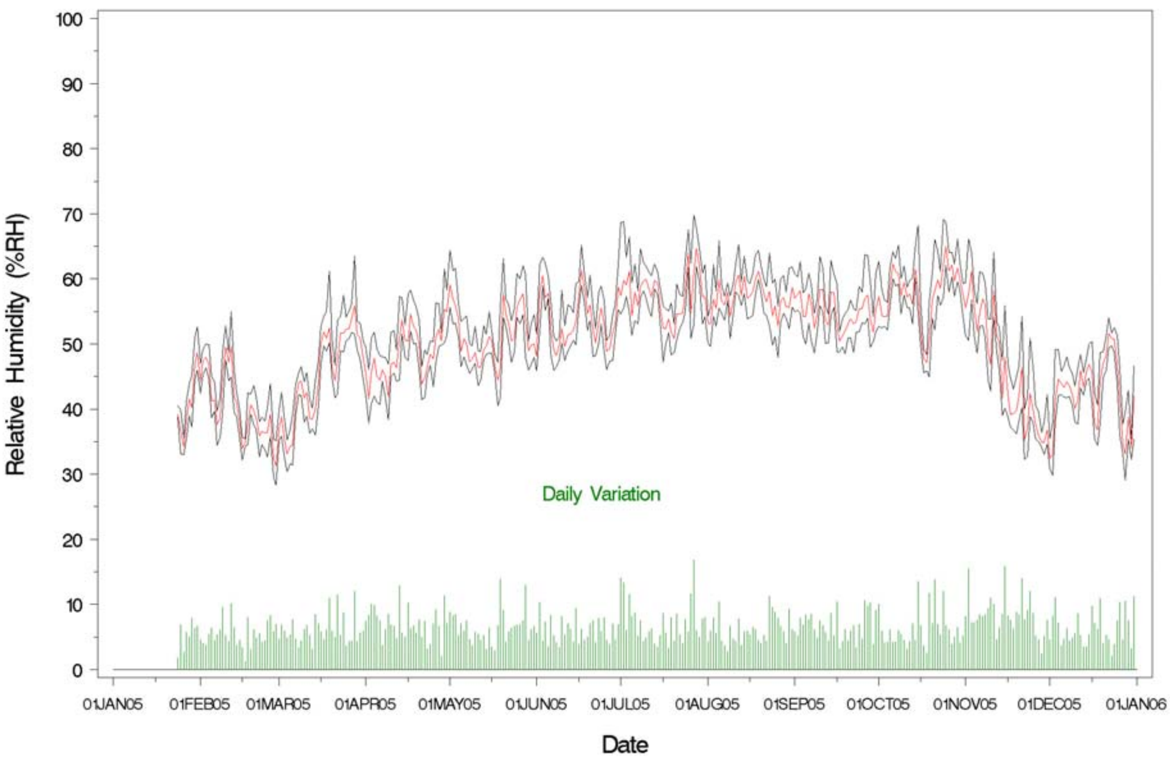
The annual average of the temperature was 20.5 oC with a standard deviation of 2.0 oC. It ranged from 13.1 oC at 8 am on March 1 to 27.8 oC at 3 pm, June 24, 2005 and remained very stable in winter (November to May) at approximately 18 oC, except for a few irregular events. However, it increased to upper 20's during spring and summer months. Majority of daily fluctuations remained between 0.2 and 2.5 oC throughout the year, with an average of 1.27 oC. Larger daily fluctuations ranging from 4 to 6.8 oC were only recorded in winter months. These may be related to malfunctioning of the heating system.



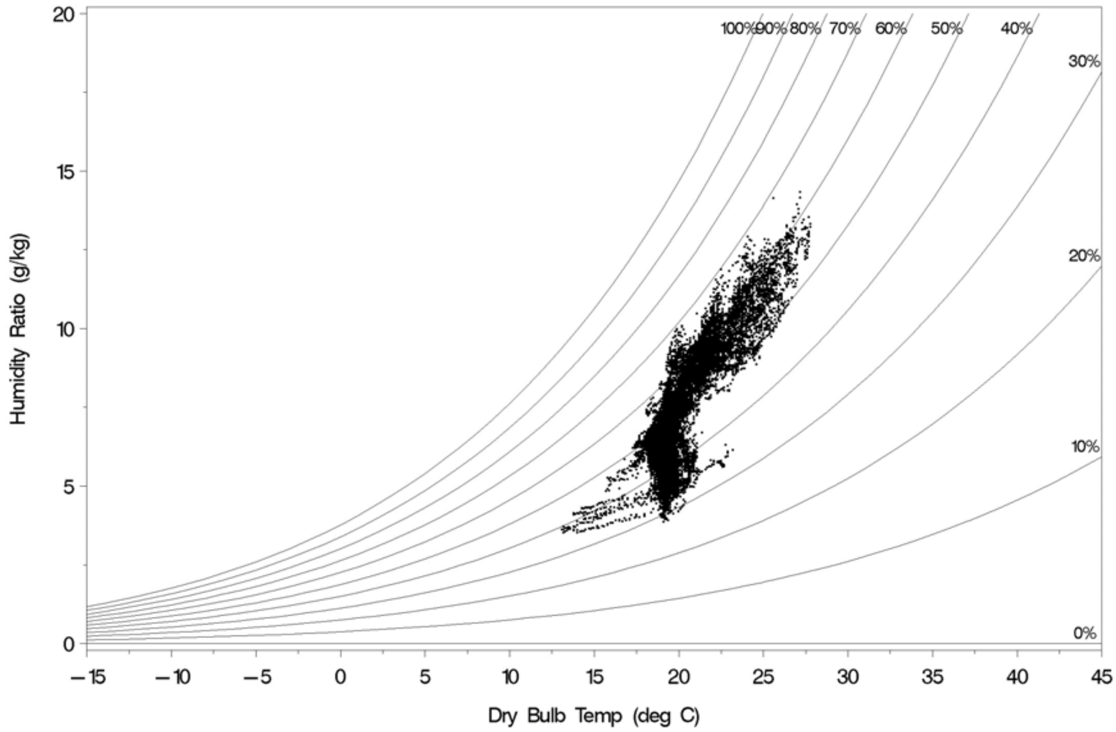
The minimum, maximum and average of daily temperature in 2005 in the Sael. The green lines present the daily variation.

Annual Relative Humidity

The annual average of the relative humidity was 50% RH, with a standard deviation of 8.1%. The maximum relative humidity of 70% was recorded at 3: 30 pm, July 27, and the minimum of 28% was logged at 9 am, February 27, 2005. Over the year a mean daily fluctuation of 6% RH is calculated. During summer, the relative humidity in the Sael remained between 45% and 70% with most of the daily fluctuations at less than 10%. However, when analyzing day-to-day fluctuations, values of 5-17% can be observed. Relative humidity started to drop early November and reached 40-50% by the end of the month and remained at that level throughout the winter.



The minimum, maximum and average of relative humidity in 2005 in the Sael. The green lines present the daily variation.

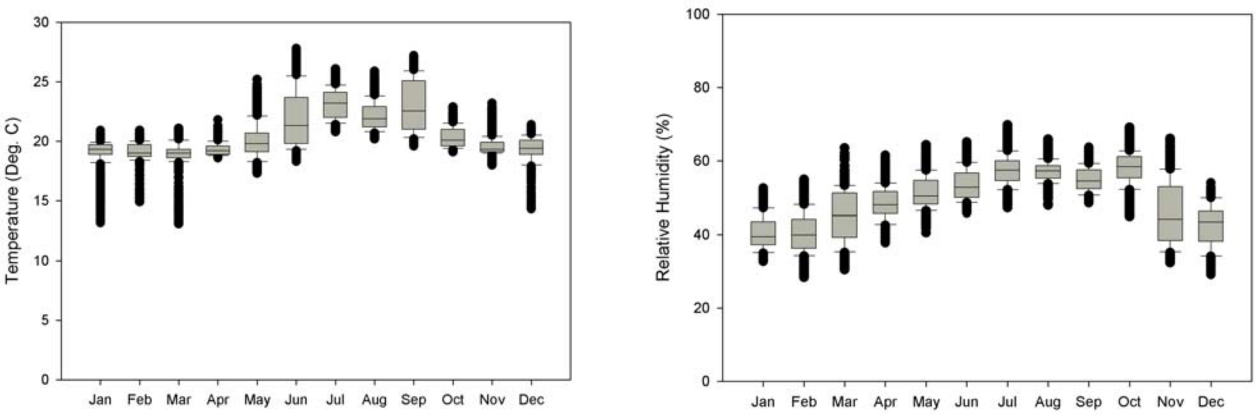


Sael climate data (2005) in psychometric chart

Failing of the central heating can directly be seen in the psychometric chart as a row of points, with a fixed humidity ratio, but decreasing temperature.

Seasonal Temperature

From the box plots on the next page it can be seen that the monthly average values range from 19 °C in March to 23 °C in July. Winter fluctuations are relatively small (typically 2-3 °C), most likely because of thermostatically controlled heating. It should be noted, that especially in winter large extremes appear only on the low end extreme. These can most likely be attributed to a failing heating system. During the summer, temperature variations that fall within the ± 40% around the mean are larger and range from 19 to 25 °C. In the month of June, the largest variation of approximately 6 °C is observed. The temperature variations during summer are most likely due to direct impact of the outdoor climate and not due to solar radiation.



Box plot of temperature (left) and relative humidity (right) in Sael (2005)

Seasonal RH

From the box plots it can also be seen that the monthly average values range from 40% in December to 58% in July and October. The majority of the months within the ± 25% around the mean limit are between 5% and 10%. The exceptions are March, November and December when a higher RH variation, of 10 to 15% is observed. The largest spread in the data is observed in November. This may be related to the activation of the heating system in late November.

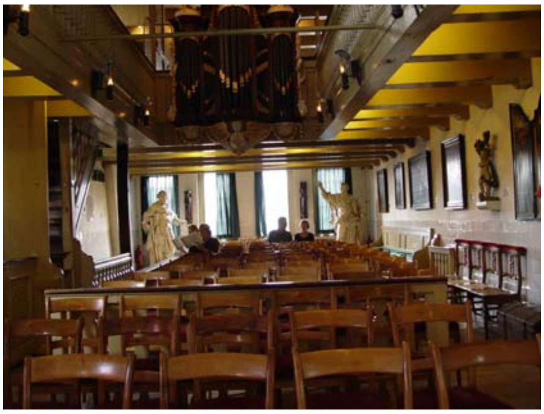
7.4.3 Church

The Church is located in the middle of the building and expands over several floors (from the 3rd till the 5th floor – refer to floor plans). The church has 2 galleries, which extend over the northeast, southeast and southwest walls. The largest part (south end) of the southeast wall is adjacent to another building, the wall facing northeast is adjacent to the alley. The church has a floor surface of approximately 150 m^2 and a height of approximately 9 m (internal volume of 1350 m^3). The altar is located on the northwest side of the church, opposite the organ (on the 1st gallery, southeast end).

The brick walls are plastered. The floor and galleries are constructed from wood. The painted wooden and plastered ceiling has an opening (diameter 0.55 m) leading to the attic above. The 'Lamp of God' is hung from this opening.

There are several entrances (exits) into the Church: one entrance on the northeast and two on either side of the altar on the northwest side of the room.

A variety of objects, such as paintings (both on canvas and on panel) and wooden sculptures (many are polychrome), are on open display. Some (precious) metal objects are exhibited in showcases.[1] The most valuable object, in terms of cultural value, is a painted wooden Maria sculpture (just behind the altar, in a separate room referred to as the Lady or Mary Chapel), which is thought to have been in the Church since its beginning.

The Church (photos: ICN)

[1] Exact amount of objects in 2005: 9 paintings on canvas, 15 paintings on panel, 5 wooden sculptures, 17 painted wooden sculptures, 25 pieces of furniture, 5 textiles, 4 ceramics, 1 book, 39 metal objects and 3 variables.

The regular occupation of the church is less than 10, with high extremes of 20–40 visitors in the room at any one time during normal museum visitation. The Church (including the galleries) can nowadays seat 87 people and is used for weddings and christenings (approximately 30 times a year), Sunday mass (every 1st Sunday of each month, for part of the year, attended by approximately 50 people), special mass (e.g. Christmas), concerts and other events (e.g. Sinterklaas). On occasion, there are about 100 people present in the Church.

The Church has thermostatically controlled radiators, placed:

- Underneath the windows on the southeast end,
- Underneath the benches on the main floor at both sides of the room (radiators are heating tubes) – no longer in function and possibly dating back to 1938,
- On the first gallery on the northeast side,
- On the first gallery under the window on the southwest side,
- On the first floor behind the altar underneath the windows on southeast side,
- On the second gallery, tubes at floor level on both the northeast and southwest side.

The thermostat is believed to be set at 20 °C in winter. A total of 8 portable humidifiers (type Defensor P14) are placed in the Church. On the main floor of the Church, 2 humidifiers are located on the southeast end of the building; on the first gallery 2 are located on both sides of the organ and 2 on the far northwest side; on the second gallery 2 humidifiers are placed in the middle of the room. The humidifiers are set to maintain 50%.

The windows in the Church are always closed. The southeast windows, which capture direct sunlight, can be blocked with curtains. The windows near the altar and the Lady Chapel have roller blinds. Staff from Technical Services opens and closes these when appropriate.

It is expected that both floor and ceiling allow some air movement through the planks.

