An Analytical Method for the Determination of the Climatic Distance between Different Microclimates for the Conservation of Wooden

RESEARCH PAPER

An Analytical Method for the Determination of the Climatic Distance between Different Microclimates for the Conservation of Wooden Cultural Heritage Objects

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This paper describes a statistical methodological approach for the comparison of different microclimates. This method was developed as a tool for choosing a new microclimate for temporary moves. At the present stage of development, this method is not intended to be used for identifying harmful conditions. The proposed method is based on experimental evidence indicating that the sensitivity of wooden objects to environmental fluctuations can differ from object to object, depending on many physical and mechanical parameters. Some objects could be affected by fluctuations that would not be significant for other objects. The parameter adopted in this work is equilibrium moisture content, that is the equilibrium value that a wooden object would tend to maintain under stable temperature and relative humidity values for a long period of time. It must be considered potential *because in a fluctuating climate it is never reached. The methodology is based on two parts. The first describes in a mathematically simplified way how climate is perceived by objects with different sensitivities. The second analyzes the* climatic distance *between different climatic data sets using the mathematical technique of principal components analysis, according to the previously defined object's sensitivity. As a test of the proposed method, four different microclimatic cases studies are analyzed and the results described.*

INTRODUCTION

For the conservation of wooden cultural heritage, microclimatic variations need to be investigated, and when necessary and possible controlled, because of the modifications they can produce on wooden artifacts. It is well known that wood is a hygroscopic material. It can adsorb or desorb moisture from the surrounding air, tending to reach an equilibrium condition defined mainly by air temperature and humidity. Sorption isotherms define such equilibrium, but it is also influenced by several other factors including the wood species and previous sorption history [1]. However, under unstable environmental conditions moisture exchanges occur continuously, according to complex laws, and equilibrium is rarely reached. Hence during the transient phases before equilibrium is reached, the finite diffusion velocity of moisture in wood material causes the formation of moisture gradients across the thickness and length of wooden objects.

Wood is also a highly anisotropic material. Its anisotropy is especially significant in its hygroscopic, shrinkage and swelling, rheological and mechano-sorptive behavior [2]. The resulting dimensional variations and internal strains and stresses can greatly influence the well-being and the correct conservation of objects made of wood, which in situations of climatic variation may undergo unacceptable stresses, cracks, permanent deformations, distortions and structural disconnections.

Moreover, wooden works of art typically include other materials as well, such as paint layers, which may be severely damaged even by deformations not sufficiently large to damage the wooden support. Conservation of wooden artifacts of cultural importance must therefore take into consideration not only average or typical values of the microclimatic environment in which they are conserved, but also the history and the variations of such conditions, which can endanger the survival of unique masterpieces [3]. The most traditional, and widely diffused, approach

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for preventing damage to wooden works of art due to environmental conditions relies on specifications that such conditions are maintained 'stable' within given limits. Examples of this approach may be found in the relevant literature, such as in Thomson [4] or in UNI 10829:1999 [5], where the approach to stability is described by means of classes of acceptable variation intervals, empirically defined as more or less safe.

However, prescribing 'optimal' ranges of environmental conditions may lead to satisfactory conservation only in appropriate situations. For instance, perfect stability is difficult to obtain, and it is even more difficult to guarantee for the entire lifetime of the objects to be conserved. Different classes of objects and materials have different 'optimal' ranges, and individual objects have their own individual characteristics and reactions, even when they are made of similar materials and belong to the same typologies. Most important, such an approach can be properly applied only for materials that do not preserve a 'memory' of the climate to which they have been exposed (e.g. metals, minerals). On the contrary, for the conservation of works of art made of hygroscopic materials which preserve a memory of the past microclimate (e.g. wood, ivory), the specific problems of each individual object are much more complex than those defined by average properties of materials and average microclimatic conditions used to define hypothetical well-being intervals. A synthetic analysis of the state of the art of microclimatic standardization can be found in Dionisi-Vici et al. [6]. Further standardization work is being performed in CEN/TC 346 (the European Technical Committee dealing with the conservation of cultural property), where the notion of 'historic climate' (i.e. the climate to which a given work of art has been exposed during most recent periods) is being introduced, in order to suggest appropriate criteria for identifying 'optimal' conditions for individual works of art [7]. Even in that framework, the work reported in this paper can contribute to the objective appraisal of climatic parameters.

