Hygrothermal performance of log walls in a building of 18th century and prediction of climate change impact on biological deterioration

Petros Choidis[1,*], *Katerina* Tsikaloudaki[2], and *Dimitrios* Kraniotis[1]

[1]Department of Civil Engineering and Energy Technology, Oslo Metropolitan University – OsloMet, St. Olavs plass 4, N-0130, Oslo, Norway
[2]Laboratory of Building Construction & Building Physics (LBCP), Department of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki (A.U.Th.), Thessaloniki, Gr-54124, Greece

Abstract. Several studies underline the dramatic changes that are expected to take place in nature and environment due to climate change. The latter is also expected to affect the built environment. Particular emphasis is currently given to the impact of climate change on historical structures. Within this context, it is important to use simple methods and novel tools in order to investigate specific case studies. In this study, the climate change impact on the hygrothermal performance of the log walls in a historic timber building is presented. The building under investigation is the Fadum storehouse, also known as 'the coated house', located in Tønsberg, Norway. The storehouse dates to the late 18th century. It has a particular design with the main features of stumps or piles up to which it stands and the 'coating' that covers its outer walls. The main damage of the construction is related to the biological degradation of the wood. The hygrothermal performance of the log walls, as well as the exterior and interior climate, have been monitored and the results have been used to validate a Heat, Air and Moisture transport (HAM) model. The validated HAM model is then used to examine the performance of the log walls for both current and potential future climate conditions. The transient hygrothermal boundary conditions serve as the input parameters to a biohygrothermal model that is used to investigate the biological deterioration of the building components. The findings reveal that currently there is no mould risk for the main body of the construction, which is in accordance with the visual inspection. The passive systems of the building are highly conducive to these results, since they protect it from driving rain and other sources of moisture and eliminate the potential impact of future climate change risk scenarios.

Nomenclature	
θ	air temperature [°C]
θ_d	dew point [°C]
φ	relative humidity [-]
AH	absolute humidity [g/m^3]
θ_{wood}	temperature in wood [°C]
u	equilibrium moisture content [-]
R	electrical resistance [kΩ]
u_k	temperature corrected moisture content [-]
θ_e	exterior air temperature [°C]
φ_e	exterior relative humidity [-]
θ_i	interior air temperature [°C]
φ_i	interior relative humidity [-]
RR	precipitation [mm]
FF	wind speed [m/s]
DD	wind direction [grad]
H_{Gh}	mean irradiance of global radiation horizontal [W/m^2]
H_{Dh}	mean irradiance of diffuse radiation horizontal [W/m^2]
N	cloud cover fraction [octas]
G_{Lin}	mean irradiance of longwave radiation incoming [W/m^2]
ρ	bulk density [kg/m^3]
ε	porosity [m^3/m^3]
c_p	specific heat capacity [J/(kg·K)]
λ	thermal conductivity [W/(m·K)]
μ	water vapor diffusion resistance factor [-]

1 Introduction

Several studies underline the dramatic changes that are expected to take place in nature and environment due to climate change [1, 2]. In Norway, long-term climate projections up to the year 2100 have demonstrated that the country will face an increase of annual temperature up to 6.4°C and precipitation up to 18% [3].

Higher temperature and humidity levels will intensify the decay of the building materials in historic structures resulting to invaluable damages [4, 5]. Timber historic buildings are mostly at risk, because they are vulnerable to biodeterioration, such as fungi that germinate

---

[*] Corresponding author: petrosch@oslomet.no

favourably under the predicted future climate conditions [5, 6].

The biodeterioration risk of each individual construction may vary depending on its microclimate, design and building material properties. Accurate modelling of specific case studies should consider all these three parameters. It is also important that simple methods leveraging novel tools should be employed.

The purpose of this work is to assess the climate change impact on the biodegradation of the log walls of a historic timber construction in southern Norway. In the framework of this study, both measurements and simulations are employed. The measurements concern the monitoring of the exterior microclimatic conditions and the indoor environment as well as the temperature and water content in the building elements. The set of the numerical simulations consist of i) a hygrothermal model, used for the estimation of the temperature and moisture content in the building components and ii) a biohygrothermal model, used to assess the mould risk on various cross sections of the logs on the basis of the temperature and moisture content results. The hygrothermal model is validated through the measurements, while the biohygrothermal results are verified by the on site inspection.

2 Materials and methods

The methodology followed in the current study is summarized in Fig. 1.

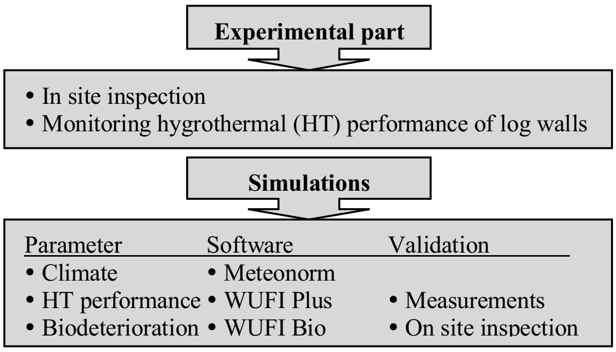

Fig. 1. Schematic representation of the methodology of the study.

