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RESEARCH

Climate-induced risk assessment of the quarantine room in a University Library

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Abstract
Microclimate conditions in conservation spaces such as museums, galleries, storages, archives, and libraries significantly impact the preservation of cultural materials, potentially leading to permanent damage. This study focuses on quarantine rooms, essential for isolating and inspecting incoming collections for infestations or contamination. Despite their importance, systematic microclimate investigations in such spaces have not been conducted until now. In this research, temperature and relative humidity monitoring has been conducted over the past 3 years (i.e., 2021-2022-2023) within the quarantine room of the Norwegian University of Science and Technology (NTNU) University Library (located within the DORA I concrete bunker, Trondheim, Norway). Data analysis revealed stable indoor conditions due to the buffering capacity of the massive building envelope together with climate control system. Specific metrics for the estimation of climate-induced chemical and biological risks on vulnerable artifacts were applied to compute the percentage of time for which thermohygrometric conditions could favour cellulose hydrolysis and biodeteriogens proliferation on a yearly basis. In this way, the study provided a decision-making tool useful to evaluate the best time (in terms of safest temperature and relative humidity conditions) when to introduce incoming collections into the quarantine room, depending on the material they are made of and on the timeframe selected for their isolation.

Keywords: Microclimate · Thermohygrometric monitoring · Quarantine room · Paper collections · Archival materials · Microclimate impact-drivers · Bunker

1 Introduction

Microclimate conditions in buildings such as museums, galleries, storages, archives, and libraries, whether they are temporary or permanent conservation spaces, could strongly impact the chemo-physical and mechanical properties of cultural materials with serious consequences, even resulting in potentially permanent damage. Therefore, microclimate investigation can support the climate-induced risk assessment within these spaces.

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Quarantine rooms represent holding areas where *"objects can be isolated, and inspected over a set period of time for signs of infestation/contamination"* and where, according to (EN 16790:2016) a specific strategy for the preservation of objects is adopted (Integrated Pest Management - IPM), in order to avoid and manage pest activity. Based on this, it should be a common practice that conservation spaces in the process of hosting incoming collections ideally have specific quarantine areas (De Ruijter et al. 2010). However, the implementation of this is very often challenged by the absence of dedicated spaces. Incoming objects should be temporarily isolated (i.e., from 2 weeks to 40 days) and visual inspections regularly carried out by conservators, preferably combined with continuous monitoring of entomological species to assess pest activity using adhesive traps. Once the quarantine period is over, and hence there is no risk of biological contamination spreading to other collections, the objects can be then transferred to a permanent conservation or exhibition area where they can be safely stored or displayed.

Quarantine rooms in libraries and archives are of crucial importance as the collections in such spaces are mainly constituted by a wide range of organic hygroscopic materials (e.g., paper, leather, bookbinding glue). Such materials naturally undergo an unavoidable aging process and are vulnerable to biological and chemical processes. Specifically, in this case books and paper-based materials are inspected by paper conservators to check for signs of fungal and/or insect pests' infestation, as well as of ongoing and progressive chemical reactions taking place in the materials. These processes are influenced by various factors such as the acidity of paper and degree of polymerisation (Strlič et al. 2020), but they are also significantly affected by indoor climate conditions (Menart et al. 2011).

Microclimate investigations in quarantine rooms have never been systematically conducted. The present research demonstrates for the first time the importance of monitoring thermohygrometric conditions within such spaces. In fact, this investigation is crucial not only to support IPM procedures in avoiding biological infestation and contamination, but also to evaluate other aspects such as the chemical risks potentially associated with the cultural objects. This paper aims to assess the climate-induced risks based on the analysis of microclimate observations collected over three years (i.e., 2021-2022-2023) within the quarantine room of the Norwegian University of Science and Technology (NTNU) University Library. The approach allows to identify the most favourable periods for bringing incoming collections of archival materials into the room, representing a useful decision-making tool for archival staff.