OBJECTIVES, LIMITS AND FIELD OF APPLICATION

The work reported here was performed in the framework of standardization studies, aiming to establish criteria for evaluating the suitability of given real microclimates for the conservation of wooden artifacts of cultural importance, from the point of view of preventing decay and/or physical-mechanical damage [8, 9]. Specifically, the aim of this study is to establish a method for analyzing the microclimatic sets:

- for describing the evolution in time of an individual set of microclimatic data; and
- for comparing different microclimatic data sets that can characterize different sites or different periods in a same site.[1]

This method does not provide criteria for assessing which environmental conditions may lead to damage of wooden materials and/or objects. However, it has been conceived so that it can objectively provide evidence of thermo-hygrometric conditions and their variations, which may be significant from the conservation/damage point of view. Such damages may be grouped in the following main categories:

- moisture conditions that may favor fungal decay (i.e. wood moisture content is more than 18–20% for sufficiently long periods of time) or some aspects of insect attack; and
- moisture values (at equilibrium) or moisture gradients (during transients) that may lead to damage, such as unacceptable distortions and/or stresses, caused by shrinkage, swelling and related mechanical phenomena.

Many other factors may be involved in the damage of wooden artifacts (including other aspects of insect attack, radiation, chemicals, vibrations, impact, past history of the artifact itself), but they are not considered by this method.

The main aim of this method is to support those responsible for the conservation of wooden objects of cultural importance (such as museum directors, conservators, restorers, etc., the caretakers of much of the world's cultural heritage), by providing a tool capable of (a) characterizing significant climatic variations in exhibition sites, and (b) comparing different micro-environments (e.g. when modifying a site's microclimate or when transporting objects for restoration or temporary exhibitions).

THE BASICS OF THE PROPOSED METHOD

A prerequisite for the implementation of the proposed method is the availability of a set of climatic data,

[1] *Microclimate = the usual trend of physical parameters (temperature, relative humidity, etc.) that characterize the air of a limited environment, such as the room of a museum where wooden works of art are exhibited. Set of microclimatic data = the set of physical parameters (temperature, relative humidity, etc.) that characterize the air of a limited environment.*

recorded from the considered environment with a sufficiently high acquisition rate, during a sufficiently long length of time. Typically, a data-logger is used, with a sampling interval of 15 minutes, and it is considered that the monitoring interval should not be shorter than one year [9]. The analysis of data is then performed according to the two following phases:

- Phase 1 (see section on Description and Implementation of the Analytical Model, Part 1) processes the raw data into synthetic parameters, describing the considered environment with reference to the considered object. Stable and transient periods of climatic sets are derived from the raw data by using a procedure implementing the two parameters, called δ (the largest range of variation which is assumed to be irrelevant for the examined phenomena) and T_{min} (the minimal duration for a period to be considered as *stable*). These two parameters should be chosen according to needs identified by competent conservators/scientists for individual objects. Phase 1 leads to the characterization of given micro-environmental conditions by providing parameters that may help experts in conservation express objective judgments/evaluations based in general on the characteristics and the conservation needs of whole classes of objects, and in many cases on the properties, history, present conditions and needs of individual objects. For instance, it is obvious that the requirements for an environment acceptable for timber beams, supporting the roof of a historic building, may not be the same as those for conserving a precious panel painting. The characterization can be functional both for evaluating the suitability of an existing micro-environment and for specifying the characteristics required for an environment to be implemented. Phase 1 has been described in detail elsewhere [6], and will only be briefly recalled in this paper.
- Phase 2 (see section on Description and Implementation of the Analytical Model, Part 2) enables the comparison between different microclimatic situations by providing a synthetic parameter that expresses the microclimatic distance between two microclimatic sets. The stable and transient periods obtained in Phase 1 are analyzed and compared using a multivariate statistical method able to highlight 'climatic differences'. This method is presented and discussed in greater detail in this paper.