2.1 Experimental site

The building under investigation is located in southern Norway, in the county of Vestfold (Fig. 2). Some typical features of this area are the cold climate and the usage of wood as the main building material. The analysed structure is a timber storehouse, dated back to the late 18th century. It was built in the region of Fadum, in Sem and thus it got the name 'Fadum storehouse'. In 1958, it was moved approximately 5km south-east to the Slottsfjellet hill, in Tønsberg, where it still stands as a property of the Slottsfjell museum (Fig. 2). Its current location is 250m far from the coast and on 50m above sea level.

Fig. 2. The Slottsfjellet hill (in the picture) in the county of Vestfold (highlighted with red colour on the map), in Norway.

The building has a rectangular plan with its major axis East-West oriented (Fig. 3a). Its entrance is in the southern façade (Fig. 3b). It is a two-storey building, with the ground floor used as a storehouse, where food was kept, while the upper floor may have served as a bedroom. The building's unique design could ensure cool and dry conditions for the products stored in the ground floor, as well as protection from animals such as mice and insects.

The passive systems incorporated in the historic building's design are the pillars or stumps upon which it stands, the shed or coating that surrounds its outer walls, as well as the openings in the eastern and western façade of both ground and upper floor (Fig. 3b). The stumps contribute to keep the lower part of the construction dry, since they protect it from the ground rising damp and also allow the wind to pass under the main body of the construction. The coating protects the outer walls from rain, wind and solar radiation. Finally, the openings in the smaller facades of the building ensure adequate natural ventilation to its interior.

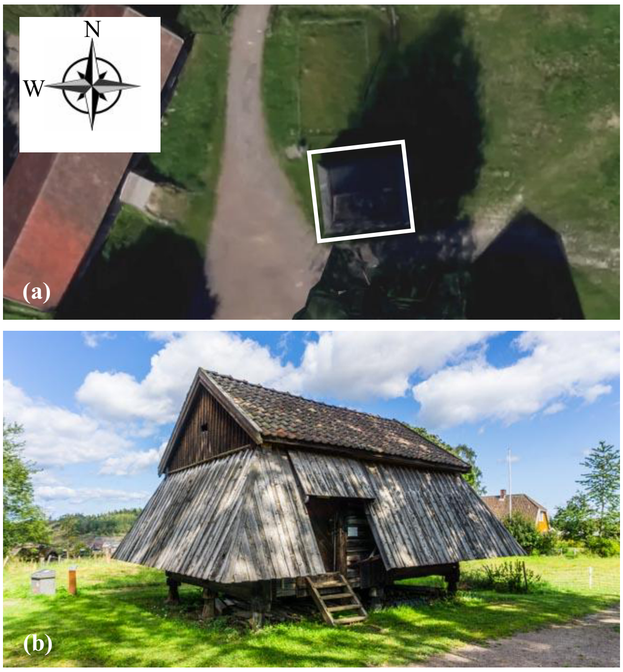

Fig. 3. The Fadum storehouse as observed (a) from a satellite view and (b) in situ picture from south-west.

The Fadum storehouse is a purely timber construction. Its main body is built of horizontal logs notched at the corners. The log walls are made of softwood, most likely Scotch pine, i.e. *pinus sylvestris*, or Norway Spruce, i.e. *picea abies*, treated with tar on their outer surface. The log walls are preserved unaltered throughout the years.

The historic building's design has contributed significantly to its well-preserved condition. The in-situ inspection confirmed that the log walls have not experienced significant weathering. Their good maintenance is attributed to their protection from rain, wind and solar radiation. However, damages were observed on the coating and the roof of the building. More specifically, the outer surfaces of these two building elements were infested by lichen and green moss (Fig. 4). In addition, some timber boards of the inner side of the roof were attacked by fungi. The key climate parameter affecting these two types of deterioration is rain. On the outer surfaces, direct exposure to rain strengthens lichen and moss growth, while in the inner side of the roof mould grows in wet areas close to leakages. Restoration of the above-mentioned damages includes scraping of lichen and moss, as well as replacement of the timber boards colonized by mould fungi.

Fig. 4. Microclimatic conditions have a strong impact on the discolouring as well as the development of lichen on coating's surface.

2.2 Experimental set-up

The micro-climate conditions, as well as the temperature and moisture content in the log walls of the Fadum storehouse, are monitored by a set of sensors presented in Table 1 and Fig. 5. Air temperature and humidity sensors are installed on the first level (sensor 1), the second level (sensor 2) and outside the building in a position shielded by the coating (sensor 8). Furthermore, on the first level there is a sensor monitoring the temperature inside the south-oriented log wall (sensor 2). The installation depth of sensor 2 is 10mm and its measurements correspond to the average temperature along the installation depth. Finally, on both levels there are sensors monitoring the water content in the interior side of the south and north-oriented log walls (sensors 3, 4, 6, 7). These devices measure the electrical resistance between two electrodes and convert it to water content units based on a function that is presented later in this subsection. The electrodes are installed in depth of 10mm and the distance between them is 20mm. Sensors' measurements correspond to the average moisture content along the installation depth. All sensors operate from the 22nd of November 2019. For the aims of this study, a seven-week period of measurements is processed.