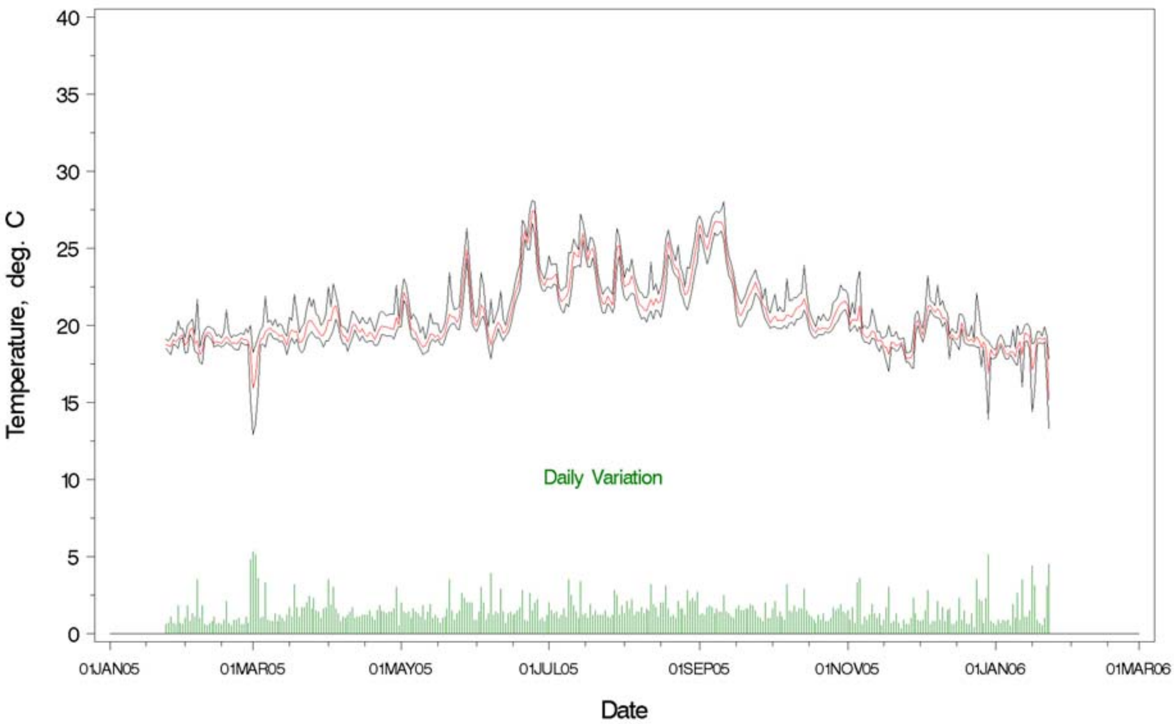
Of the five sensors in Church, only the data from the sensor on the organ is discussed in detail, because of the similarity of the data. Difference among other sensors will be discussed in the 'Church climate stratification' section.

Annual Value Statistics Variable	Church organ (°C)	Church organ RH (%)	Church organ W (g/kg)
Mean	20.7	52	7.96
Maximum	28.1	72	16.11
Minimum	12.9	34	4.24
Standard deviation	2.2	5.2	1.70

Daily Variation Statistics Variable	Church organ (°C)	Church organ RH (%)
Mean	1.5	5
Maximum	5.3	16
Minimum	0.3	1.2
Standard deviation	0.8	2.4

Annual Temperature

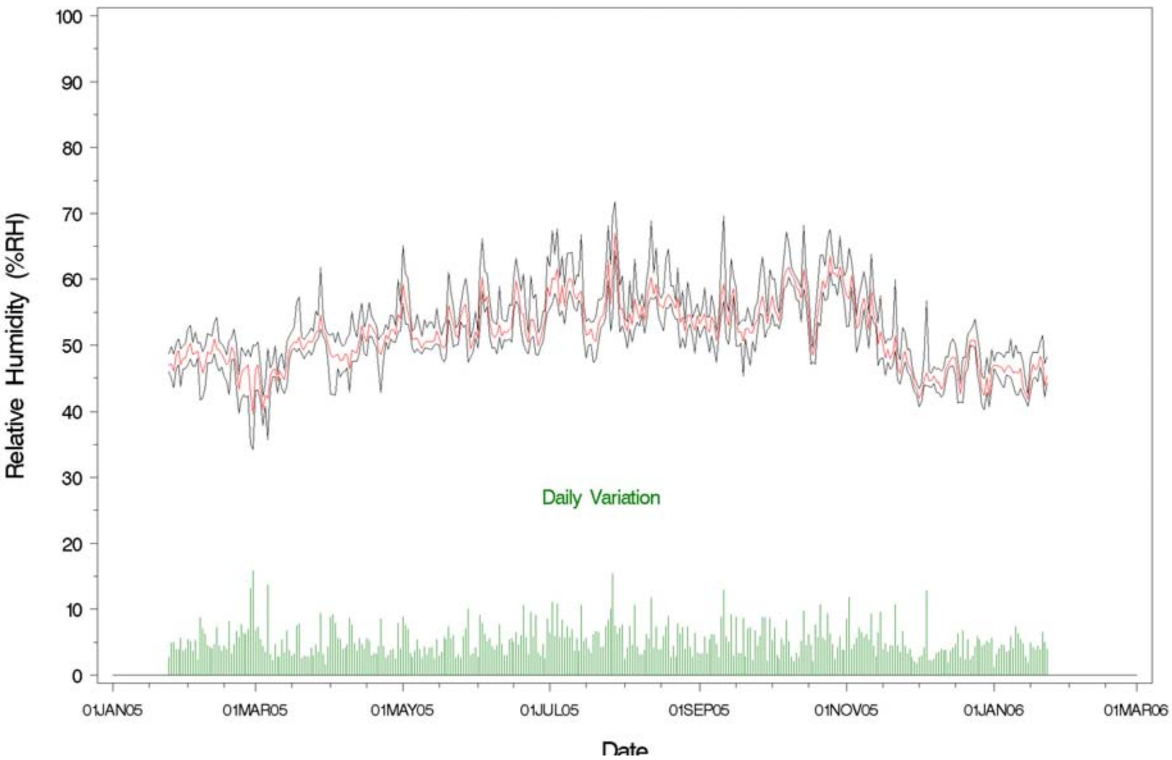
The annual average of the temperature was 20.7 °C with a standard deviation of 2.2 °C. It ranged from 12.9 °C at 8 to 8:30 am on March 1 to 28.1 °C from 15:30 to 21:00 pm, June 24, 2005 and remained very stable in winter (November to May) at approximately 19 °C, except for a few irregular events. However, it increased to the upper 20's during spring and summer months, with larger week-to-week fluctuations. The majority of these daily fluctuations remained between 0.3 and 2 °C throughout the year, with an average of 1.5 °C. Larger daily fluctuations ranging up to 5 °C were only recorded in winter months. These may be related to malfunctioning of the heating system.



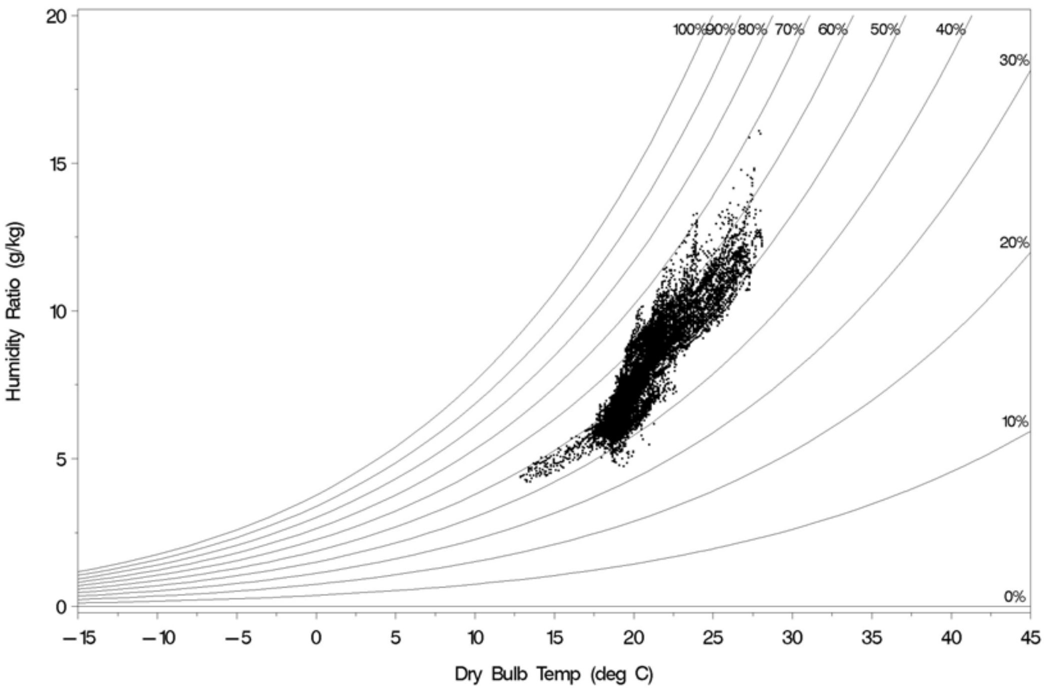
The minimum, maximum and average of daily temperature in 2005 in the Church. The green lines present the daily variation.

Annual Relative Humidity

The annual average of the relative humidity was 52% RH, with a standard deviation of 5.2%. The maximum relative humidity of 72% was recorded at 3 pm, July 28, and the minimum of 34% was logged at 9:30 am, February 28, 2005. Over the year a mean daily fluctuation of 5% RH was calculated. During summer, relative humidity in Church remained mainly between 50 and 65% with most of daily fluctuations approximately 5%. However, if day-to-day fluctuations are analyzed, a slight increase to 7% can be observed, with peaks up to 16%. Relative humidity started to drop early November to reach 40-50% by the end of the month and remained at that level throughout the winter.



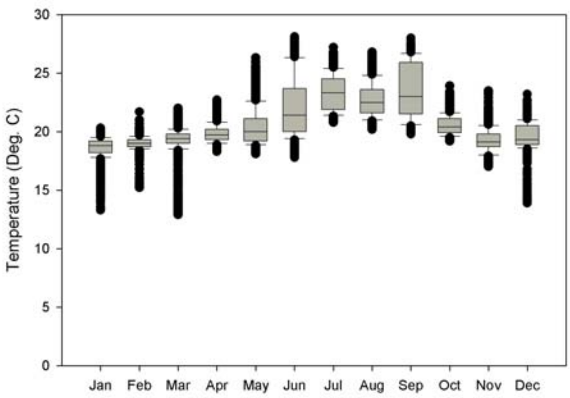
The minimum, maximum and average of daily relative humidity in 2005 in the Church. The green lines present the daily variation.

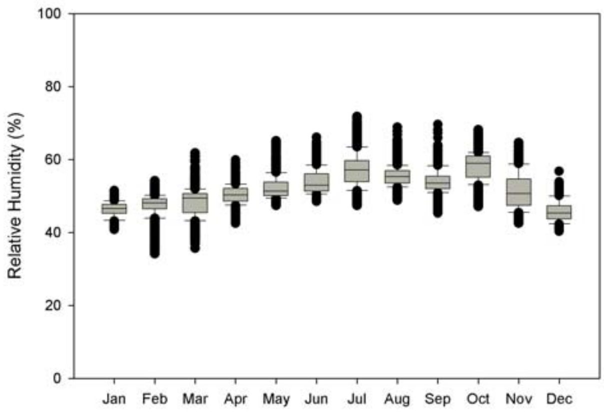


Church climate data (2005) in psychometric chart

Seasonal Temperature

From the box plots it can be seen that the monthly average values range from 19 °C in January to 23 °C in July. Winter fluctuations are surprisingly small (typically 1 °C), most likely because of thermostatically controlled heating. It should be noted however, that especially in winter, large outliers appear only on the low end extreme. These can most likely be attributed to failure of the heating system. During the summer temperature variations that fall within the ± 40% around the mean are larger and range from 19 to 26 °C. In the month of June the largest variation (± 40% around the mean) of approximately 7 °C is observed. The temperature variations during summer are most likely due to direct impact of the outdoor climate and solar radiation.





Box plot of temperature (left) and relative humidity (right) in Church (2005)

Seasonal RH
From the box plots it can also be seen that the monthly average values are small and range from 45% in December to 59% in October. The monthly fluctuations within the ±40% around the mean limit are between 5% and 12%. The largest spread in the data is observed in March. This is related to malfunctioning of the heating system in the first 3 days of March. September also shows a relatively large spread of data of nearly 30%, this is most likely a result of very high visitor numbers (1064 people) during the so-called 'open monument-day'.

7.4.4 Church climate stratification

The Church is the most important space in the museum and the one most used for events. Masses and weddings often involve large groups sitting in Church longer than museum visitors would do. During some of these events, especially in summer, visitors are exposed to an indoor climate that is not optimal for human comfort: there is limited fresh air (CO_2 levels increase) and temperature and relative humidity rise.

To get a better understanding of the specific issues related to the indoor climate in Church, four RH/T sensors were placed on different locations: in the center underneath the 'Lamp of God' at different heights (3, 6 and 8 meters from floor level) and on top of the organ. This allowed for vertical stratification and horizontal differences to be analyzed.

The following table shows the yearly and daily variation statistics for the sensors. From these data it can be seen that there is hardly any difference between the low and high statistical data.

Yearly Variation Statistics									
	T_{low}	RH_{low}	W_{low}	T_{middle}	RH_{middle}	W_{middle}	T_{high}	RH_{high}	W_{high}
Mean	20.0	53.7	8.0	20.1	53.2	7.9	20.3	52.5	7.9
Max	28.6	71.5	16.4	28.5	78.6	16.6	28.5	74.5	16.3
Min	11.8	39.8	4.3	12.0	38.8	4.2	12.0	38.8	4.2
SD	2.3	4.9	1.7	2.3	5.3	1.8	2.2	5.3	1.7

Daily Variation Statistics						
	T_{low}	RH_{low}	T_{middle}	RH_{middle}	T_{high}	RH_{high}
Mean	1.9	5.2	1.8	4.9	1.7	4.9
Max	6.2	14.1	5.5	13.8	5.8	13.0
Min	0.5	1.5	0.4	1.4	0.5	1.4
SD	1.0	2.4	0.8	2.3	0.8	2.3

Annual and daily extremes in Church at three different heights: low= 3 m, middle= 6 m and high= 8 m from floor level.