It should be emphasized that although the analysis carried out on the microclimatic sets in this paper describes the microclimatic conditions through two parameters defined (see below) as *values* and *duration of plateaus* and magnitude of *ramps* (amount of variations between plateaus), other criteria and/or parameters could also be adopted. It could be possible, for example, to consider as an expression of stability the rate of variation between the plateaus (more or less steep ramps) and the magnitude of the differences between the plateaus. In Phase 1 the method computes, on the basis of parameters chosen according to the assumed sensitivity of the object, the number and magnitude of plateaus and ramps, but the comparison criteria adopted in Phase 2 can be applied to any kind of parameters.

DESCRIPTION AND IMPLEMENTATION OF THE ANALYTICAL MODEL

PART 1: PROCEDURE FOR IDENTIFYING STABLE AND TRANSIENT PERIODS

Data verification and smoothing

After checking the consistency and the congruence of microclimatic data sets (air temperature and air relative humidity), a set of wood equilibrium moisture content (EMC) [10] values is calculated from them (see subsection on calculation of wood equilibrium moisture content). EMC data are processed with a smoothing technique (moving average) to avoid non-systematic components, sudden transitions (strong variations in very short times) and noise [11–13]. In this paper, in order to make them comparable, after the calculation of EMC the microclimatic data were organized in periods of the same length (one year).

Choosing the significant parameters

δ, the 'stability parameter', is chosen 'arbitrarily', on the basis of the kind of object considered. δ identifies the maximum variation within which, by definition, the EMC is to be assumed 'stable' for the considered object.

T_{min}, the 'duration parameter', is also chosen 'arbitrarily', on the basis of the kind of object considered. T_{min} is the minimum length of time during which EMC may be considered approximately stable. It might be interpreted as the minimum period required for a given wooden artifact to start reacting significantly to a change in environmental conditions, i.e. the minimum time required for thermo-hygrometric variations to affect a sufficient thickness of wood such that the physical-mechanical effects may be considered significant.

Any specific data sets, collected by monitoring a selected environment during a sufficiently long period of time, can be analyzed and characterized by means of a synthetic algorithm on the basis of 'arbitrarily' chosen values of δ and of T_{min}.

EMC (potential equilibrium moisture content) has been chosen in place of the two main thermo-hygrometric parameters, i.e. air temperature (Ta) and relative humidity (RH), in order to simplify the analysis and the whole procedure. In fact, EMC results from the combination of Ta and RH, since equilibrium isotherms for wood are basically the same regardless of the wood species [1]. Therefore, an equation has been fitted to Giordano's set of data representing typical wood EMC corresponding to combinations of air temperature and relative humidity.

It should be emphasized that EMC represents a property *of the air*, i.e. the MC equilibrium value *towards which the wood tends, instant by instant*. In fact, the actual MC of wood may be different, even by a large amount, depending on its recent history. The MC of wood would coincide with the EMC only if thermo-hygrometric conditions have been stable for a long time. Otherwise, only the very surface of wood would approach EMC, and moisture gradients would be present along the thickness and length of the piece. EMC may influence both the possibility of biological attack and the possible tendency to undergo dimensional changes.

Computing the resulting parameters

The parameters taken into consideration for Phase 1, in order to characterize a microclimate, are outlined in the following [6]:

1 EMC values are computed from the recorded air temperature (Ta) and relative humidity (RH).
2 EMC differences between two adjacent stable situations are then computed by the algorithm.
3 The speed of variation of EMC (which may affect the steepness of moisture gradients along the wood thickness and the magnitude of consequent strains and stresses) is also computed by the algorithm.

Calculation of wood EMC

The EMC values for wood are computed [6] using the following equation (1), derived by applying a special fitting procedure to EMC typical values as reported by Giordano [1]:

$$EMC = 100 \cdot \left[-0.0991 \cdot \tanh\left(-10.0529 \frac{RH}{100} + 0.0034 \cdot Ta + 9.9448 \right) + 16.0049 \cdot \tanh\left(0.5071 \frac{RH}{100} - 0.0014 \cdot Ta - 2.8132 \right) + 16.0152 \right] \quad (1)$$

where $0 \leq EMC \leq 30$, expressed as the percentage of dry wood mass; Ta is air temperature [°C]; and RH is air relative humidity, ranging between 0% and 100%.