Table 1. Characteristics of the sensors installed in the Fadum storehouse.

Sensor	Parameter	Range	Accuracy	Interval
1,5,8	θ [°C] θ_d [°C] φ [-] AH [g/m^3]	-30°C to +60°C 0 to 100%	±0.4°C ±3%	3 min
2	θ_{wood} [°C]	-30°C to +90°C	±0.2°C	3 min
3,4,6,7	u [-]	7.9 to 50%		240 min

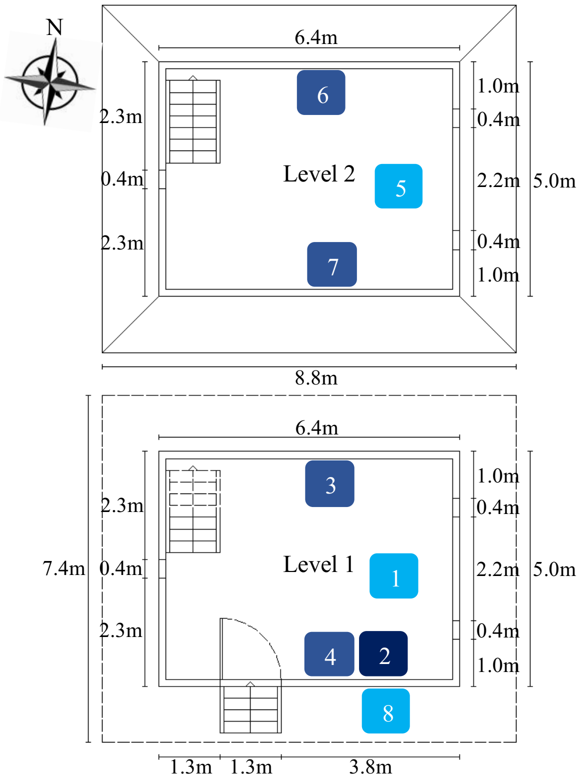

Fig. 5. Plan view presenting the sensors position.

The moisture content values are estimated from Eq. 1, knowing the electrical resistance measurements. Moreover, Eq. 2 is used in order to calculate the temperature corrected moisture content values. For all four moisture content sensors the temperatures measured by sensor 2 were used in Eq. 2.

$$u = \frac{1.055 - \log(\log(R+1))}{0.040} \tag{1}$$

$$u_k = \frac{u + 0.567 - 0.0260 \cdot (\theta_{wood} + 2.8) + 0.000051 \cdot (\theta_{wood} + 2.8)^2}{0.881 \cdot (1.0056)^{(\theta_{wood} + 2.8)}} \tag{2}$$

Where
u: equilibrium moisture content [-],
R: electrical resistance [kΩ],
u_k: temperature corrected moisture content [-],
θ_{wood}: temperature in wood [°C].

2.3 Assessment of the current and future climate conditions

Climate data of temperature (*θ*), precipitation (*RR*), relative humidity (*φ*), wind speed (*FF*) and direction (*DD*), shortwave global (H_{Gh}) and diffuse (H_{Dh}) radiation, longwave radiation (G_{Lin}) and cloud cover (*N*) were generated for the project's site for both past and potential future years. For the climate data generation Meteonorm software [7] has been used. Meteonorm produces monthly values for all climate parameters for the project's site (latitude: 59.2744°N, longitude: 10.4036° E, and altitude: 50m) by interpolating data from Rygge, Ferder, Nordkoster, Oslo-Blindern, Blomskog and Lyngor weather stations, that are 24km, 28km, 54km, 77km, 96km and 101km far from the site, respectively. From the monthly values, the software calculates hourly values of all parameters using a stochastic model. For the aims of the study, past climate conditions are represented by a typical year consisting of data from the period 1991-2010 for radiation and 2000-2009 for the rest climate parameters.

Meteonorm has been also used for the generation of future climate data. In that case, instead of measured climate values, the software use IPCC AR4 [8] results as an input [7]. From all 18 public models it creates an average one with special resolution of 1° [7]. In order to produce the future climate data for the pilot area, the software interpolates data referring to As, Oslo-Blindern, Oslo/Gardermoen and Karlstad weather stations, that are 48km, 77km, 111km and 174 km far from the site, respectively. Within the current study, analysed future conditions correspond to the years 2050 and 2100, under the Standardized Reference Emission Scenarios (SRES) B1 and A2 [8]. The B1 storyline considers rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies [8]. On the other hand, the A2 storyline describes a very heterogeneous world, in which economic development is primarily regionally oriented and the per capita economic growth and technological change are more fragmented and slower [8]. It is worth mentioning that even though the IPCC AR5 [9] provides different emission scenarios, the current study considers the IPCC AR4 [8] projections. This is a limitation linked to the selection of Meteonorm in order to acquire the climate data.