The temperature difference between the sensors underneath the 'Lamp of God' was never larger than 2.3 °C, with an average of 0.4 °C. Temperature differences are slightly larger in winter, when the Church is heated. It was expected that reductions of relative humidity with height would correspond to these temperature variations. However, humidity ratios were virtually identical at all three heights. The largest RH difference was 9%, with an average of 1%.

Comparing the data in this table with data collected near the organ reveals that the statistical data are more or less the same, indicating that the air in church is well mixed. This mixing of air was expected since the Church is in direct open contact with two open staircases leading to higher and lower floor levels. Above the ' Lamp of God' there is an opening in the ceiling with a diameter of 0.55 m. All these openings to other locations and indirectly to the outside, will allow the exchange of air in Church. This air exchange has been measured by the TU/e using tracer gas (SF_6) technique.

Air exchange rate[2] in the Church was measured in three different situations. The first measurement was performed on a cold day on March 13th 2006. Second and third measurements were performed on a warm day, September 29th 2006. During the first and second measurement all windows of the church remained closed. During the third measurement one window high in the church was opened.

The results indicate the different air exchange rates of the Church:

- On a cold day with all the windows closed: 2.3 h^{-1}.
- On a hot day with all the windows closed: 4.5 h^{-1}.
- On a hot day with one window open: 5.9 h^{-1}.

The difference of air exchange rates under cold and hot conditions might be explained by temperature differences and air flows (stack pressure) through the building when both the front door and a window are open. During winter the entrance at the reception will only be open shortly when visitors enter or leave the building. During summer however, the entrance door is open throughout the day. The reception is, through the front staircase, in connection with the Church.

[2] The rate at which outside air replaces indoor air in a space. Expressed in one of two ways: the number of changes of outside air per unit of time air changes per hour (ACH); or the rate at which a volume of outside air enters per unit of time – cubic feet per minute (cfm).

The ‘ Lamp of God’ seen from the Church and from the attic

7.4.5 Use of humidifiers and dehumidifiers

At present, moveable humidifiers and dehumidifiers are placed in several locations within the museum to create a more stable indoor relative humidity for the collections (refer to 7.3). During the monitored period, humidifiers and dehumidifiers were set to maintain a 50% RH environment by respectively adding or removing moisture from the air.

A data set (April 12, 2005 – June 29, 2006) was reviewed of the recorded amounts of water supplied to the humidifiers and removed from the dehumidifiers. With large amounts of water added to (therefore, released from) the humidifiers during winter months (especially December to April) the relative humidity in the building was kept between 40 and 55% (and the majority of the time between 45 and 50%) when a stable temperature of approximately 20°C was maintained.

Typically active climate control devices will have difficulties in controlling the relative humidity when temperature drops below 15°C. With less accurate humidistat switches used in this type of equipments, the controllable low temperature limit may be even higher. This may explain the large variations of the relative humidity recorded in the building during intermittent failure of the heating system in the winter months.

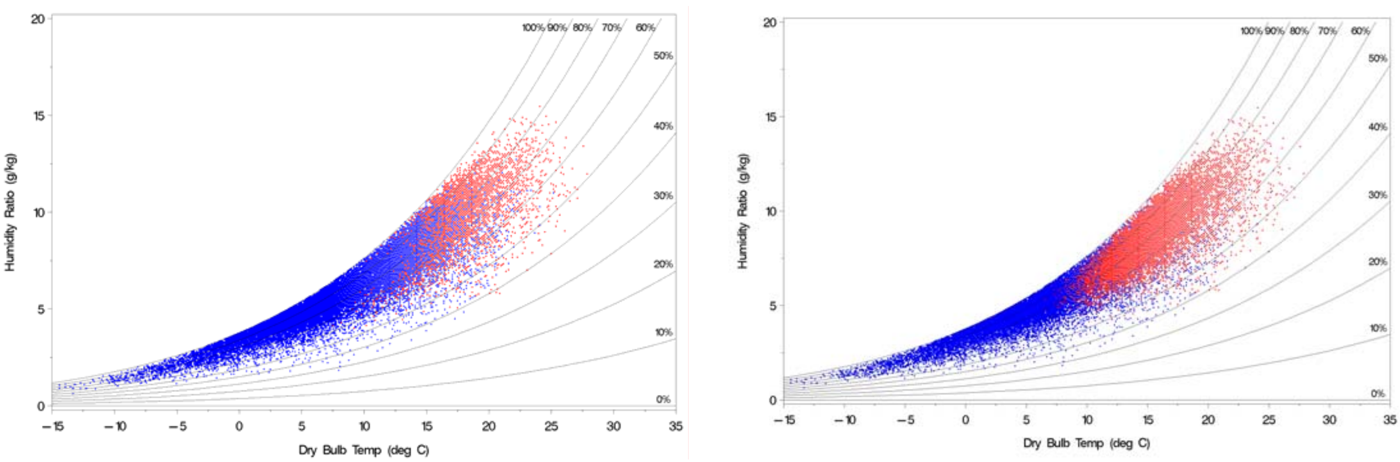
The relative humidity often exceeded 60% in the building during summer months, although daily average values remained less than 60% during the majority of the events. Therefore, it was determined that these exceeded values were caused by large visitations. Large amounts of humid air infiltrated the building during hot and rainy days as a result of large numbers of visitors entering and exiting from the building. The available dehumidification capacity was not adequate to control the environment under these circumstances. However, in general, the capacity id enough to control the relative humidity in a closed building. Therefore, utilizing additional dehumidification devices during visiting hours can effectively eliminate relative humidity peaks.

7.5 Reconstruction of historic indoor climate conditions

The current condition of the objects in ‘Our Lord in the Attic’ is related to the climate these objects have been exposed to. Some of the damage currently observed in objects that can be attributed to an incorrect indoor climate may not just be caused by the climate of the recent past – the timeframe in which damage occurs depends on the preservation history of the objects. Assuming objects have never been restored or conserved, visible damage is a result of the exposure to all climatic conditions from the time the object was created up to the present, and may well include damage caused by incorrect climatic conditions of its previous environment(s) or original location (which for many objects was a different building). This section describes the reconstruction of the historic indoor climate conditions in the 20th century.

7.5.1 Historic outdoor climate conditions

The historic indoor climate was modeled using existing historic data of outdoor climatic conditions in the Netherlands. 20th Century data was downloaded from the KNMI website.[1] The daily average temperature and humidity data were derived from existing data for De Bilt (just outside the city of Utrecht) for the period 1901-1950 and Schiphol (Amsterdam airport) for the period 1951-2000. It is assumed that the climatic conditions in Amsterdam were similar to Utrecht and Schiphol, since they are only 45 and 15 km apart respectively. The relative humidity is almost always higher than 60% and temperatures vary from -10 to 25 °C.

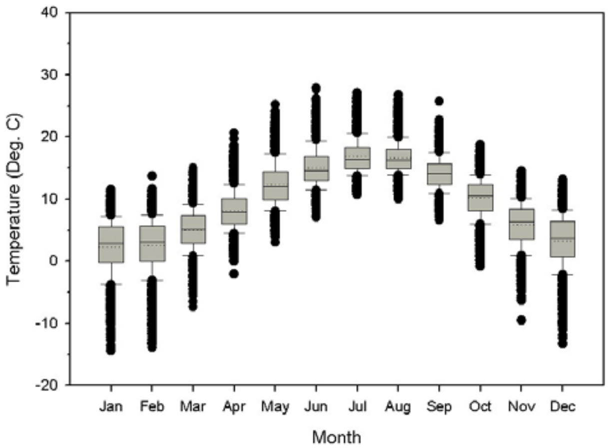


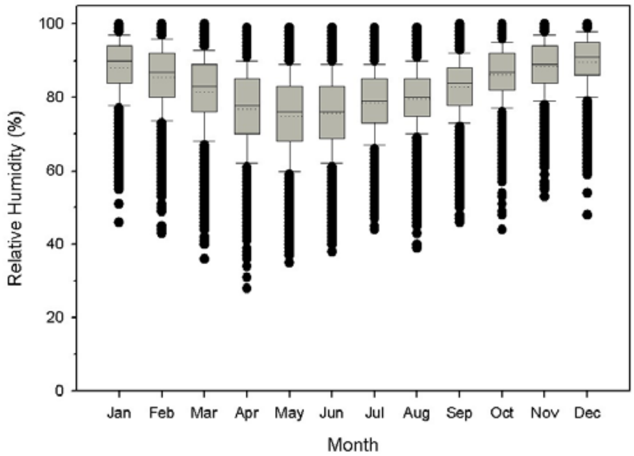
Psychometric data of the outdoor climate in the Netherlands in the 20th Century.
Data points in blue represent October-May and the red data June-September. As there is overlap between summer and winter-designated points and in order to enhance visually distinction between the 2 seasons, the figure on the left shows winter points atop those of summer and the figure on the right summer points atop those of winter.

[1] http://www.knmi.nl/klimatologie/

Average seasonal changes of temperature and relative humidity

From the box plots below it can be seen that the monthly average outdoor temperature values over the 20th century range from 2 ^{o}C in January to 16 ^{o}C in July. The data within the 80% limit of the box plot are more or less similar throughout the year, with a slightly larger spread in winter.





Box plots of temperature and relative humidity of monthly values over 1901-2000

The monthly average outdoor RH values range from 75% in May and June to 90% in December and January. An interesting aspect of the data within the 80% limit of the box plot is that the monthly RH variations in winter (i.e. October through February) are smaller (between 75% and 95%) then the variations observed in summer (between 60% and 90% in April through September).

In order to estimate the most extreme indoor climate conditions, the most extreme situations outdoors, i.e. coldest winter, hottest summer, most humid summer and driest winter that occurred in this century were identified. The coldest winter occurred in 1963, the hottest summer in 1947, 1965 was the most humid summer, and 1964 turned out to be the driest winter.

	Coldest winter (1963)		Hottest summer (1947)		Most humid summer (1965)		Driest winter (1964)	
	Temp January	Temp February	Temp July	Temp August	RH July	RH August	RH February	RH March
Max	1.3	1.3	24.6	26.1	97,0	94	93.0	95.0
Mean	-5.0	-5.0	18.8	19.8	82,5	79.3	82.3	78.9
Min	-10.2	-10.2	12.2	15.5	69,0	67.0	62.0	59.0
SD	3.60	3.60	3.50	2.59	5,50	5.91	8.26	11.77

Average (mean), maximum, minimum and standard deviation (SD) of the most extreme seasons: coldest winter, hottest summer, most humid summer and driest winter.

From this table it can be seen that the average lowest outdoor mean temperature was -5 ºC and that it was not dryer than approximately 80% RH. The hottest months had an average temperature just below 20 ºC with an RH of around 80% for prolonged periods of time. These average values were used to establish the historic indoor climate in museum 'Our Lord in the Attic'.

Before the indoor temperature and relative humidity was estimated, several relevant parameters had to be defined.

- How much air leaked into or out of the building?
  The current air exchange rates of the building was measured by TU/E (refer to 7.4.4) and it is assumed that these were similar in the past; the air exchange rate in winter would have been lower than in summer, when windows were opened for human comfort. For this reconstruction, the air exchange rate is estimated in winter to have been around 1 to 1.5 air exchanges per hour, while during summer it would have increased to 2 to 3 times per hour.

- What was the temperature of the air inside the building in winter and summer?
  The building would have heated up during summer by the radiation of the sun. The outside air that entered the building would have also been heated to a certain extend. Measurements from the summer of 2005 show that indoor air temperatures never dropped below 17.5 ºC. In winter, the building was (or some rooms were) heated to provide human comfort. The heating systems changed over the years:
  1661 - 1953: local heating by fireplaces and stoves
  1953 - 1990: central heating

- Were there any sources (such as sinks) of moisture in the building that might have influenced the humidity ratio indoors?
  Even though the building was both a church and house, it is assumed that the amount of moisture released by human activity from the period 1901-1990 can be ignored. After 1990 humidification and dehumidification were implemented using local (de)humidifiers to create better environmental conditions for the preservation of objects. Three different indoor climate periods can therefore be distinguished:
  1661 - 1953: localized heating, no de- and humidification
  1953 - 1990: central heating, no de- and humidification
  1990 - today: central heating and de- and humidification


Humidification and central heating in 2006 (photos: TU/e)

7.5.2 Localized heating (1901-1953)

From 1900 until 1953 the humidity ratio indoors would have been very similar to the one outdoors. Incoming air would have been heated: in summer, by solar radiation or by the temperature of the building. It is assumed that the current indoor temperatures during summer are similar to the period 1901—1953. Measurements from the summer of 2005 show that indoor air temperatures never dropped below 17.5 °C.
In wintertime, however, localized heating by fireplaces and stoves would have been used to provide human comfort. Estimating indoor temperatures in this canal house with this type of heating is complicated. However, indoor climate data was collected by the ICN in two Dutch non-heated buildings. Both the ' Gevangenpoort' (a prison tower, dating from around 1370) in The Hague and 'kasteel Amerongen' (a brick castle, dating around 1680) in Amerongen suggest that temperatures in winter would never have dropped below 8 °C. These findings are in accordance with data provided by Taylor et al.[2] of indoor temperatures in January in the UK that vary from 4 to 13 °C in a non-heated library.