Identification of stability and transition periods

The method aims to transform the actual microclimatic set in a succession of stable EMC periods, called *plateaus*, and of transition periods (called *ramps*), according to the specific sensitivity of individual wooden objects [6]. After the analysis, the original set becomes a succession of alternating plateaus (flat segments) and of transient periods connecting the plateaus. The parameters used to identify the plateaus are δ and T_{min}. If the EMC values remain within an interval 2δ wide for a time span ('period') longer than T_{min} the period is considered stable from an EMC point of view (according to this schematization, during such a stability period the object will react to achieve the corresponding average equilibrium conditions). Whenever the two conditions are not met, the period will be considered as part of a transient period from one plateau to the next (according to this schematization, during a transient period the object will react to achieve linearly changing equilibrium conditions). The choice of different δ and T_{min} produces plateaus different both in duration and frequency and a consequent different number of transients of different duration.

The algorithm operates according to the following steps:

1 On the basis of the chosen value for δ, the model identifies the stable periods (plateaus) of wood EMC, and computes duration and mean value of each stable period.
2 Given the chosen value of T_{min}, the model then describes the transition periods between two successive plateaus, and for each of these computes the extreme duration and EMC values; the average transition speed for each plateau is also computed.
3 The set of results thus obtained, on the basis of selected values of δ and T_{min}, characterizes the analyzed climate.

The stable period (plateau) for EMC is defined as a period of time during which EMC data verify the following conditions (Equations 2, 3 and 4):

$$\left|EMC(n) - EMC(n-1)\right| < \delta \quad (2)$$

where EMC(n) is the equilibrium moisture content at the time n; and EMC(n − 1) is the equilibrium moisture content at the time (n − 1).

$$\left|\max_{i=Iniz,\ldots,n}\left(EMC(i)\right) - \frac{1}{n+2-Iniz}\sum_{i=Iniz}^{n+1} EMC(i)\right| < \delta \quad (3)$$

where $\max_{i=Iniz,\ldots,n}\left(EMC(i)\right)$ is the maximum value of the EMC(i) values within i = Iniz, Iniz+1,…, n; Iniz is the initial instant of stable period that it is analyzing; and

EMC(i) is the equilibrium moisture content at the time (i).

$$\left|\min_{i=Iniz,\ldots,n}\left(EMC(i)\right) - \frac{1}{n+2-Iniz}\sum_{i=Iniz}^{n+1} EMC(i)\right| < \delta \quad (4)$$

where $\min_{i=Iniz,\ldots,n}\left(EMC(i)\right)$ is the minimum value of EMC (i) values with i = Iniz, Iniz+1,…, n.

The choice of parameter δ is arbitrary. However, several factors should be considered in choosing δ, including the precision of measuring devices, the accuracy of the model for EMC estimation, and the error propagation due to the use of such a model. For the analyses reported here, the following values of δ (most suitable for characterizing environments where sensitive artistic objects are preserved) were chosen:

- δ = 1: allows analysis of the very small microclimatic variations of the environment, i.e. a very fine analysis, suitable to the high sensitivity of precious objects such as painted panels, for which variations of more than 1% of the EMC can be significant;
- δ = 2: allows analysis of microclimatic variations of greater magnitude (±2% EMC), i.e. a coarser analysis of microclimatic processes, for objects with lower sensitivities.

Preliminary studies have shown that choosing parameter δ > 2 would result in a great loss of information regarding the analysis of microclimatic phenomena. It would lead to an excessively low sensitivity for locations where wooden cultural heritage objects are stored. In fact, the resulting 'smoothing' effect results in neglecting micro-environmental variations that may have a significant effect on such artifacts, which are very sensitive to small variations in EMC.

As mentioned above, T_{min} is the minimum duration (hours) for a time period to be considered in the analysis. It might be interpreted as the minimum period required for a given wooden artifact to start reacting significantly to a change in environmental conditions. It is noted that wooden artifacts may be influenced by several factors, including the physical-mechanical characteristics of the wood as well as of other materials constituting or coating the object, such as paint layers, etc. [14].

For the identification of the plateaus, the algorithm verifies whether or not the duration of each period is more than T_{min} (i.e. if the period is long enough to allow for the wooden artifact to start reacting to the changes in environmental conditions). If not (length of time period less than T_{min}), it includes the plateau into the previous transition period. After the plateaus are defined, the algorithm computes the magnitude and slope of the transition periods. In conclusion, all the values provided by the algorithm (the mean value and duration of plateaus, and magnitude and slope of the transition periods) derive from the choice of the two parameters δ and T_{min}. Several values of δ and T_{min} need to be used in order to explore different aspects of the micro-environment and to allow for a characterization corresponding to physical-mechanical characteristics of various types of wooden objects.