2 Materials and methods

The quarantine room of the University Library in NTNU is located within the World War II U-boat facility of Dora I (Trondheim, Norway) (Fig. 1a). Dora I is a marine and terrestrial reinforced concrete bunker, characterized by a massive structure (covering approximately 16,000 m² in area and standing 22 m tall) and very thick external walls (up to 3.5 m at their base, slightly decreasing their thickness as the construction rises in height). Nowadays, it houses several collections from various archives, museums, and cultural institutions, thus preserving a rich heritage of significant cultural value. Incoming cellulose-based heritage objects (Fig. 1b) are kept within the quarantine room– an open space shared with different

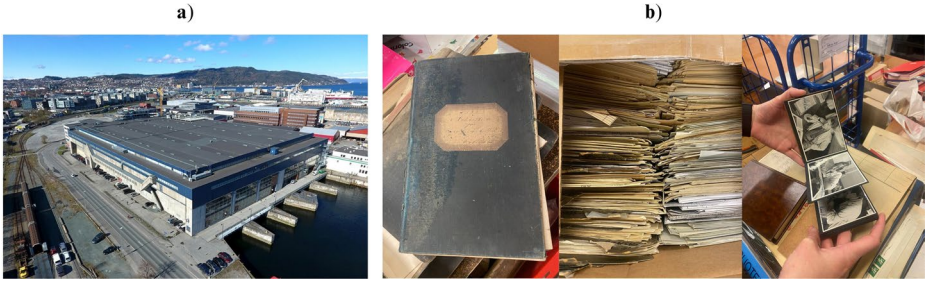

Fig. 1 (**a**) DORA I U-boat bunker with an indication of the location of the quarantine room within the building. (**b**) Incoming cellulose-based heritage objects stored within the quarantine room

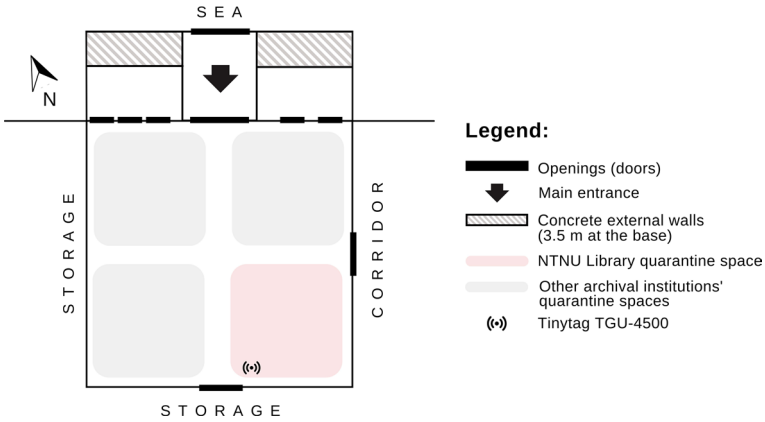

Fig. 2 Plan of the quarantine room

archival institutions - from 2 weeks to 40 days, to monitor for signs of infestation or contamination before being transferred to the library's permanent storage.

Figure 2 shows the area of 390 m^2 within Dora I devoted to the quarantine room (pink square is the NTNU Library's space under study). Temperature (T) and relative humidity (RH) data were collected through one TinyTag-TGU-4500 (manufactured by Gemini Data Loggers) in total, located at 1.6 m above the floor, near to the southern wall, as shown in Fig. 2. Data were analysed for the period 2021–2023, also considering T-RH outdoor data monitored by the WMO compliant weather station (SN68050, Lat. 63.4ºN Long. 10.4ºE) ~ 2 km far from the case study. The uncertainties of the TinyTag-TGU-4500 T and RH sensors, equal to ±0.5 °C and ±3.0% respectively, are in accordance with European Standards (EN 15758:2010; EN 16242:2012), and the time interval between consecutive observations was set to 3 h.

The overall quality of both indoor and outdoor data was assessed by using the Completeness Index (CoI) and the Continuity Index (CI) as reported in (Frasca et al. 2017). Afterward, climate-induced chemical and biological risks on the paper collection were evaluated through the metrics reported in Table 1.