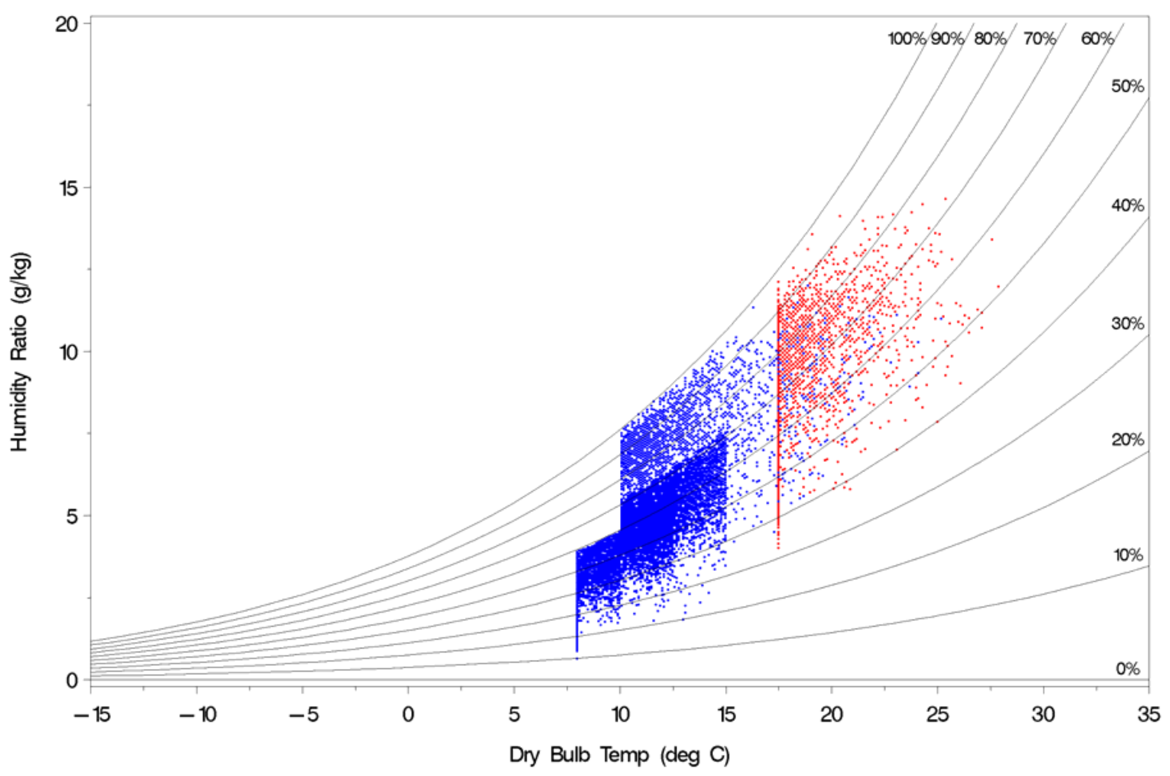
The Sael and the Canal Room have respectively a fireplace and a stove. It is estimated that the amount of heating of the indoor air depended on the temperature of the outdoor air and that of the building: if the outdoor air temperature was below -5 °C the room would have been heated more than on a day when the outside temperature was 10 °C.

The following assumptions were made:

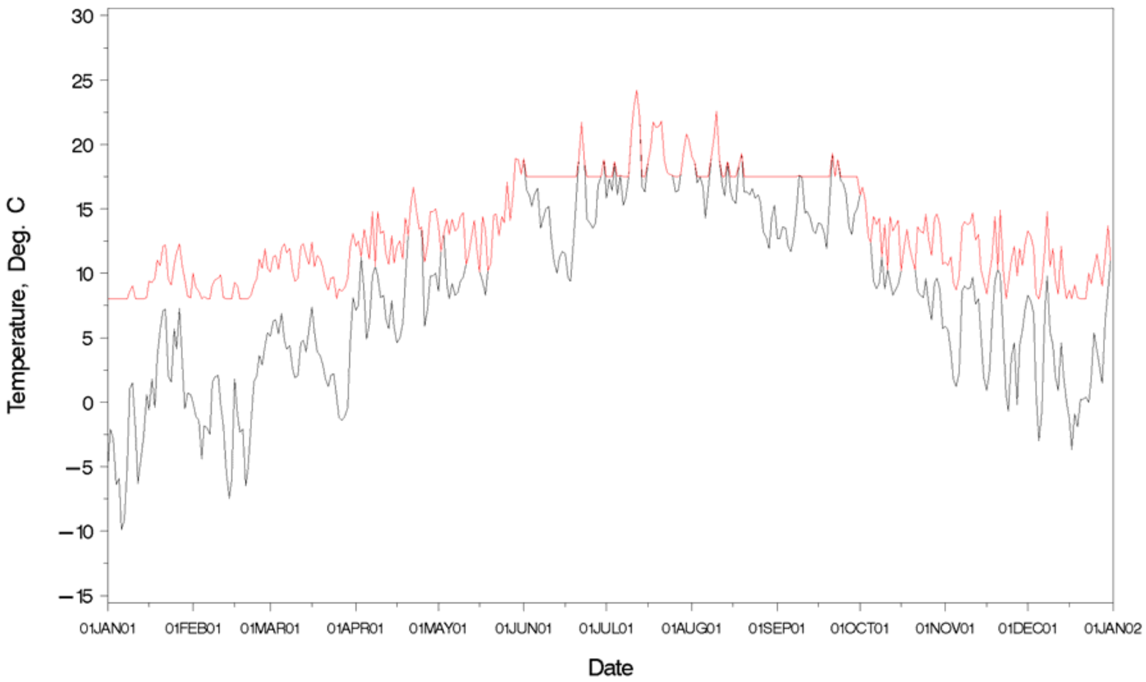
- There is no difference between night and day operation of the fireplaces and stoves. Since daily average values are used for outdoor temperature and relative humidity (with no distinction between night and day), the amount of heating is also averaged.
- The temperature indoors is never below 8 °C: $T_{min.\ indoor} \geq 8$ °C
- -5 °C $\leq T_{outside} \leq 0$ °C: room heated by 10 °C: 8 °C $\leq T_{indoor} \leq 10$ °C
- 0 °C $\leq T_{outside} \leq 5$ °C: room heated by 7.5 °C: 8 °C $\leq T_{indoor} \leq 12.5$ °C
- 5 °C $\leq T_{outside} \leq 10$ °C: room heated by 5 °C: 10 °C $\leq T_{indoor} \leq 15$ °C
- $T_{outside} \geq 10$ °C: room is not heated: $T_{indoor} = T_{outside}$ and never < 17.5 °C

The effect of these heating scenarios in Sael and Canal Room are presented in a psychometric plot.

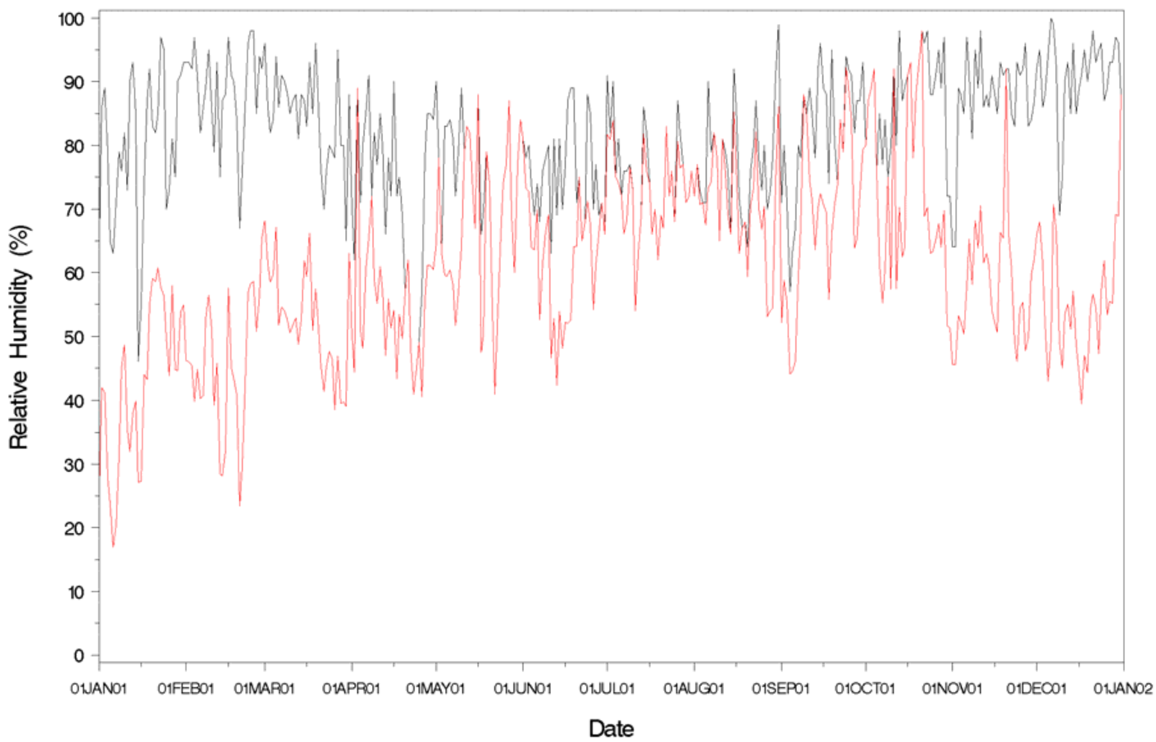
[2] Taylor, Joel; Blades, Nigel; Cassar, May; Ridley, Ian (2005) Reviewing past environments in a historic house library using building simulation. In: *14th triennial meeting, The Hague, 12-16 September 2005: preprints (ICOM Committee for Conservation)*. Verger, Isabelle (Editor). James & James (Science Publishers) Ltd.: p. 708-715.



Psychometric chart showing the modeled indoor climate in Sael and Canal Room with localized heating (January 1901 to December 1952). Data points in blue represent October-May and in red June-September.



Exterior (black) and modeled indoor (red) daily temperature in Sael and Canal Room from January 1901 to December 1901, based on local heating scenario.



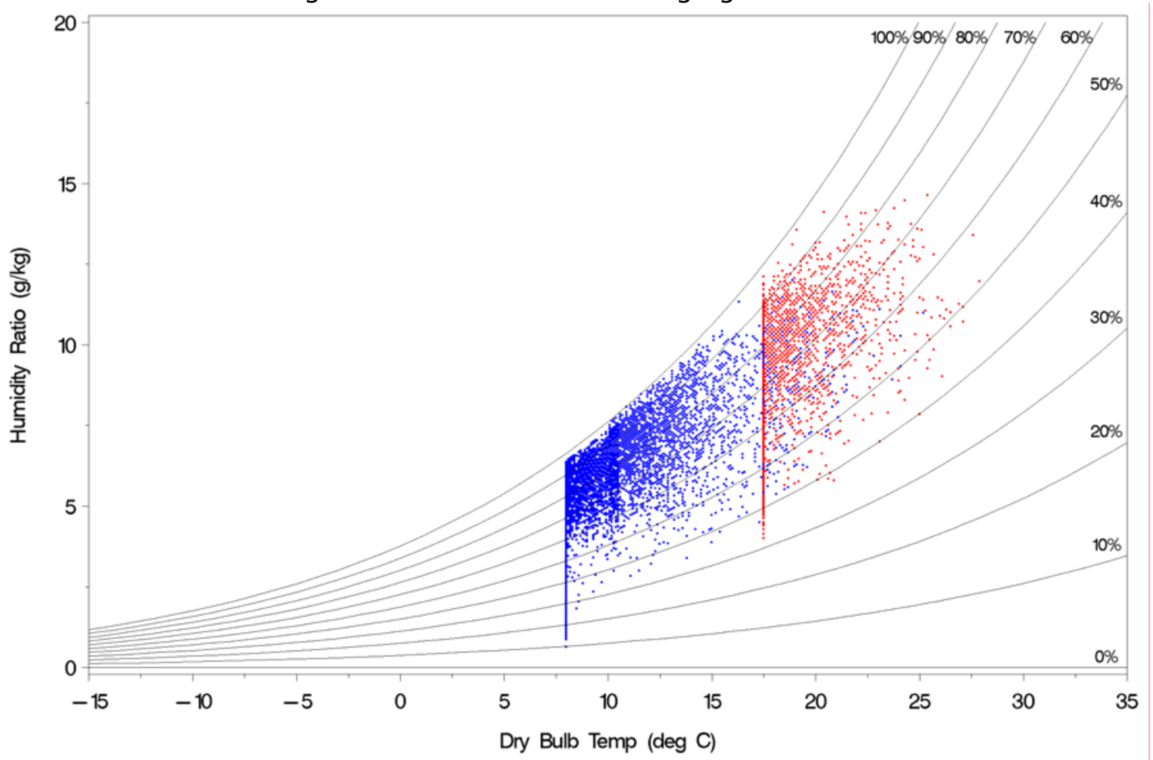
Exterior (black) and modeled indoor (red) daily RH in Sael and Canal Room from January 1901 to December 1901, based on local heating scenario.

From these graphs it can be seen that the relative humidity in winter probably fluctuated between 30 to 60%, and occasionally would have dropped to values below 30%. In summer the indoor RH would have been similar to the outside – this is in accordance with measurements taken in the building in 2005 and 2006, which show RH values to vary between 45% and 70%. This gives a relative humidity difference between winter and summer of 20%, with extremes of up to 45% for shorter periods of time.