A program, created using Matlab® ver. 7.0, was used to determine the plateaus of EMC (or rather the EMC periods satisfying the conditions of the Equations 2, 3 and 4) and the characteristics of the transition periods. Program input is a file of smoothed EMC values. For output, the program provides four files of data:

1 The values of the piecewise-linear curve fit onto the EMC curve (see Figure 1).
2 For each plateau, the mean EMC value, the beginning time and the length of the stable period.
3 The magnitude of the ramp between two adjacent EMC plateaus is established with the following equation (5):

$$s = EMC(n) - EMC(m) \quad (5)$$

where s is the ramp magnitude; n is the beginning time of a plateau; m is the ending time of the previous plateau; and EMC(n) and EMC(m) are values of EMC of wood at times n and m.

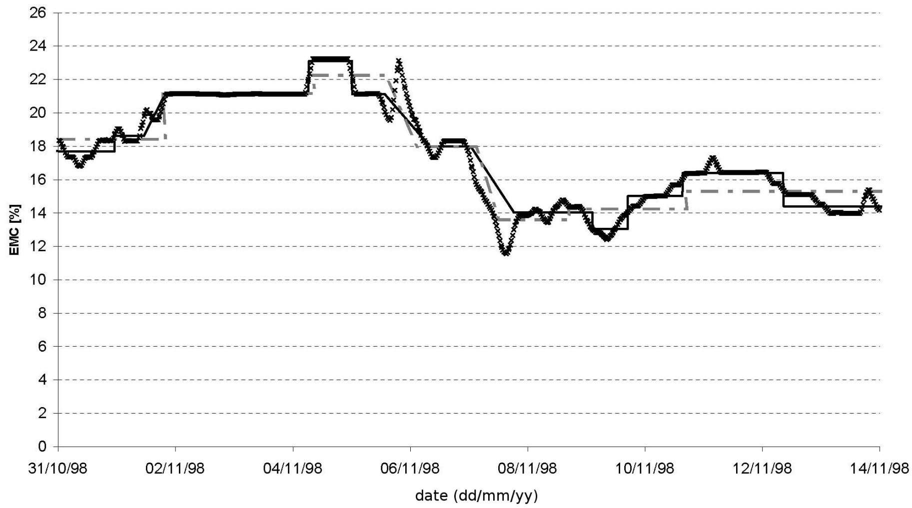

Figure 1 *Application of the method using data recorded in the San Donato church. The (x) line indicates original data; the continuous straight line indicates data after processing with δ = 1, the grey line (– · –) indicates data after processing with δ = 2.*

4 The slope (angular coefficient) of each part of EMC piecewise-linear curve represents the transition rate from one plateau to the next. The slope can be expressed with the following equation (6):

$$P = \frac{EMC(n) - EMC(m)}{n - m} \quad (6)$$

where P is the slope; n is the beginning instant of a plateau; m is the ending instant of the previous plateau; and EMC(n) and EMC(m) are the values of EMC of wood at times n and m.

DESCRIPTION AND IMPLEMENTATION OF THE ANALYTICAL MODEL

PART 2: PROCEDURE FOR ANALYZING 'DISTANCE' BETWEEN DIFFERENT MICROCLIMATES

In order to express synthetically the differences between microclimatic data sets recorded in different periods and/or sites, the following procedure is proposed, based on multivariate statistical techniques. This procedure (known as the *ellipses method*) allows a correct attribution of the examined samples to a restricted micro-environmental scope, and then samples become more easily detectable in comparison with the reference set (or sets). The aim is to define the variability context of the microclimates describing different conditions. This procedure [15, 16] makes it possible to compare two different sets of data at a time, correlating bivariated samples after each set has been analyzed by principal components analysis (PCA) [17–19].