The chemical risk was assessed through three different metrics by estimating the risk for cellulose hydrolysis to affect acidic paper, cellulose acetate, and generic cellulose materi-

Table 1 Summary of the climate-induced risk metrics

Material	Process	MCID*	Metric	Code	Ref.
Acidic paper	Cellulose hydrolysis	T-RH	Expected Lifetime (EL)	CHEM_1	(Strlič et al. 2015; Verticchio et al. 2022)
Cellulose acetate		T-RH	Preservation Index (PI)	CHEM_2	(Nishimura 2011; Reilly et al. 1995)
Generic cellulose material		T-RH	Lifetime Multiplier (LM)	CHEM_3	(Michalski 2002)
	Mould spore germination	T-RH	Lowest Isopleth for Mould (LIM)	BIO_1	(Sedlbauer 2001)
	Insect growth	T RH	Growth Index (GI)	BIO_2 BIO_3	(Brimblecombe and Lankester 2013; Verticchio et al. 2023)

*MicroClimate Impact-Driver

als (e.g., books, newspapers, photographs and photographic films). This mechanism is the major recognized deterioration risk for unstable museum materials such as paper collections (Michalski 2002). A brief description of the applied risk metrics is reported as follows:

- *Expected Lifetime (EL)* - indicates the time required for objects to become unfit for use, computed as a function of the initial degree of polymerisation (DP = 600 in the case of acidic paper) and the critical degree of polymerisation (DP_0 = 300 typically), at which objects are no longer suitable for general access (Strlič et al. 2015). The damage function from which it is derived relates the DP loss with the pH of paper and the indoor T and RH at the reference conditions of dark storage (i.e., natural and artificial lights are not considered). 500 years is considered to be the threshold below which T and RH levels affect the durability of acidic paper.
- *Preservation Index (PI)*– expresses the "preservation quality" of a storage environment at the time of measurement (Nishimura 2011). It was developed in the case of chemical degradation of acetate cellulose (Reilly et al. 1995), but it can be extended to other organic materials. PI values, expressed in units of years, show the combined effect of T and RH on the decay rate of vulnerable organic materials in collections and provide an estimate of the time it would take for significant deterioration to occur. A period of 45 years is considered as the threshold below which T and RH levels affect the durability of acidic paper.
- *Lifetime Multiplier (LM)*– returns a multiplier factor that compares the pairs of monitored T and RH with an indoor reference temperature of T_{ref} = 20 °C and of relative humidity RH_{ref} = 50%, allowing a comparison with the standard values (Michalski 2002). LM values lower than 1 are considered high risk for the proper conservation of generic cellulose materials.

At the same time, biological risk was evaluated through the following two metrics to estimate respectively the risk for mould spore germination and T/RH-dependent insect growth. The metrics are synthetically described as follows:

- *Lowest Isopleth for Mould (LIM)* - defined by (Sedlbauer 2001). Isopleths are curves of equal risk defining the T and RH conditions at which some species of fungi can germinate and grow on cellulose material. T and RH from the room under investigation have been compared with the Sedlbauer isopleths, considering the critical RH* as the one

associated with the LIM (i.e., the lowest curve where mould activity is assumed to begin for a specific substrate (Verticchio et al. 2023).

- *Growth Index (GI)*– here defined as the number of days in a year when T and RH are favourable to the growth and proliferation of insects that could pose a substantial threat to cellulose material. The following thresholds have been considered according to the literature (Brimblecombe and Lankester 2013; Child Robert 2007): T ≥ 15 °C and RH ≥ 30% for temperature dependent insects (i.e., *Stegobium paniceum*) and T ≥ 15 °C and RH ≥ 70 °C for humidity-dependent insects (i.e., *Anobium punctatum*).

Three years of daily microclimate observations were analysed to assess changes in the climate-induced risks over time, and to identify the optimal period for temporarily hosting incoming collections. To this purpose, the periods of the year when T and RH conditions exceeded the defined risk thresholds for each of the six metrics were highlighted. Specifically, the risky conditions in terms of chemical processes were estimated as the number of days when: EL < 500 years for acidic paper (CHEM_1); PI < 45 years for cellulose acetate (CHEM_2); LM < 1 for generic cellulose materials (CHEM_3). Similarly, the risk of biological degradation was estimated as the number of days when: RH > critical RH* for generic cellulose materials (BIO_1); T ≥ 15 °C and RH ≥ 30% for T-dependent insect growth (BIO_2) and T ≥ 15 °C and RH ≥ 70% for RH-dependent insect growth (BIO_3), for generic cellulose materials.