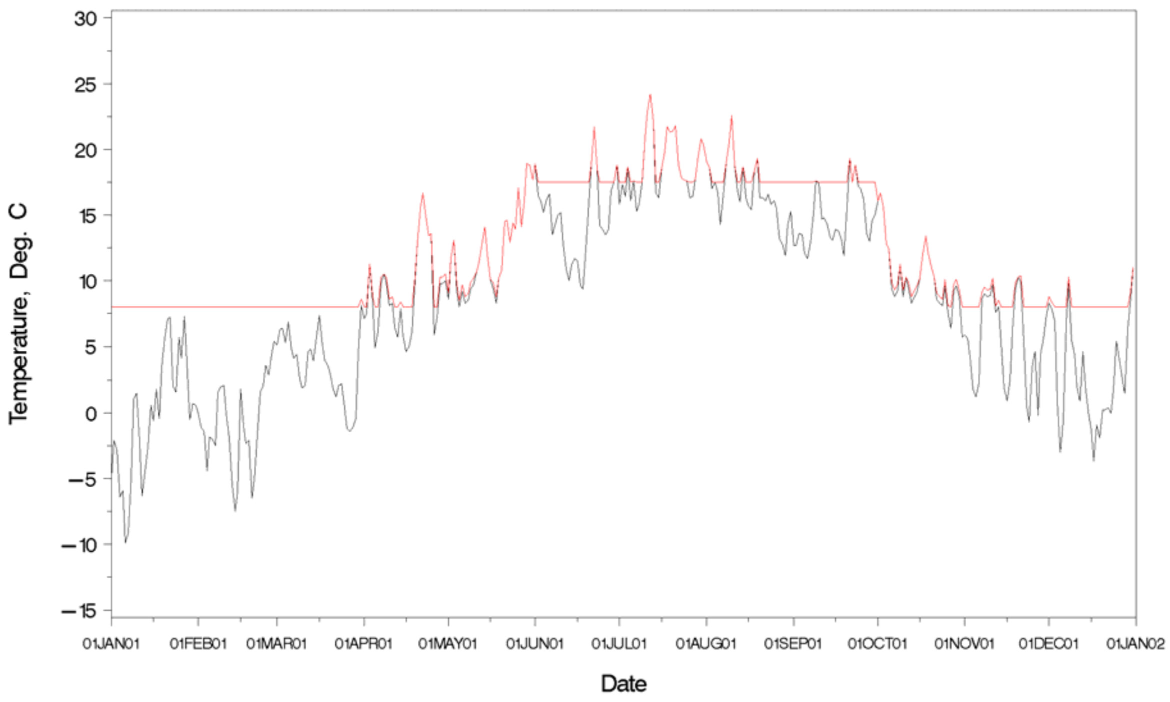
The climate in Church would have been different, as it was not heated. During Mass, churchgoers would have used small stoves with glowing peat to provide local comfort. The unheated Church would have had a temperature that was a result of the temperature of the building and some residual heat from the rooms with fireplaces, stoves and the chimneys. The overall effect of the localized heating in the Canal Room and Sael to the temperature in the Church is expected to have been relatively small. Similar as for the rooms, the heating of the air in the Church depended on the outside temperature. The following assumptions were made:

- The indoor temperature difference between night and day can be neglected.
- The temperature indoors is never below 8 °C: $T_{min. indoor} \geq 8$ °C
- 8 °C $\leq T_{outside} \leq$ 9.5 °C: room heated by 0.5 °C: 8.5 °C $\leq T_{indoor} \leq$ 10 °C
- $T_{outside} \geq$ 10 °C: room is not heated: $T_{indoor} = T_{outside}$ and never < 17.5 °C

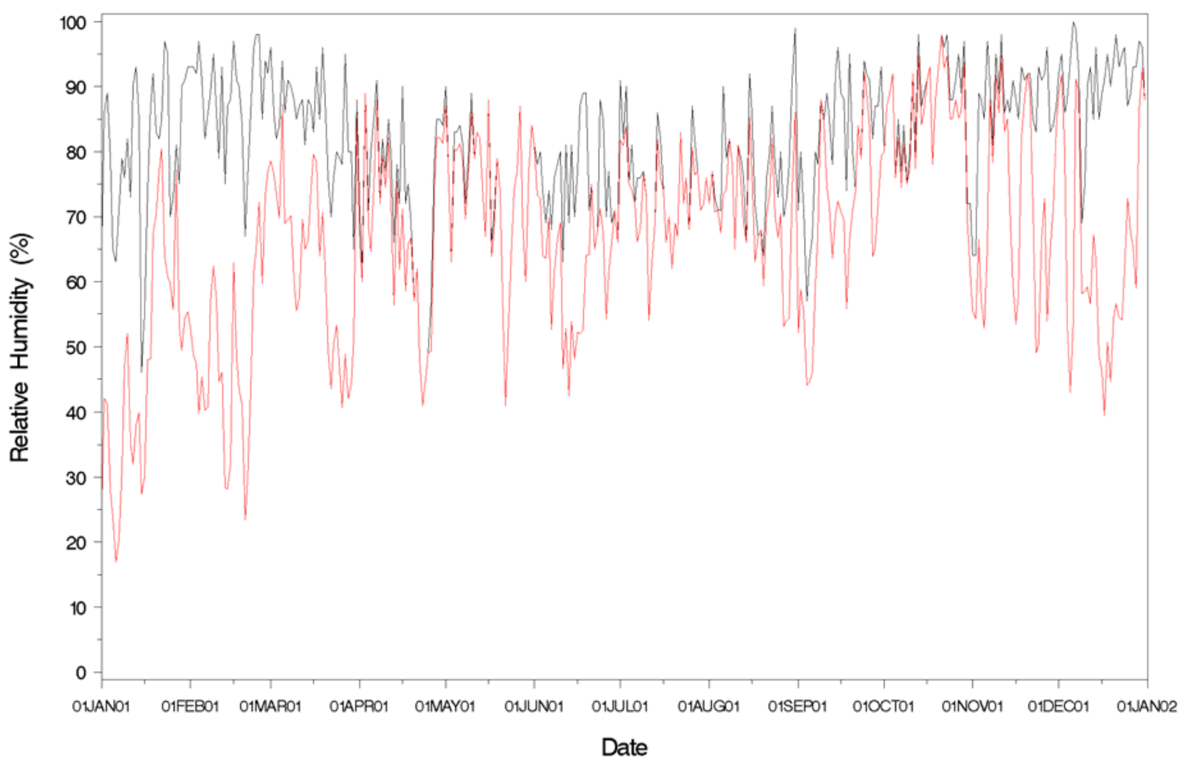
The effect of this heating can be seen in the following figures.



Psychometric chart showing the modeled indoor climate in Church with no heating (January 1901 to December 1952). Data points in blue represent October–May and in red June–September



Exterior (black) and modeled indoor (red) daily temperature in Church from January 1901 to December 1901, based on local heating scenario.



Exterior (black) and modeled indoor (red) daily RH in Church from January 1901 to December 1901, based on local heating scenario.

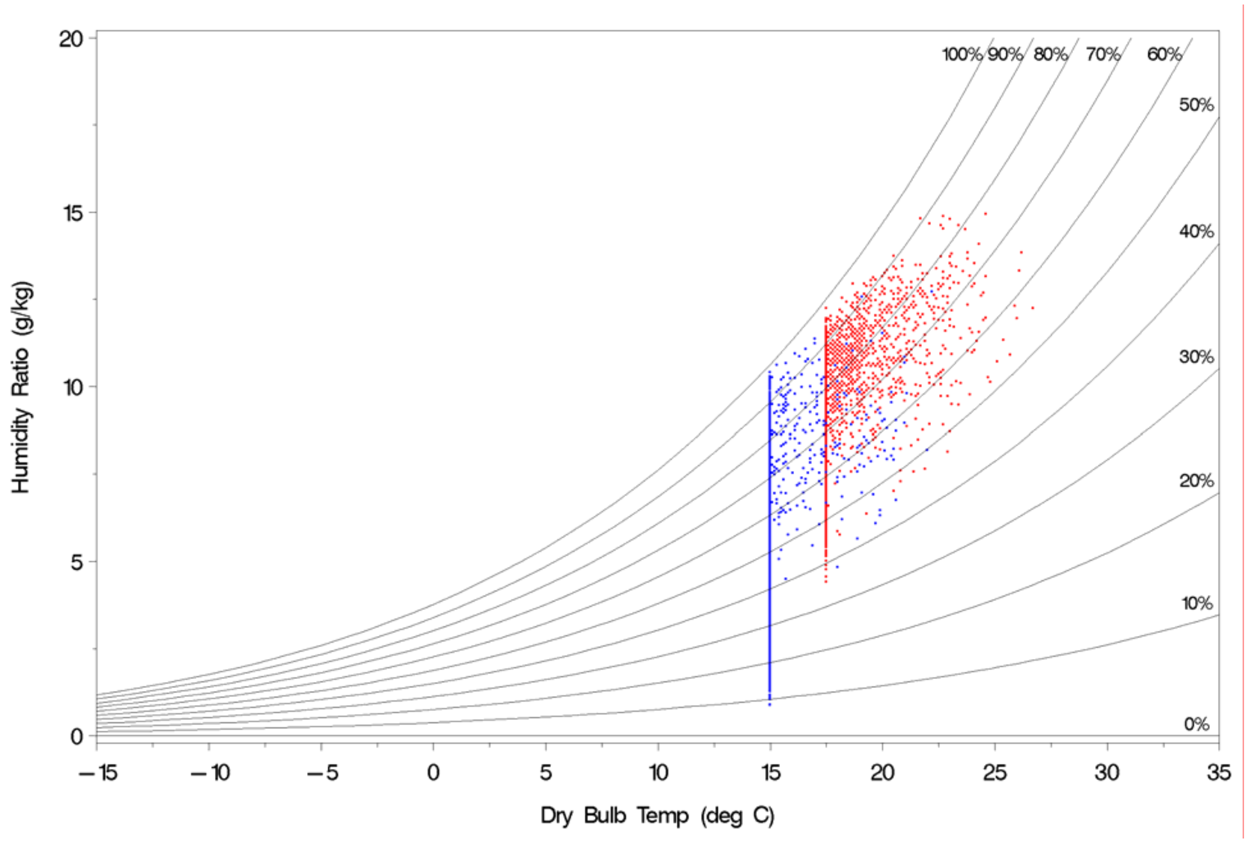
The temperature indoors in winter will have been close to 8°C throughout the year. The relative humidity in 1901 winter varied between 17% to 95%. September, monthly averages vary between 50% and 55%. The RH values, within the 80% limit during summer, range from approximately 48% to 62%.

Conclusion

Objects that were present during the time prior to central heating (1901–1953) may have been exposed to an indoor climate with a temperature ranging from 8 °C to about 25 °C. The relative humidity in the Church would have been slightly different from the heated rooms in winter. In Church the RH would have fluctuated annually between 20% and 90%, while in the heated Seal and Canal Room the RH (refer to graph on page 86) would have varied between 20% and 70% with extremes to 90%.

7.5.3. Central heating (1953-1990)

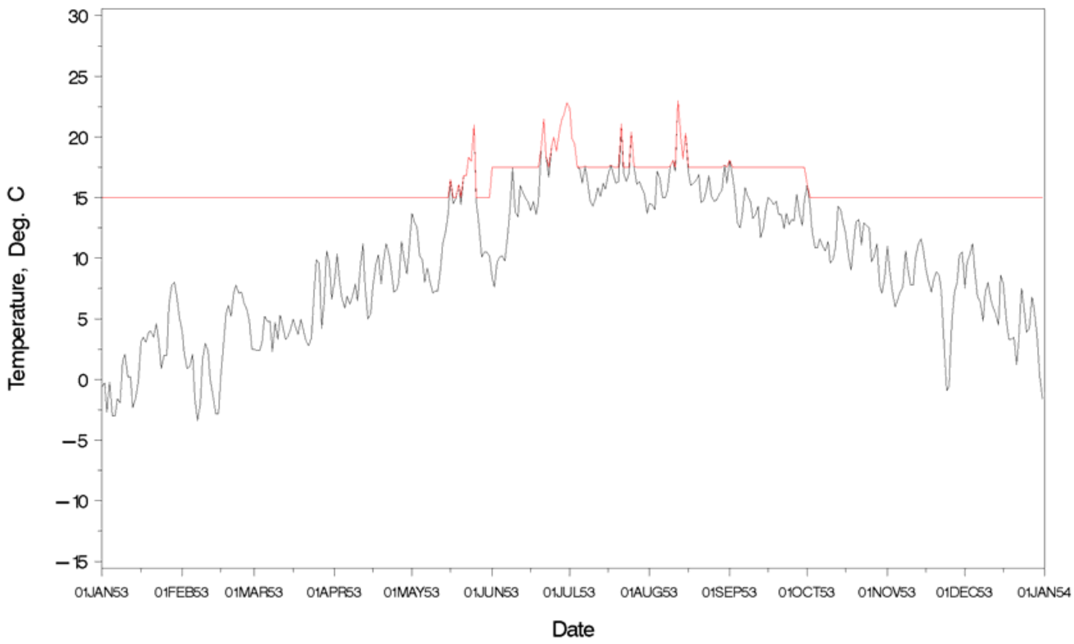
When central heating was installed in 1953, indoor temperatures during the winter were easier to control. The possibility of maintaining the temperature at a certain set point became real. It is not known what that set point was in those days. Using a conservative estimate allows for a scenario that describes what is possibly not the worst indoor climate that could have existed. It is assumed that indoor temperature was maintained at 17 °C[3] during the day and that at night the temperature would drop to 13 °C. This gives an estimate of a daily average temperature around 15 °C. Again it is assumed that the humidity ratio indoors was the same as the humidity ratio outdoors, as no moisture was added to the outside air upon entering the building.
In summer the central heating would have been switched off and indoor temperatures would have been similar to those observed in 2005 and 2006, when indoor temperatures were never below 17.5 °C.