Each sample is represented by the plateau mean value (EMC), and by its duration (Time). The principal components of a set of N bi-dimensional samples are the variables of a new coordinate system obtained by means of a roto-translation of the original system. The first principal component is a linear combination of original variables (normalized as to its own modulus), which corresponds with the maximum variance. At this point the original coordinate system (EMC, Time) is transformed into a new coordinate system (EMC', Time'), rotated by an angle α_m that shows the maximum variance compared to the previous coordinates. Geometrically, every set of samples can be represented as an ellipse, with the center in the mean point of the set, the major half-axis as the first principal component, and the minor half-axis as the second principal component.

In order to compare two sets of data, the method calculates the coefficient, T_{ij}:

$$T_{ij} = \frac{|M_i - M_j|}{\sqrt{S_i^2 + S_j^2}} \quad (7)$$

where $|M_i - M_j|$ represents the distance between the centers C and C' of the two ellipses (mean points of the two sets); and S_i and S_j represent the standard

(a) (b)

Figure 2 *(a) Separated ellipses:* $T_{ij} > 1$*; (b) the centers C, C' fall in the common zone of the two ellipses:* $T_{ij} < 1$*.*

deviation of the first and second sample, respectively. From the geometrical point of view S_i (S_j) is the length of the segment delimited by C (C') and P (P'), the intersection point of the straight line that passes through the centers of both ellipses. The two sets are significantly distinguishable if $T_{ij} > 1$, i.e. the greater the coefficient T_{ij}, the more the sets will be distinguishable.

We indicate with E1 and E2, respectively, the regions of a plane delimited by two ellipses. If the two ellipses are external: $T_{ij} > 1$ (Figure 2a), the two sets are separated. If the centers of the two ellipses are in the overlapping zone of the two ellipses, $T_{ij} < 1$, the two sets can be considered indistinguishable (Figure 2b) [15, 18, 19]. Further observations on this method are reported in the Appendix.

The same time period of one year was chosen for all the examined microclimatic data sets, in order to allow a consistent analysis. Furthermore, to avoid problems related to arithmetic instability of the algorithm and data overflow, the EMC values and the length of the plateaus were normalized according to the range. Thus, the variation range has been limited between 0 and 1.

After the calculation of the T_{ij} coefficient, expressing the microclimatic distance between different sets, the normalized values of the new reference system were re-transformed in the experimental value range in order to allow plotting on a graph. Finally, the method shows in a synthetic way the differences between microclimatic sets. For example, it would allow evaluating *a priori* how different (better or worse, according to the opinion of the people in charge of its conservation) a new location proposed for a wooden object would be, as compared to a previous one.

In order to guarantee a more fluid readability, the analysis of Phase 1 will be limited to a synthetic description of the groups of events that can be obtained applying different δ and T_{min} to the same raw set. The complete description of the results can be found in a previously published work [6]. The histograms representing the frequency distribution can be limited to the plateaus, considering that the ramps' magnitude and the slope classes are obtained as a 'statistical' difference between the total set duration and the time reserved to the plateaus. An example of the possible analysis will be displayed only for the first case, the Orsanmichele church.

EXAMPLE: TESTING THE METHOD ON REAL MICRO-ENVIRONMENTS

Description of the environments

In order to test the analytical method, it has been applied to real microclimatic data (Ta and RH) collected during various periods from the following four quite different micro-environments:

- the interior of the monumental medieval hall of the church of Orsanmichele, in the centre of Florence, Italy (data collected from December 2000 to November 2005);
- the interior of the twelfth-century parish church of San Donato in Polverosa [20], located in the western suburbs of Florence, Italy (data collected from September 1998 to August 1999);
- the interior of an historic building located in a desert mountain location outside Italy (data collected from 2003 to 2005); and
- the garden of the former Convent of Quaracchi, in the plain near the Arno river west of Florence, Italy (data collected from 1998 to 2002).

In the Medieval Hall, the measured parameters were logged at 15-minute intervals by Hobo® Pro devices placed close to a panel painting, on which further monitoring was also taking place [21]. In San Donato in Polverosa measured parameters were logged at 10-minute intervals by Hobo® Pro devices placed close to the left side of the transept, near the organ (seventeenth century). In the interior of the historic building in the desert area, data were measured at 15-minute intervals by Hobo® Pro devices. The Quaracchi data were taken at the CNR-IBIMET weather station, located in Florence, (latitude 43° 47' 40" N, Longitude 11° 10' 37" E; 39 m above sea level); the data were logged at 2-minute intervals and the mean value of each parameter was calculated and stored every 20 minutes.