From the climate data referring to the past years, it is observed that the prevailing temperatures (*θ*) are low with an annual average of 7.8°C (Fig. 6a). Precipitation (*RR*) is moderate and well distributed throughout the year, with a mean annual value of 685mm. Maximum rainfall takes place between summer and autumn and minimum in spring (Fig 6b). Relative humidity (*φ*) remains in high levels during the whole year, having a mean annual value of 76%. Relative humidity fluctuates around 70% during spring and summer and around 80% during autumn and winter. In addition, mean monthly wind speed (*FF*) fluctuates between 3.5m/s and 5m/s (gentle breeze, according to the Beaufort scale), while the predominant wind direction (*DD*) is from South. The solar radiation related parameters vary extremely over the course of the year. The energy absorbed by a horizontal surface due to short-wave radiation (H_{Gh}) reaches a maximum during June, with a mean monthly value of 238W/m². Almost half of this energy corresponds to the contribution of diffuse radiation (H_{Dh}). On the other hand, during December the mean monthly global radiation is only 6W/m². The cloud cover fraction (*N*) fluctuates between 4 and 7 octas, with the lower values occurring during summer. Finally, the average hourly long-wave radiation from the sky (G_{Lin}) fluctuates between 260W/m² and 35W/m², with the lowest values occurring during winter and the highest ones during summer.

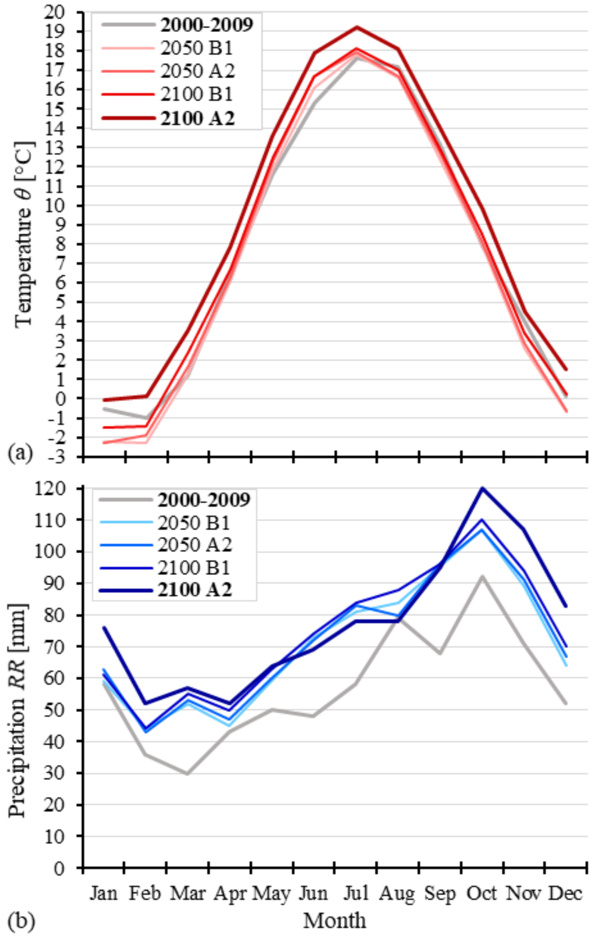

Fig. 6. Mean monthly (a) air temperature and (b) precipitation for past and future (under SRES B1 and A2) years for the project's site.

According to the data referring to the future conditions, most of the climate parameters change slightly or does not change at all. The most significant changes are predicted for temperature and precipitation (Fig. 6a and b), the mean annual values of which are predicted to increase by 1.2°C and 36% respectively in 2100 under the SRES A2. Temperature predictions for the rest three examined cases (SRES B1 and A2 for 2050 and SRES B1 for 2100) indicate a decrease in air temperature during the coldest months of the year. The temperature decrease contradicts to other studies [3, 8, 9] and thus, these three cases are not considered as potential future climate profiles.

2.4 Bio- and hygrothermal simulations

Within this study the one-dimensional hygrothermal simulation tool WUFI Pro [10] has been used to calculate the surface temperature and humidity conditions. The transient hygrothermal boundary conditions served as the input parameters to the software WUFI Bio [11] that is used to predict the risk of mould growth on the building components. WUFI Bio is a biohygrothermal model that is used to estimate the accumulative mould growth in mm on material surfaces on an annual basis. Apart from the temperature and humidity conditions, it also accounts for the substrate material, which in this this study is considered to be a biologically degradable one (i.e. class I) [11]. Moreover, the software incorporates a transformation function allowing to express mould risk in terms of mould index [12].

2.4.2 Material Properties and Boundary Conditions

Building components of the Fadum storehouse are made of softwood simulated under the physical, thermal and hygric properties presented in Table 2.