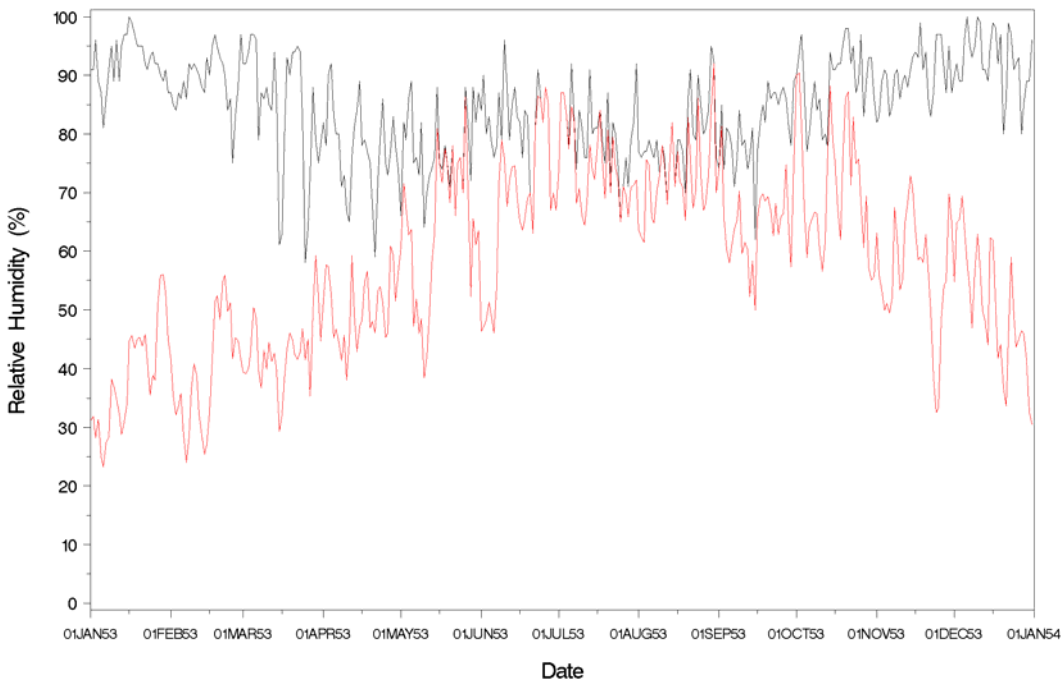
Psychometric data indoor 1953-1990, with central heating and no humidification. Data points in blue represent October -May and the red data June-September.

It can be seen that in winter the temperature is stable around 15 °C but the relative humidity shows a large spread (10% < RH < 95%) and a slightly smaller spread in summer (30% < RH < 95%) over the time between 1953 and 1990.

[3] Nowadays the thermostat has a set point of 20 °C during winter.



Exterior (black) and modeled indoor (red) daily temperature in the building (including the Church) from January 1953 to December 1953, based on central heating scenario.



Exterior (black) and modeled indoor (red) daily relative humidity in the building (including the Church) from January 1953 to December 1953, based on central heating scenario.

Conclusions

Objects that were present during this time (1953–1990) may have been exposed to an indoor climate with a temperature ranging from 15 °C to about 25 °C. The relative humidity may have fluctuated annually between 10% and 90%.

7.5.4. Central heating and (de)humidification (1990–present)

When humidification was introduced into the building not only the temperature, but also the humidity ratio of the air could be better controlled.

From January 1st 2005 until present day, climate data have been collected at different locations throughout the building. Relative humidity (RH) and temperature (T) data have been collected in five locations in the Church (at 3 different heights in the center of Church, on top of the organ and behind the altar), in the Sael, the Canal Room and the Entrance Room.

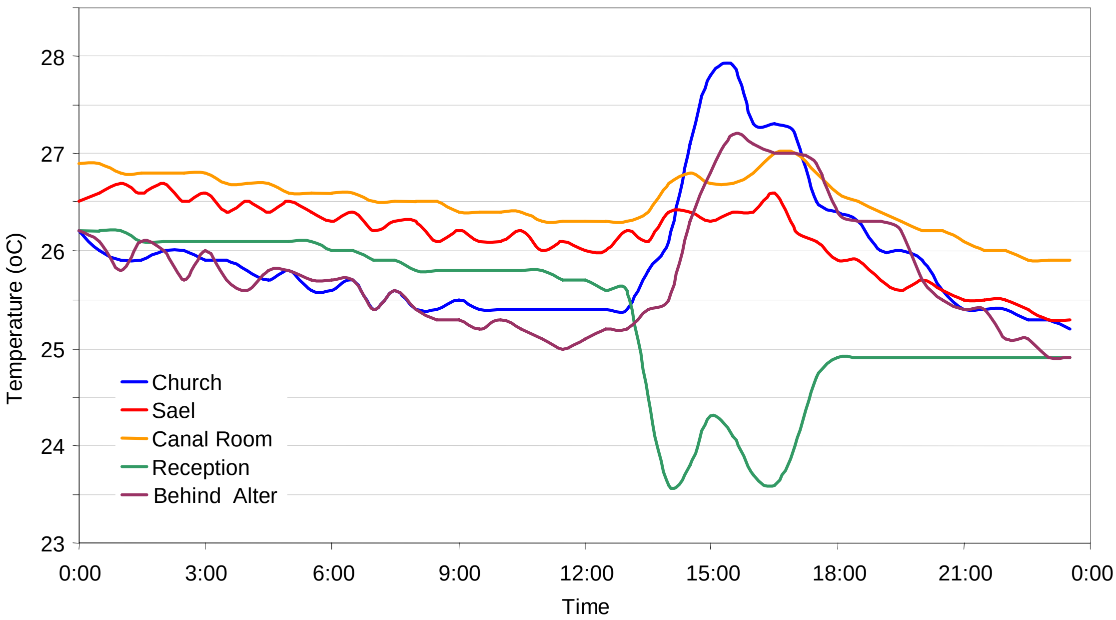
7.6 The impact of visitors on the indoor climate

The following discussion focuses on analyzing the effect of visitors on the indoor climate during special events, which attracted large numbers of visitors for both shorter and slightly longer durations (e.g. Open Monument Day, Museum Night, a wedding, and a special mass). The carbon dioxide levels in the Church will also be discussed.

A note on stratification and localization of moisture in the Church:
Statistical values of annual as well as average daily variations of temperature and relative humidity were measured (and the humidity ratio was calculated from the temperature and relative humidity) at three different heights in the Church (refer to table on page 79). The temperature was slightly higher for higher locations above the Church floor. It was expected that reductions of relative humidity with height would correspond to these temperature variations. However, humidity ratios were virtually identical at all three heights. These values were also similar to those evaluated near the organ (southeast end of the Church). The results indicate that the water vapor in the Church emitted by visitors was well mixed, so there was neither stratification nor localization of moisture.

7.6.1 The effect of high visitation events

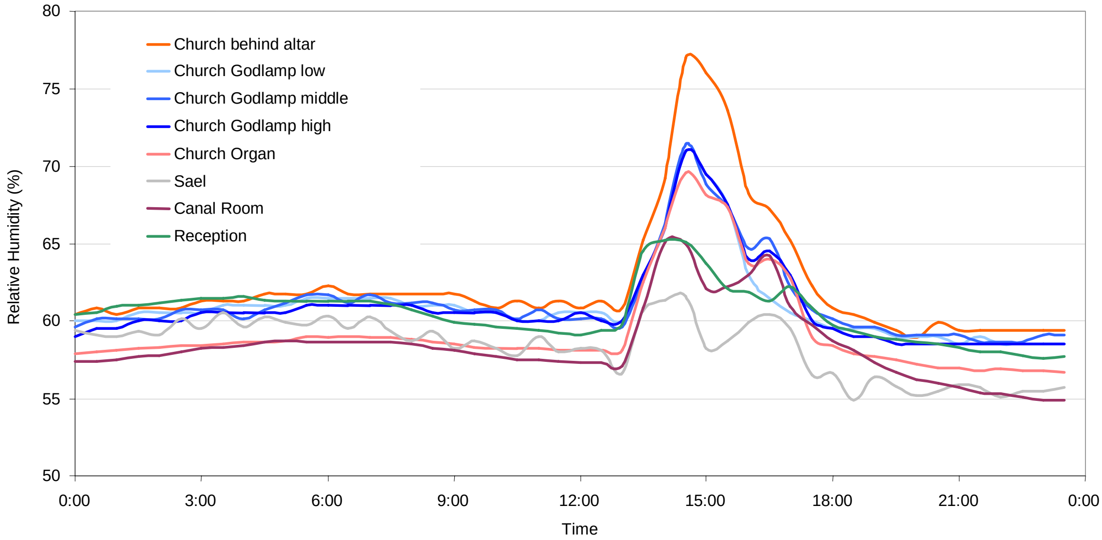
Open Monument day
An extraordinarily high number of visitors (1,064) was recorded at museum 'Our Lord in the Attic' on Open Monument Day in September 2005. Visitors entered the museum over a four-hour period, between 13:00 and 17:00. The impact of visitors on the indoor climate was easily recognizable in temperature and relative humidity plots shown in the next figure.



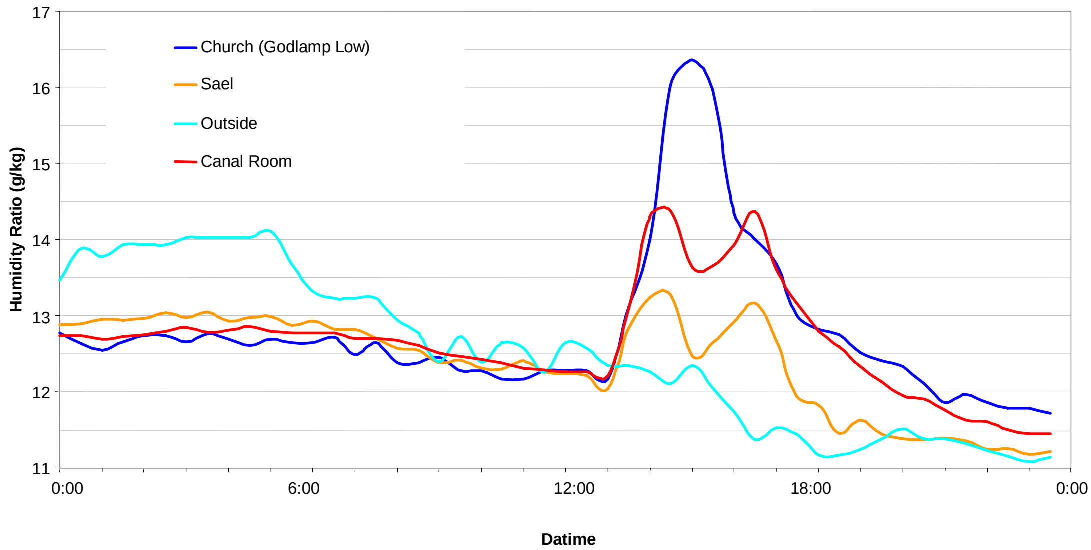
Temperature plots in the Church (God lamp low), Sael, Canal Room and Reception on September 9, 2005 (Open Monument Day).

Except in the Reception area, temperature increases were observed starting at 13:00 in all parts of the building, with the largest increase (approximately 2.5°C) in the Church and the least (0.5°C) in Sael. The Reception's temperature drop during this period is probably due to the front door being opened continuously and the cooler outside air entering the room. Temperatures in the building returned to normal before midnight.

24-Hour variations of relative humidity and the humidity ratio in various rooms of the building on the same day are plotted in the figures below. Both relative humidity and the humidity ratio increased significantly over the four-hour period in all rooms, including the Reception. Surprisingly, the biggest increase of relative humidity (from 60 to 77%) was observed in the space behind the altar. And again, the least increase was observed in Sael. Relative humidity values throughout the building returned to normal by midnight.



Relative humidity plots in Church (God lamp low, middle, high and on the organ), Sael, Canal Room and Reception on September 9, 2005 (Open Monument Day).

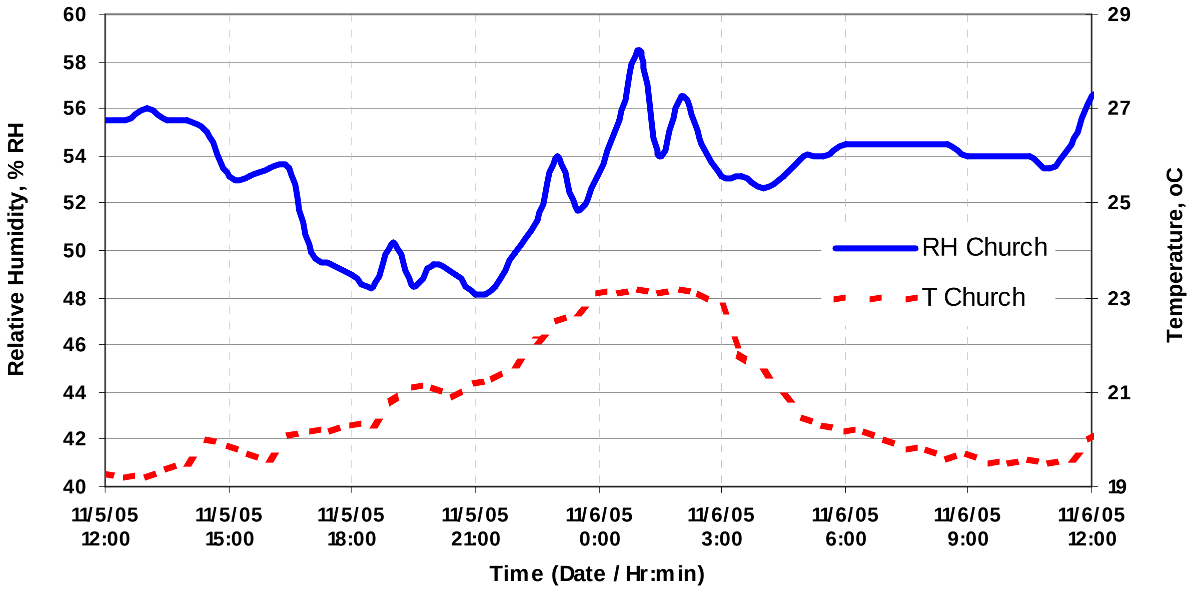


24-Hour variations of humidity ratio in Church (God lamp low), Sael, Canal Room and Outside on September 9, 2005 (Open-Monument Day).

Humidity ratios in both Canal Room and Sael peaked around 14:30, decreased for half an hour, and then started to increase again, producing the second peak at 16:30 before again decreasing towards the end of the visitation at 17:00. However, only one peak of the humidity ratio in the Church was found throughout the day. This indicates that the visitors stayed both in the Canal Room and Sael for relatively short periods of time after they entered the museum. Therefore, visitors in the rooms were directly affected by the rate of museum admission. However, visitors remained in the Church longer than in those rooms, probably more than 30 minutes. The highest occupancy in the Church was reached at 14:30, then, it gradually reduced toward the 17:00 closing time. The humidity ratio in the building returned to normal by the following morning.