Identification of transient and stable periods

The distribution of the stable periods (plateaus) and the characteristics (extreme values and rate of variation) of the ramps between two plateaus were computed using the algorithm specified above for the four monitored sites, for selected values of δ and T_{min}. T_{min} = 12 hours was chosen as the minimum time duration for a stable period. T_{min} less than 12 hours was considered part of a transient period.

The mean values of the plateaus were divided into the following EMC classes to allow better examination of the results:

- class 6 contains the plateaus with EMC ≤ 6;
- class 10 contains the plateaus with EMC from 6 to < 10;
- class 14 contains the plateaus with EMC from 10 to < 14;
- class 18 contains the plateaus with EMC from 14 to < 18;
- class 22 contains the plateaus with EMC from 18 to < 22;
- class 26 contains the plateaus with EMC from 22 to < 26; and
- class 'Above' contains the plateaus with EMC ≥ 26.

In a similar way, the number of ramps between two adjacent plateaus and the slopes of the unstable segments were classified:

- The 'Ramp number' classes include the values that are not greater than the identifying number, e.g. class –4 includes ramp values from –6 to –4.
- The 'Slope' classes include the values that are not greater than the identifying number, e.g. class –4 includes slopes from –6 to –4.

Orsanmichele

Data collected in Orsanmichele are made of five sets, each with a one-year duration. Figures 3 and 4 show the number of elements in the EMC classes for the five periods, for T_{min} = 12 hours and for δ = 1 and δ = 2. For both the chosen δ values, it is shown that the classes 10, 14 and 18 include the largest number of elements; in particular the maximum number of plateaus is located in class 14. Plateaus with an EMC > 18 are found only during the period December 2000–November 2001 (Figure 3). The increase of parameter δ produces a decrease of number of plateaus and consequently a decrease of ramps and, in absolute value, of slopes.

The magnitudes of the ramps between two plateaus are useful for identifying slow EMC variations that can be analyzed using δ = 1. Figure 5 presents a classification of the magnitude of the ramps between plateaus in the different periods. The ramps generally evidence small magnitudes and are located between classes –2 and +4. For δ = 2 (Figure 6) the distribution of ramps is quite similar to the previous case, only there are some ramps in the extreme classes (–6, 6, 8 and Above).

For δ = 1 (Figure 7), though the slope varies between –8 and +10, with peaks in the central classes (from –4 to +8), the maximum number of elements is in class 0 for all the periods considered. For δ = 2, the slopes are widely scattered in all classes (Figure 8). It is possible to observe that the transition rates, from one plateau to the next, are in absolute value high for δ = 2. In other words, the variation speed from one stable period to another increases for the latter choice of δ.

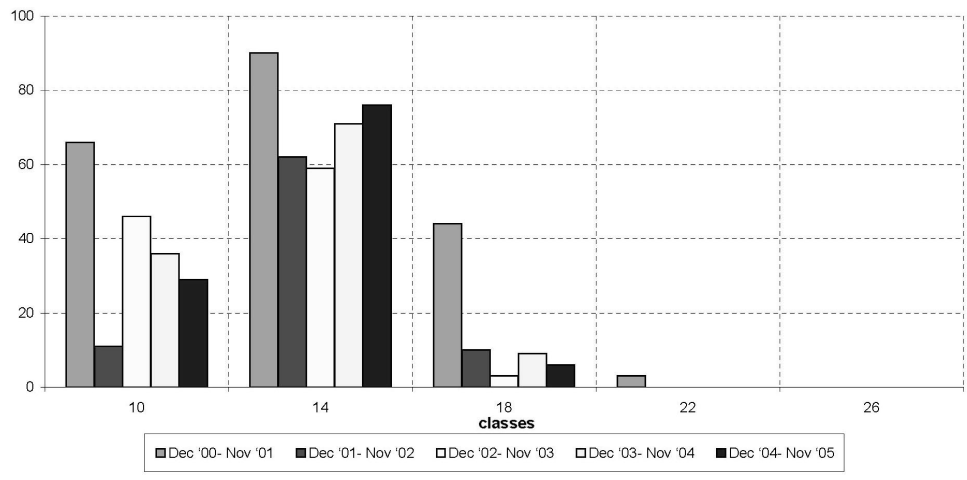

Figure 3 *Orsanmichele: distribution of the magnitude of plateaus, with δ = 1 and T_{min} = 12 hours, for each period of measurement.*