Table 2. Physical, thermal and hygric properties of softwood building elements.

ρ	ε	c_p	λ	μ
[kg/m^3]	[m^3/m^3]	[J/(kg K)]	[W/m K]	[-]
450	0.73	1500	0.09	200

The log walls of the Fadum storehouse are made either of pure logs treated with tar in their outer side (Fig. 7a) or logs with a layer of softwood boards in their outer side (Fig. 7b). The first type of cross section corresponds to the walls of the ground level as well as the north and south oriented walls of the upper level. These walls are protected by the coating. The second type of cross section corresponds to the east and west oriented upper gable walls. Moreover, in the framework of the simulations, it is assumed that the walls shielded by the coating are exposed only to the ambient temperature and relative humidity (Fig 7a). Both their inner and outer side are considered to be protected from rain, wind and radiation. On the other hand, the upper gable walls are exposed to rain, wind, short and long-wave radiation, ambient air temperature and relative humidity on their outer side, while on their inner side they are exposed to the indoor temperature and relative humidity (Fig. 7b).

In order to verify that the employed model represents adequately the physical problem, a comparison is made between the measured and the simulated temperature and water content in the logs. For that purpose, two different simulations are employed. The first one corresponds to the hygrothermal performance of the log walls of the ground level. In this case the simulated assembly is the one presented in Fig. 7a, while the outdoor and indoor boundary conditions correspond to the air temperature and relative humidity monitored by sensors 8 and 1, respectively. The other simulation refers to the hygrothermal performance of the north and south oriented walls of the upper level. In that case the examined assembly is also the one presented in Fig. 7a, while the outdoor and indoor boundary conditions correspond to the air temperature and relative humidity measurements from sensors 8 and 5, respectively.

After the model has been validated, the climate data derived from Meteonorm are used in order to examine the hygrothermal performance of the log walls under past and potential future conditions. In the framework of this set of simulations, it is assumed that the indoor air temperature and relative humidity are equal to the outdoor ones. This hypothesis is reasonable, since the building has neither transparent elements nor Heating Ventilation and Air Conditioning system (HVAC). Furthermore, the poor airtightness of the envelope has been verified by a pressurization test conducted within the framework of this research. The hygrothermal performance of the building components is assessed for the 10th year of the computational simulation, so that the results are not affected by initial conditions.

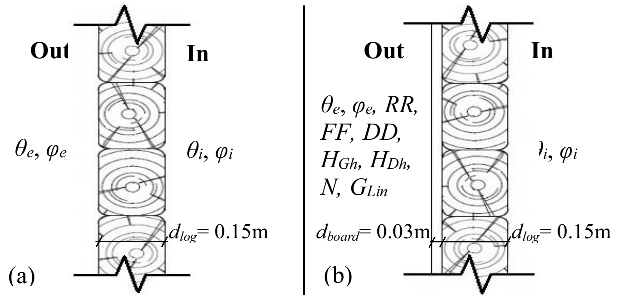

Fig. 7. Cross section and boundary conditions of (a) the log walls protected by the coating and (b) the upper gable walls.

3 Results

3.1 Measurements

From Fig. 8a and b it can be observed that the air temperature and relative humidity measurements derived from the sensors are in accordance with the respective measurements from Melsom weather station, 5.8km far from the project's site. Furthermore, it is seen that the lower mean air temperature and the higher mean relative humidity values occur outdoors, followed by the interior on the second level of the building and finally the first level. Furthermore, the highest range of these two parameters is monitored outdoors and the lowest one on the first floor. In the 1st of December, extreme high temperatures and extreme low relative humidity values were monitored by the sensors indoors. These measurements are linked to the function of a portable radiator inside the building, used by the workers conducting rehabilitation work. Due to these extreme values, measurements from that day are not considered in the description of results in this section. Moreover, in Fig. 8a, b and c it can be observed that within the fourth and the fifth week of the analysed period there is an absence of high air temperatures, which is linked to the high relative humidity and moisture content values that were recorded. On the other hand, in the last two weeks higher temperatures and lower relative humidity and water content values were observed.

In Fig. 8a, the difference between the outdoor air temperature and the air temperature on the second level is on average 0.05°C, while its maximum value is 3°C. The respective temperature differences for the first level are 0.21°C and 3.10°C, while inside the wood they are 0.24°C and 4.82°C. Moreover, the extreme minimum and maximum temperatures inside the wood occur later than the respective ones on the outdoor environment. This time lag is approximately 2 hours.

In Fig. 8b it is observed that more than 80% of the air relative humidity measurements derived from the sensors are higher than $\varphi = 85\%$. The respective measurements from Melsom weather station correspond to slightly lower values. However, taking into account that the project's site is closer to the sea and that φ is highly dependent on the local environmental conditions, measurements from sensors are considered to be credible. The difference on the relative humidity between the ambient environment and the second level of the building is on average 1.13% and at maximum 9.7%. The respective values for the first level are 3.71% and 16.4%.