Museum Night

2,300 visitors entered museum 'Our Lord in the Attic' over a seven-hour period from 19:00 on November 5 to 2:00 on November 6, 2005 during Museum Night. 24-Hour variations of temperature and relative humidity in the Church were plotted.

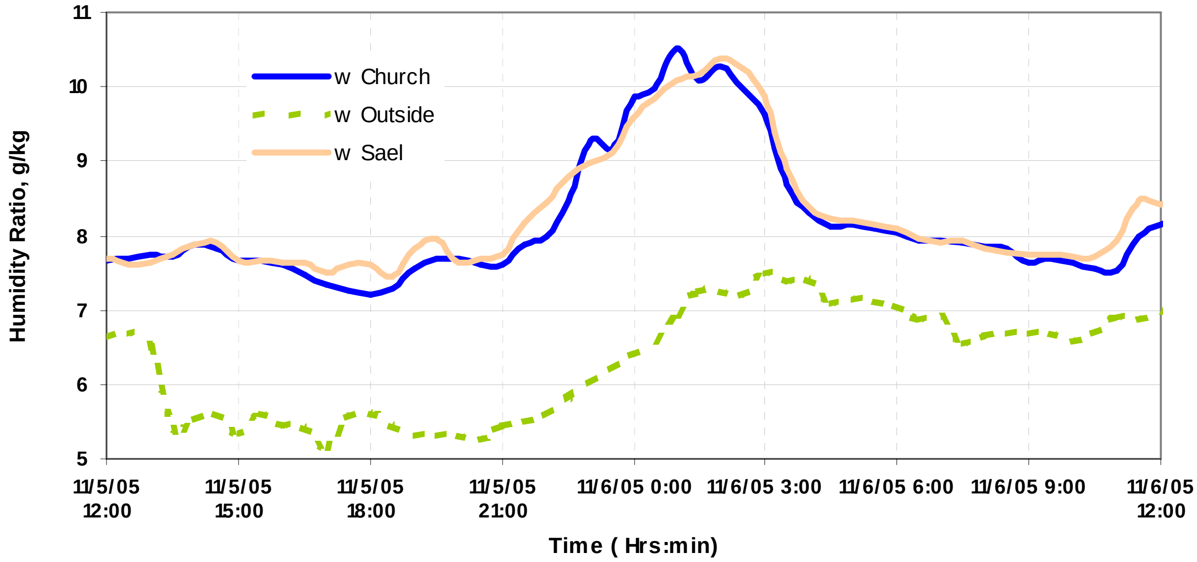


24-Hour variations of the temperature and relative humidity in the Church during Museum Night.

The temperature was approximately 20.2 °C when the event started and increased to 23.2 °C (3° C) by midnight, remaining at that temperature until the end of the event the next day. A large temperature decrease began after 3:00, and returned to the original value by 6:00.

Relative humidity was approximately 50% at the beginning of the event, then quickly increased and produced three peaks: 54% at 23:00, 58% at 1:00, and 56% at 2:00, the end of the event. Then, it reduced to 53% by 4:00, but rose to 54% where it remained until 09:00, the regular opening hour. The increase in the early morning hours may have been due to rainy outside conditions, as outside relative humidity increased from 55 to 95% during the same period.

24-Hour variations of the humidity ratios in the Church, Sael, and outside during Museum Night were plotted.



24-Hour variations of humidity ratios in the Church, Sael, and outside during Museum Night

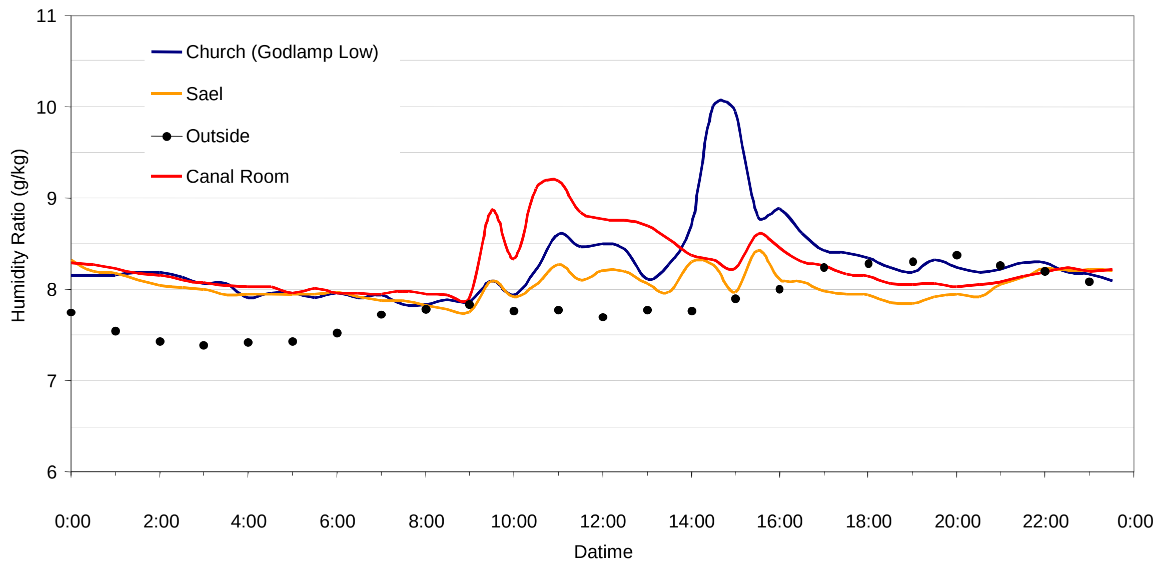
Three large peaks identified in the relative humidity plot were reduced to small saw tooth-like peaks in the plot of the humidity ratio. This indicated that the rate of visitation was steady throughout the event. The increase of humidity ratio was approximately 3.5 g of water per kg of air during the specified period. This was smaller than the increase recorded during Open Monument Day when the museum had about 1,100 visitors over a 4-hour period. This could be probably due to the infiltration of outside lower humidity ratio air into the Church. The humidity ratio in Sael was very similar to that of the Church during the event. This high level of humidity ratio is due to low infiltration of dry outside air into Sael.

7.6.2 The effect of short events

Following are examples of the effect of relatively short events in the Church with more than 100 visitors during spring and winter.

Spring wedding on May 21st, 2005

24-Hour variations of humidity ratios in the Church, Canal Room, Sael and outside air on May 21st, 2005 were plotted.



24-Hour variations of the humidity ratio in the Church, Sael, Canal Room and Outside on May 21, 2005. A wedding with 110 attendees was held in the Church between 13:00 and 15:30.

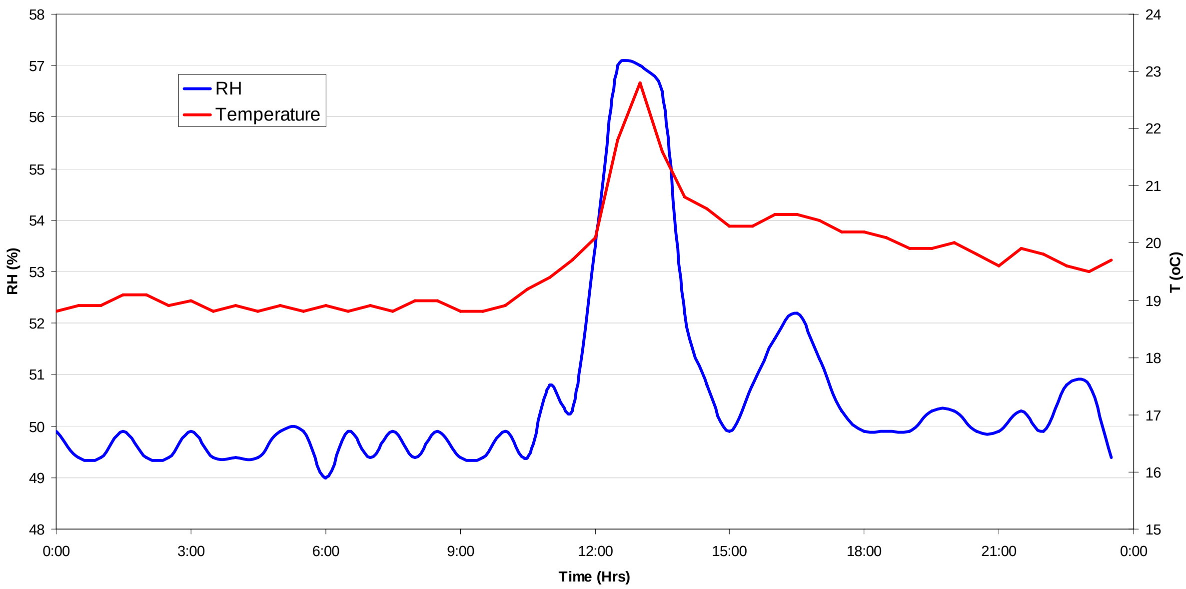
Between midnight and 09:00, the museum's opening hour, the humidity ratio was constant at 8 g/kg throughout the building. At 09:00, visitors began to enter the museum. Evidence of the visitors' presence can be noted as the humidity ratios in various locations in the building increase. At 13:00 the museum closed briefly to accommodate a wedding, starting at 14:30 and ending at 15:30. A total of 110 persons gathered in the Church, according to records kept by museum staff. When wedding attendees started to enter the Church soon after 13:00, the Church's humidity ratio was at 8 g/kg, which was the same as outside. Initially the humidity ratio in the Church exponentially increased; however, the increase soon reduced to linear, then plateaued at 10 g/kg by 15:30, indicating that the attendees had started to leave. The high rate of humidity ratio increase was due to the continuous addition of attendees in Church for a short duration. Once the last attendee entered the Church, the rate of the increase became linear, and then shortly thereafter, the linear increase was reduced by the dilution by the infiltration of outside air, which contained less moisture.

While the Church air had a significant increase in humidity ratio, both the Canal Room and Sael were only slightly affected, mainly by the attendee traffic near these spaces, as guests did not enter these rooms during the event. After all the wedding attendees had exited the building, museum visitors were allowed back into the building at 15:30. Museum visitors gradually exited the museum around 17:00 and the humidity ratios of all spaces dissipated towards that of outside. All spaces equilibrated at 8.2 g/kg in 5 hours by 22:00.

During the wedding, the temperature and relative humidity increased from 20.9°C to 22.6°C and 54% to 60%, respectively. Relative humidity returned to 54%, a normal value without visitors, within two hours after the event. These peak values are within the limit considered to be “safe” for both objects and the building interior, as neither the objects nor the building interior in the Church had time to respond to the change.

Special church mass in winter

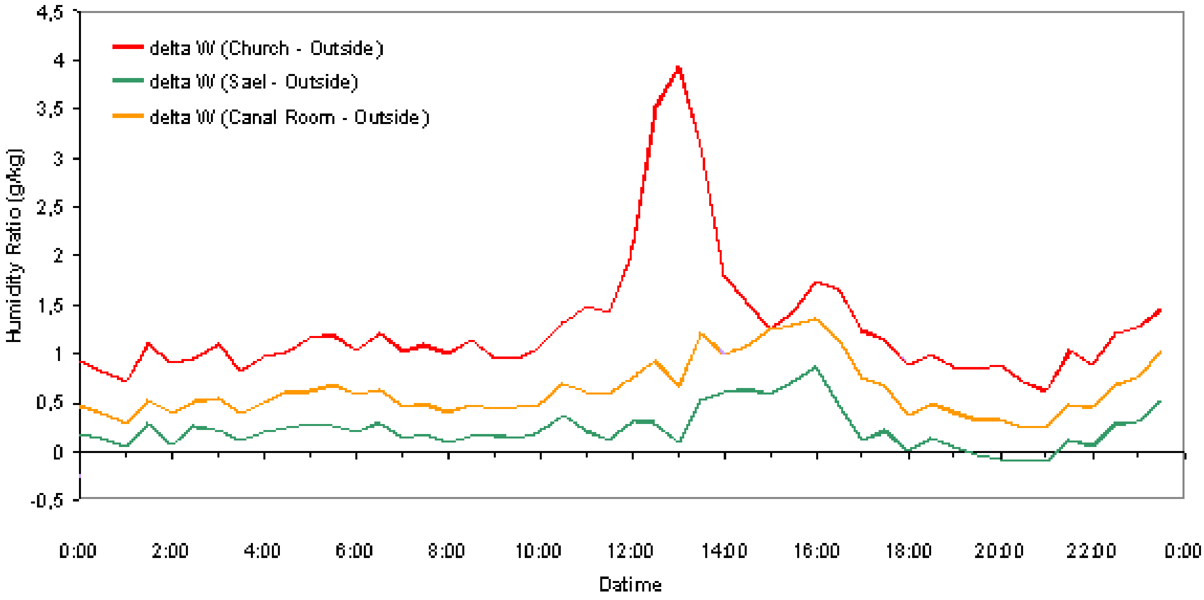
According to museum records, a group of 151 artists attended a special mass on December 4th, 2005. The mass started at noon and lasted for one hour. 24-Hour variations of relative humidity and temperature recorded on December 4th, 2005 were plotted.



24-Hour variations of temperature and relative humidity at the Church God Lamp (low) on December 4, 2005.

The temperature was stable at 19°C until the museum opened at 9:00 and had a low increase at the rate of 0.3°C/hour to 20°C by noon. Then during the mass, the rate increased to 3.0°C/hour during the first 30 minutes, and 2.0°C/hour to 22.8°C in the second 30 minutes.

Relative humidity showed a similar trend, with a 3.3% increase from morning visitors. Attendance at the mass produced an approximate 3.5% increase to a peak of 52% at 12:30. However, the value dropped slightly during the next half hour due to heat produced by the attendees. Both the temperature and relative humidity peaks quickly dissipated after the mass ended. And by 17:00, both values returned to normal. Again, neither the peak values nor the short duration of the elevated value were considered to be affecting the collection or the historic interior of the Church.