3 Results and discussion

The quality of indoor temperature and relative humidity time series (by using CoI and CI) is complete and continue with CoI and CI close to the unity, while outdoor time series have few missing values in 2023. The high quality demonstrated by the indices for all the considered years made them suitable for subsequent data analysis. In Fig. 3, the time series of daily indoor (black line) and outdoor (grey line) T and RH are reported. It can be noted that indoor T is poorly affected by outdoor climate. This can be attributed to the combined effect of a climate control system (only designed for maintaining a constant temperature) and of

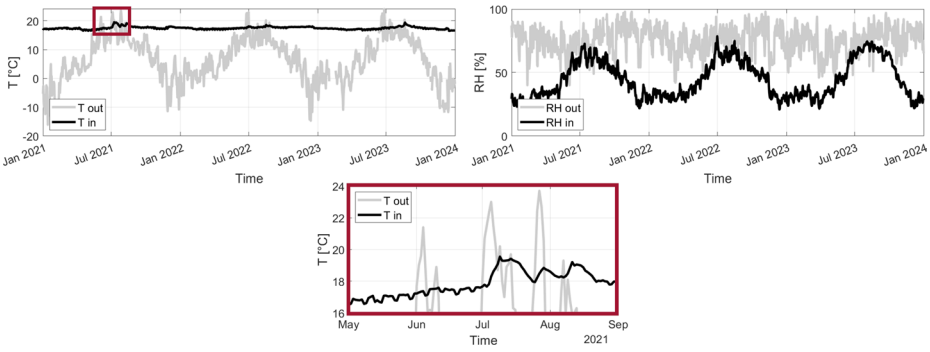

Fig. 3 Time evolution of indoor and outdoor temperature (left panel) and relative humidity (right panel) data from the TinyTag-TGU-4500. In the red box (central panel), a zoom of the temperature conditions during the summer season of 2021

the building envelope features (being a reinforced concrete construction with very thick walls up to 3.5 m at their base that can smooth out the largest outdoor thermal variability).

Within the red box (lower panel in Fig. 3), the summer temperatures of 2021 are shown as an example. In this case, when the control system for heating and ventilation is turned off (as it is during the weekends), the thermal inertia of the indoor space is still ensured by the heavy walls of the bunker (indoor T daily peaks are delayed with respect to the outdoor ones for a minimum of 2 days in 2023, to a maximum of 35 days in 2021).

In Fig. 4a, a tool for quarantine room management in NTNU Library is presented. Times of the year when temperature and relative humidity conditions exceeded the defined risk thresholds for each of the six metrics are highlighted in red (different types of red per year). It should be noted that for the purpose of this study, time intervals equal to or less than 14 days between one risk period and another were still counted within the risk period. This choice was made considering that objects are kept within the quarantine room for a minimum time limit of 2 weeks.

The risk of chemical degradation due to cellulose hydrolysis is proved to be generally higher in summer (especially in July and August) for all three years, but also during autumn (from September until mid-November) for acidic paper (CHEM_1). The biological risk of mould spore germination (BIO_1) is minimal (i.e., almost 2 months at maximum) and mainly verified during July and August. Temperature-dependent insects (BIO_2) can pose a year-round threat due to the temperature values always being consistently above the threshold set at 15 °C, as the heating and ventilation system is designed to keep constant the temperature between 17 and 18 °C throughout the whole year. Relative-humidity dependent insects (BIO_3) could find suitable development conditions only during the summer months (July and partially August), when RH values exceed 70% for a sufficient period.

It is worth noticing that while the occurrence of chemical risk for acidic paper (CHEM_1) only slightly varies among the years, CHEM_2 for cellulose acetate and CHEM_3 for generic cellulose material seem to increase in 2023 as reported in Fig. 4b (especially in comparison with the year 2021). On the other hand, the occurrence of biological risk remains consistently high throughout all the considered periods for T-dependent insect growth (BIO_2), while it is proved to be higher in 2022 in the case of mould spore germination (BIO_1) and RH-dependent insect growth (BIO_3) when the quarantine room seems to experience greater occurrences of risky T-RH conditions.