In Fig. 8c it is observed that high moisture content values are monitored by all four sensors. However, the fact that the air temperature remains in low levels within the examined period is determinant to the insignificant mould risk of the logs. The highest mean values and range of the water content measurements in the log walls are observed on the second level. Within the second level, the respective values for the south oriented wall are higher and exceed the ones measured for the north oriented wall by 0.98% on average and 2.39% at maximum. Moisture content measurements on the first level appear to have smoother fluctuations.

3.2 Validation of the model

In Fig. 9a and b simulated, and the respective measured temperature and moisture content values are presented. Simulation results correspond to the average values of the examined parameters along a depth of 10mm from the inner side of the wall. This approach makes simulation results consistent with the actual measurements that take place in the installation depth of 10mm. It is worth mentioning that the simulation results are independent of the orientation of the wall configurations, based on the assumed boundary conditions. Thus, simulated values vary only between the different levels of the building.

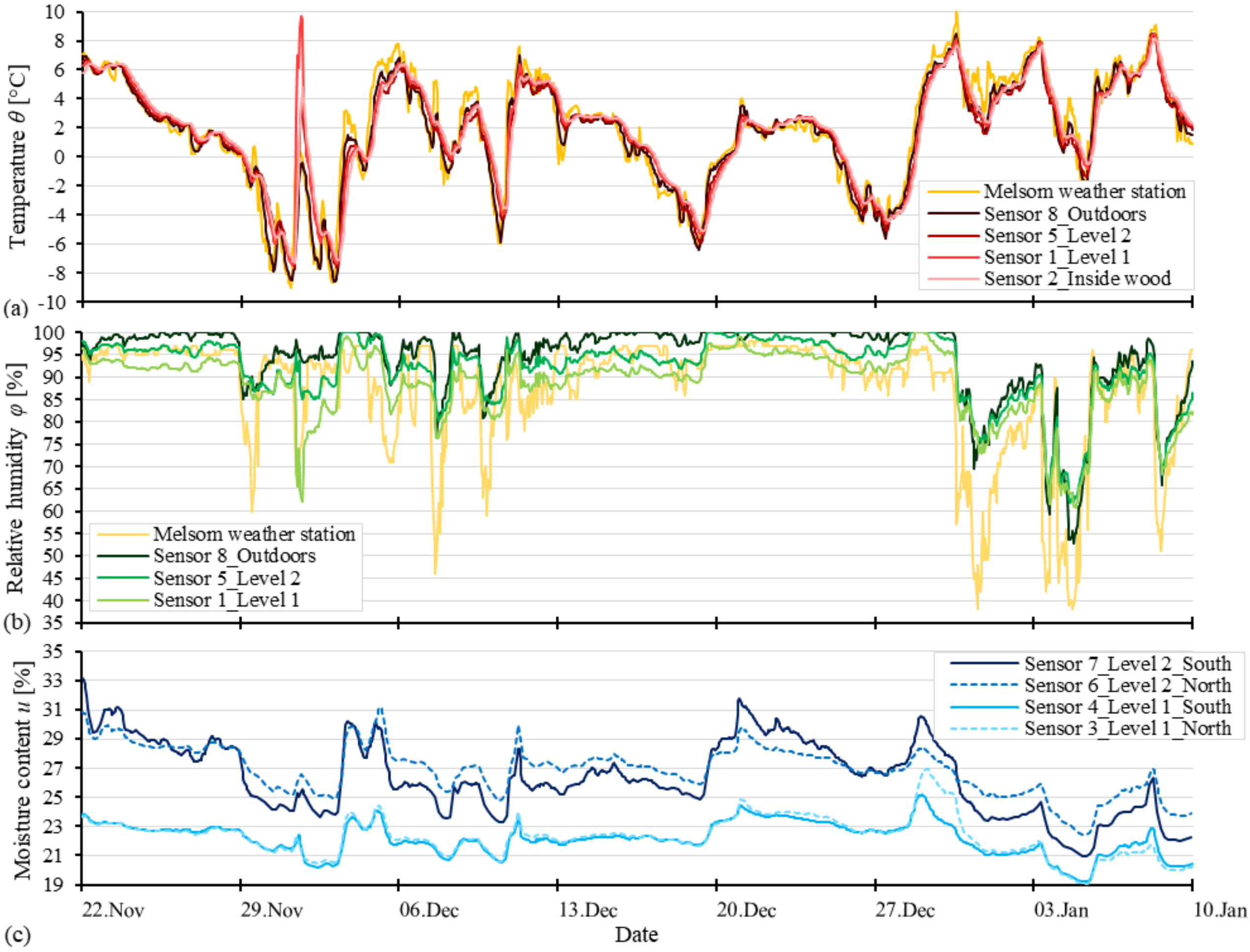

Fig. 8. Measurements of (a) air and wood temperature, (b) air relative humidity and (c) moisture content in wood.