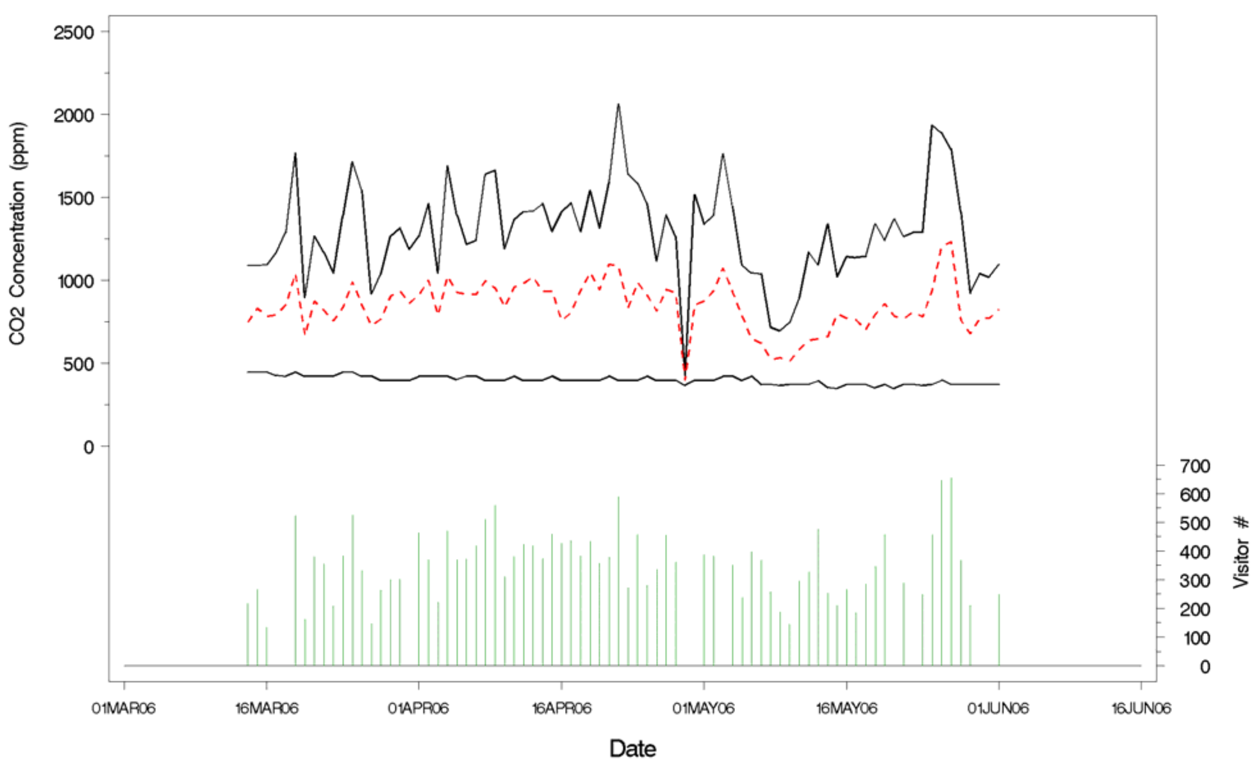


Differences of humidity ratios between inside and outside air of the Church, Sael, and Canal Rooms on December 4, 2005.

During the event, the humidity ratio increased approximately 4 g/kg. Again, this increase quickly dissipated after mass had ended. Within three hours the humidity ratio returned to its pre-mass level. The values in the Church, located at the highest point in the building, were approximately 0.7g/kg higher than that of Sael, the lowest situated room, during non-visiting hours. Museum visitors increased the humidity ratio in the Church more than in other parts of the building. And by noon, the difference was nearly 1.8 g/kg. Although a peak relative humidity was recorded at 12:30, the peak value of humidity ratio in Church was at 13:00, the same time as the peak temperature measurement. Morning visitors produced a humidity ratio rate of 1 g/kg/hr until 12:00. During the mass, the rate increased to approximately 1.5 g/kg/hr during the first 30 minutes, then dropped to 0.3 g/kg/hr during the second 30 minutes. This reduction may be due to the automatic operation of humidifiers/dehumidifiers, the infiltration of outside dry air, or a combination of the two.

7.6.3 CO_2 concentration

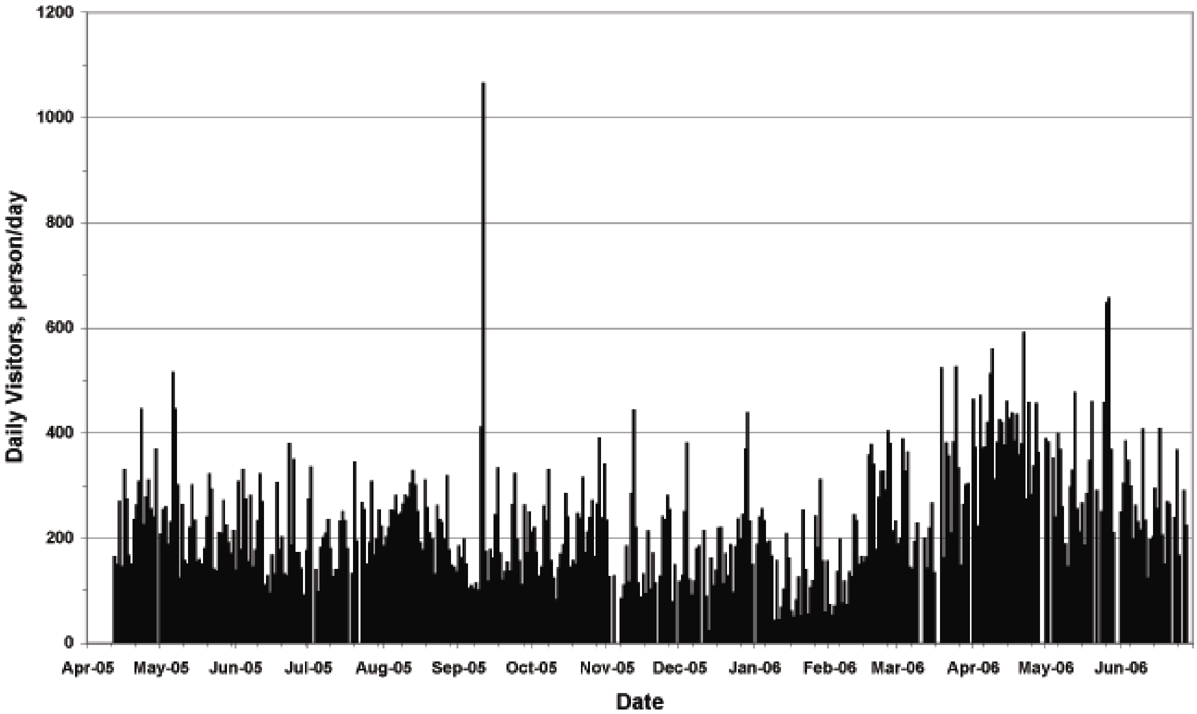
The CO_2 concentration in the air was plotted against the daily total of visitors during a period between March 13 and June 2 2006.



Daily visitation and maximum, minimum, and 08:00 – 17:00 average CO_2 concentration in the Church of Our Lord in The Attic Museum between March 13 and June 1, 2006

The CO_2 level was measured in the Church at the floor level of the first gallery, where the probe was attached to outside of the gallery near the organ, facing the center of the space. The data was collected in two periods, between March 13 and June 2; and between June 29 and August 18, 2006. Maximum concentrations measured were 2061 ppm and 1477 ppm, respectively. The majority of daily maximum values were less than 1500 ppm, and the average levels between 08:00 – 17:00 were less than 1000 ppm, which is considered a safe level for visitor long-term exposure. Daily maximum values were normally recorded during the afternoon and exceeded 1000 ppm. Larger daily totals of visitor numbers corresponded to both high daily maximums of CO_2 as well as averages over the 08:00 – 17:00 period. Daily maximums were recorded exceeding 1500 ppm when the daily visitor total exceeded 500. And averages over the 08:00 – 17:00 period exceeded 1000 ppm when more than 600 visitors were recorded. There was no sign of daily accumulation of CO_2, indicating that the infiltration of outside air completely diluted the concentration to an ambient level by the following morning.

The figure below shows daily visitor totals at Our Lord in the Attic Museum between April 2005 and June 2006. Daily visitor totals averaged approximately 233 per day, ranging from less than 100 to more than 650 per day during the given period. Visitor numbers were generally distributed evenly throughout the year. However, the museum experienced higher visitor numbers between April and June 2006.



Daily totals of visitors to the museum between April 2005 and June 2006 (Note: visitor numbers on Museum Night (2,300 visitors) were not plotted in the graph, since the value would require a larger scale and consequently compress the other daily total values.)

7.6.4 Estimated safe occupancy rate based on the CO_2 concentration

It is assumed that 600 visitors are evenly distributed throughout an estimated six-hour period (between 09:00 – 12:00 and 13:00–16:00). It is further assumed that 100 visitors enter the building each hour and stay inside for one hour.

To dilute the CO_2 concentration to 1000 ppm, ASHRAE recommends that fresh air enter the building at the rate of 7.5 [*liter* sec^{-1} $person^{-1}$]. This will give the required ventilation rate of 2700 [m^3 hr^{-1}]. It is estimated that the building has a volume of 2000 m^3 and air change rates of 1–1.5 hr^{-1} in winter and 2–3 hr^{-1} in summer[4] (these values were measured in the Church by Technical University of Eindhoven (TU/e). These infiltration rates roughly yield the necessary amount (2000 – 3000 m^3 hr^{-1} in winter and 4000–6000 m^3 hr^{-1} in summer) of fresh air. These results further indicate that in winter, a well-distributed admission of 600 visitors during the museum's daily operating hours is the maximum at which the building

[4] The difference between summer and winter can be explained by the fact that some windows and the front door are opened for ventilation.

will be able to provide a suitably safe visitor environment. During the summer, nearly twice the number can be admitted and still remain under the safe limit of CO_2 concentration in the building.

However, visitor numbers at any given hour are normally random and not well distributed unless the museum operates on a reservation system. For more random visitor numbers in individual rooms, assuming an air change rate of 2 – 3 hr^{-1}, it is estimated that the maximum allowable number of visitors as the following:

Room	Floor area [m^2]	Volume of space [m^3]	Maximum visitor numbers at any one time in winter/summer [Person]
Sael	35	190	14/21
Canal Room	28	80	6/9
Church	225	900	66/100

Note: The air change rate and room volume strongly influence the estimates.

From the environmental point of view, this simple analysis indicated that the maximum number of visitors can be nearly 600 per day in winter. It can be increased to twice the current maximum daily visitor number during the summer, especially when opening the entrance door and a window in the attic for increased natural ventilation. However, other important issues, such as safe floor loading and vibration as well as overall visitor comfort and experience, should be analyzed before any decision is made.

7.7 Thermal comfort of visitors

In summer some visitors have complaint about feeling dizzy and uncomfortable in the church. The CO_2 concentration data however shows that this is not due to unsafe conditions in the church. Other aspects are obviously playing a role.

The thermal comfort of an individual is determined by environmental conditions that allow a person to retain a constant core (body) temperature. Thermal comfort is affected by environmental factors, such as air temperature, air speed, relative humidity, and radiant temperature. Other factors include a person's physical activity, clothing insulation, physical differences, and recent thermal history. A person generates varying amounts of heat depending on the level of recent physical activity. Heat is gained from or dissipated into the environment through convection and conduction (heat transfer between the skin and the surrounding air) and radiation (between the skin and surrounding surfaces). The larger the temperature difference, the more heat will be transferred between a person's skin and the surrounding environment. A higher air speed will produce a higher rate of heat transfer. Lower relative humidity air will allow a higher rate of heat removal through latent heat loss via perspiration. And layers of clothing will certainly determine a person's level of exposure to the environment.

ASHRAE's comfort standards (ASHRAE 55-1981) suggest that the optimum operating temperature (a function of the mean radiant temperature, the mean air temperature, the mean skin temperature, and air speed) of 24.4ºC in summer for visitors with light clothing. A temperature of 28ºC is considered to be the upper limit, requiring an air movement of 0.8 m/s to provide an acceptable comfort level.

During warm summer days, visitors to museum Our Lord in the Attic often expressed discomfort from high temperatures, especially in the Church. A museum staff member noted a visitor fainting in the Church on a hot day. Since levels of CO_2 were found to be less than the critical level most of the time, it can be assumed the reason for visitor discomfort is attributable to high temperature. The Canal Room is often warmer than the Church; however, visitors are still relatively comfortable there as it is normally the first or second room they visit. Visitors must climb many additional stairways to reach the Church. By the time they reach the Church, this climb will have certainly raised physical activity levels beyond the "sedentary condition" on which comfort standards are based. The effects are more prominent on higher floors, such as the Church level and the balcony/organ level of the Church, especially on the canal side where wall temperatures can often reach into the 30's ºC. These warm walls further reduce a person's ability to disperse heat by radiation. These compounded conditions can make the visitors' experience quite unpleasant.

For three days (10% of the time) in June 2005, the temperature in the museum reached above 26ºC; and reached 28ºC for several hours during the period January 2005–January 2006. However, during the recent heat wave July 18—25, 2006, the Church's daily temperature reached above 30ºC and remained above 28ºC throughout the day. Interior surface temperatures of the Church's walls closely followed that of the air. The wall facing the canal daily reached above 31°C. Both the air and surrounding wall were too hot to provide any heat removal from visitors' skin. And, these high temperatures were considered to be beyond the range of temperature that could be relieved even with high speed of air movement. Therefore, the museum may need to consider the use of an air-cooling device on such hot summer days. Or, they could post a warning for "uncomfortable conditions" on hot days. The museum may expect more hot summer days in the future as a result of global climate changes.