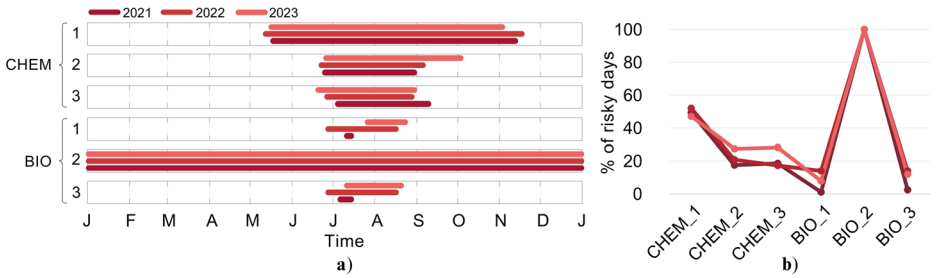

Fig. 4 (**a**) Quarantine room management plot and (**b**) the percentage of risky days for 2021-2022-2023, according to the metrics used for the estimation of climate-induced chemical and biological risks

4 Summary and conclusions

The study provided a decision-making tool useful to archival staff for estimating the best time (in terms of safest temperature and relative humidity conditions) to bring incoming collections of archival materials into the quarantine room, depending on the material they are made of and the time chosen for their isolation. To this purpose, the microclimate observations collected in the quarantine room of the NTNU University Library were analysed over three-years to create a pathway for integrating a climate diagnosis for the preservation of incoming items. Outcomes indicated stable indoor temperature conditions, attributed to the climate control system and to the buffering capacity of the massive building envelope of the bunker. Specific metrics for the estimation of climate-induced chemical and biological risks on vulnerable artifacts were applied to compute the percentage of time for which temperature and relative humidity could favour cellulose hydrolysis and biodeteriogens proliferation every year.

Chemical degradation risks were generally higher during summer, with acidic paper possibly being at risk of cellulose hydrolysis also from late May to mid-November. Biological risks were generally lower (and especially verified during summer months), except for T-dependent insect growth risk which was maximum throughout the year. Interestingly, the overall risk notably increased compared to 2021, which can be considered the year with the lowest T-RH risky conditions according to nearly all the metrics used. In contrast, 2022 shows more unsafe conditions suitable for biological proliferation (BIO_1 and BIO_3), while the last investigated year is the worst scenario for chemical degradation risk (CHEM_2 and CHEM_3). This suggests a need for ongoing monitoring and the formulation of conservation strategies to preserve vulnerable artifacts in the library's collection. In fact, to avoid further increasing of conservative risks over time, some strategies should be undertaken such as keeping the heating and ventilation system on and adjusting the set T value in the upcoming summer months, in order to manage and reduce the risks that given the trend of the investigated period, would likely tend to increase (i.e., chemical risk). However, further advanced analysis would be necessary to determine the best solution to adopt for indoor temperature control within this space throughout the year.

This contribution provided the archive staff with a decision-making tool based on microclimate impact drivers useful to evaluate the best time (in terms of safest T and RH conditions) when to introduce incoming collections into the quarantine room, depending on the material they are made of and on the timeframe selected for their isolation. In conclusion, it is worth noticing that while the 2-week minimum permanence time of cultural objects within the quarantine room may be sufficient for early detection of some risks, it might not be long enough to completely eliminate the possibility of latent issues, especially for slow-developing biological threats. Therefore, continuous monitoring and preventive measures remain crucial even after the quarantine period, while acknowledging that in some cases, these measures may not be sufficient and remedial treatments may be necessary (always prioritizing non-toxic methods).

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Author contributions G.B., F.F., C.B., AM.S. conducted the study conceptualization and methodology. TD.S. and E.L. performed data collection. G.B. performed data analysis and writing of the original draft. F.F., C.B., C.C., and AM.S. performed data analysis supervision and writing - review and editing. All authors commented on previous versions of the manuscript. All authors reviewed and approved the final manuscript.

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Data availability Data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

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