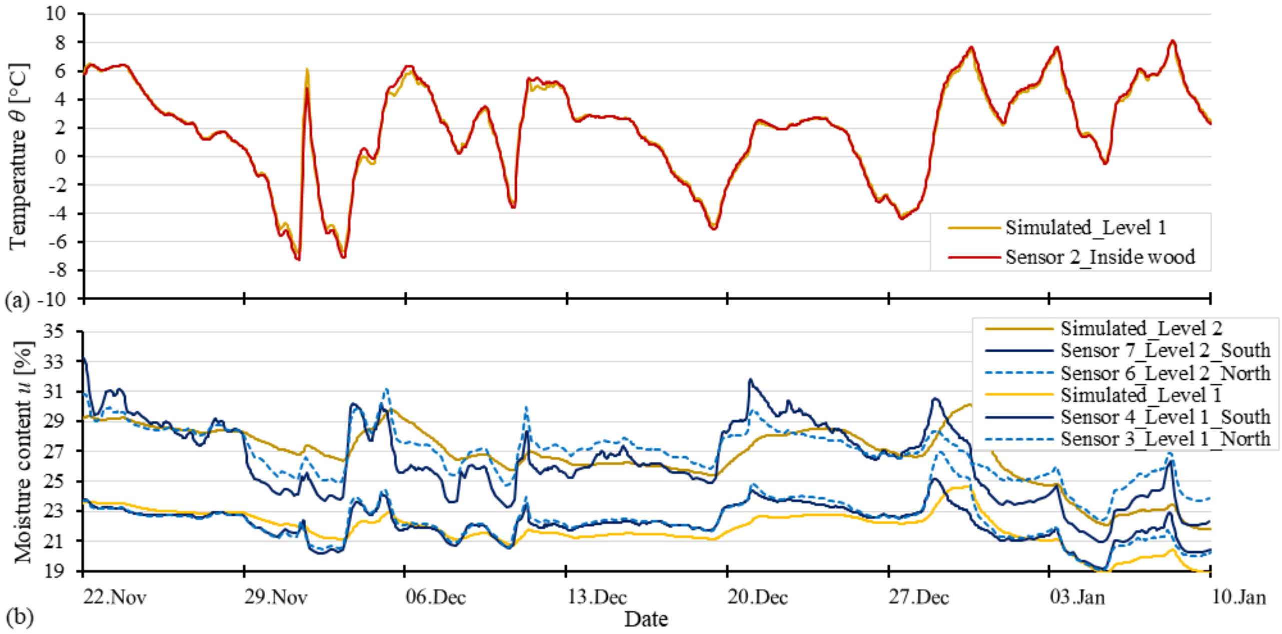

Fig. 9. Comparison between simulations and measurements of (a) wood temperature and (b, c) moisture content in wood.

From Fig. 9a and b it is observed that simulations' results fluctuate in a similar way to the respective measurements. The mean difference between the simulated and the measured temperature values is 0.015 °C, while at maximum it reaches 0.72°C. The water content simulation results fit better with measurements in the case of the first floor. Within the first level, the difference between the simulated and the measured values is equal to 0.72% on average and 2.58% at maximum for the south oriented wall, while for the north oriented wall the respective differences are equal to 0.83% and 3.29% respectively. On the second level, the greatest difference between the simulated and the measured values is observed for the south-oriented wall and it is 1.24% on average and 4.45% at maximum. The respective values for the north oriented wall are 1.02% and 3.97%. The observed differences are acceptable in order to consider the model validated.

3.4 Mould risk

The mould risk of the log walls is examined under the past and the potential future climate conditions. It is worth mentioning that the model is suitable for the interior surfaces and the interface between the boards and logs. It is also credible in the case of the exterior side of the log walls protected by the coating. However, in the case of the exterior side of the upper gable walls there are additional factors that may cause mould growth (e.g. standing water) as well as factors that mitigate mould growth (e.g. heating from sunlight, spore-kill by UV radiation, washing by rain) [11]. Thus, results for this case are not reliable.

For all the analysed cases, the calculated mould indices are found to be lower than 1, corresponding to insignificant mould risk [12]. However, comparing the mould indices of the past years to the future ones, an increasing trend can be observed. Higher values of the mould index correspond to the positions on the outer surface of the log walls that are untreated. On the other hand, the outer surfaces treated with tar have a mould index equal to zero. Zero mould index is also estimated for the interface between the logs and the boards on the upper gable walls.

Table 2. Mould indices for the log walls estimated for a one-year period under past and potential future climate.

Building element	Orientation	Surface		Mould index	
				2000-09	2100
Log wall protected by the coating	All	Interior		0.189	0.207
		Ext.	Treated with tar	0.000	0.000
			Untreated	0.961	0.997
Upper gable wall	East	Interior		0.078	0.107
		Interface between board and log		0.000	0.000
		Exterior		0.041	0.064
	West	Interior		0.072	0.104
		Interface between board and log		0.000	0.000
		Exterior		0.033	0.056

4 Discussion

In this study, measurements and analytical tools were employed in order to investigate the climate change impact on the biodegradation of a historic timber construction. From the in-situ inspection it was observed that the building is maintained in a good condition. Damages where observed on the coating and the roof, while the original log walls of the construction remain unaltered. Damages on the timber boards can be fixed by the typical rehabilitation work organized by the administrators of the monument. Thus, the focus is to investigate whether the original logs that form the main body of the building are at risk of biodeterioration. Results revealed that there is no mould risk for the logs of the construction, at least for the climate conditions upon which the study was based. These results are highly connected to the particular design of the building that protects it from moisture sources, such as rain and ground rising damp.

The hygrothermal model used in the study was validated. The simulation results of temperature and water content fit good with the respective measurements. Moreover, the biohygrothermal model's results that indicate zero mould risk for the log walls under their current condition are verified by in-situ inspection. Thus, it is considered that the employed model represents sufficiently the physical problem.

Future predictions are highly dependent on the climate conditions that are used as an input in simulations. The climate data used within this study indicate an increase of the mean annual temperature equal to 1.2°C. This temperature increase is lower than the one accounted in other studies, which is considered equal to 4.4°C for the investigated area [3].

Furthermore, in the numerical simulations for the future years, it is considered that in the interior climate has no significant variation from the exterior one. Based on the nowadays measurements, this assumption is valid to a high degree and it can be explained by the poor airtightness of the building, the absence of transparent elements and HVAC systems. It would be more accurate to produce and use a function that estimates the indoor temperature and humidity values from the outdoor ones. In order to create a function representative of the actual phenomenon, measurements of indoor and outdoor air temperature and humidity for at least one year should be collected and processed. Finally, a more thorough investigation of the geometry and the exact shape of the log walls would reveal possible weak points of the historic building that need more detailed analysis.

5 Conclusions

The purpose of this research is to investigate the climate change impact on the biodeterioration of the log walls of a historic timber construction in southern Norway. The main changes in climate parameters considered for the studied area are an increase of the annual air temperature by 1.2°C and of the precipitation by 36% until 2100. Under the influence of these changes, the deterioration of the building elements exposed to rain are expected to intensify. However, the logs that form the main body of the construction are not threatened by mould. Higher values of the mould index correspond to the positions on the outer surface of the log walls where the tar treatment have been removed throughout the years. The good condition of the log walls is highly dependent on the passive systems integrated on the initial building design. More specifically, these systems are the coating, the stumps and the openings that protect the building from rain, ground rising dump and indoor sources of moisture. Future work should focus on a more detailed modelling of the microclimatic conditions and the vulnerable building parts of the construction.

This work is a part of the HYPERION project. HYPERION has received funding from the European Union's Framework Programme for Research and Innovation (Horizon 2020) under grant agreement No 821054. The contents of this publication are the sole responsibility of Oslo Metropolitan University and do not necessarily reflect the opinion of the European Union.

References

1. K. Dow, T. E. Downing, The Atlas of Climate Change: Mapping the World's Greatest Challenge, Univ of California Press (2016).
2. B. C. O'Neill, M. Oppenheimer, R. Warren, S. Hallegatte, R. E. Kopp, H. O. Pörtner, R. Scholes, J. Birkmann, W. Foden, R. Licker, IPCC reasons for concern regarding climate change risks, Nat. Clim. Change. **7,** 28-37 (2017)
3. I. Hanssen-Bauer, E.J. Førland, I. Haddeland, H. Hisdal, S. Mayer, A. Nesje, J.E.Ø. Nilsen, S. Sandven, A.B. Sandø, A. Sorteberg, B. Ådlandsvik, Climate in Norway 2100–a knowledge base for climate adaption, NCCS report (2017).
4. A. S. Kaslegard, Climate Change and Cultural Heritage in the Nordic Countries, Nordic Council of Ministers (2011).
5. A. Loli, C. Bertoli, Indoor multi-risk scenarios of climate change effects on building materials in Scandinavian countries, Geosci. J **8** (9), 347 (2018)
6. T. Grøntoft, Observed Recent Change in Climate and Potential for Decay of Norwegian Wood Structures, J. Clim. **7**(2) 33 (2019)
7. J. Remund, S. Müller, M. Schmutz, D. Barsotti, C. Studer, R. Cattin, Metenorm–Global Meteorological Database Version 7, Handbook Part I: Software, Meteotest, Swiss Federal Office for Energy, Bern (2020).
8. IPCC, Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland (2007)
9. IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland (2014)
10. A. Karagiozis, H. Künzel, A. Holm, WUFI-ORNL/IBP-a North American hygrothermal model, Performance of Exterior Envelopes of Whole Buildings, **VIII**, 2-7 (2001)
11. K. Sedlbauer, Prediction of mould fungus formation on the surface of and inside building components, Fraunhofer Institute (2001).
12. H. Viitanen, M. Krus, T. Ojanen, V. Eitner, D. Zirkelbach, Mold Risk Classification Based on ComparativeEevaluation of Two Established Growth Models, *Energy Procedia* **78**, 1425-1430 (2015).