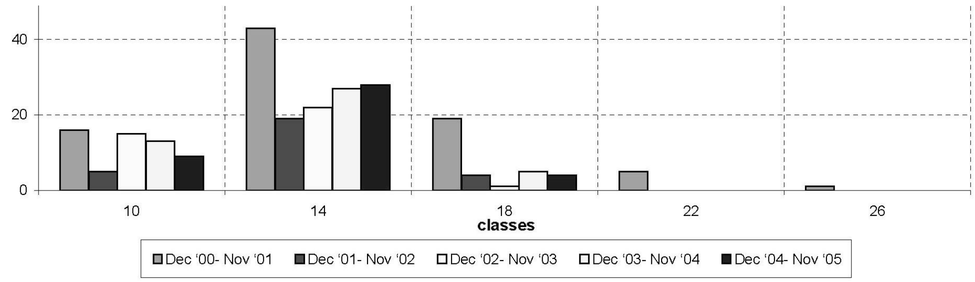

Figure 4 *Orsanmichele: distribution of the magnitude of plateaus, with δ = 2 and T_{min} = 12 hours, for each period of measurement.*

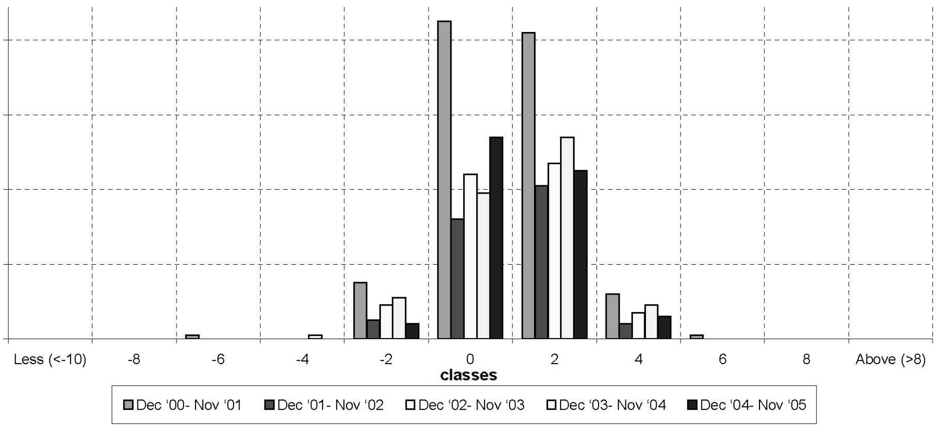

Figure 5 *Orsanmichele: distribution of the magnitude of ramps between plateaus in the different periods, with T_{min} = 12 hours and δ = 1.*

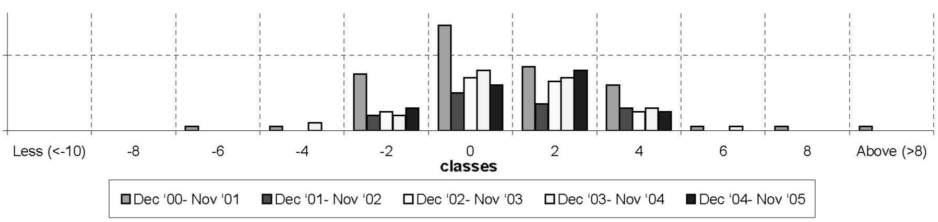

Figure 6 *Orsanmichele: distribution of the magnitude of ramps between plateaus in the different periods, with T_{min} = 12 hours and δ = 2.*

San Donato church

The application of our procedure to the analysis of the data collected inside the parish church of San Donato in Polverosa during the period September 1998–August 1999 showed 181 plateaus for δ = 1 and T_{min} = 12 hours. Classification according to EMC plateaus values shows that about 47% of these plateaus lie in class 18, whereas there were no plateaus in classes EMC < 6 and EMC > 23 (and class 26 contains only two elements) in this period. The duration of the plateaus, obtained using the specified δ and T_{min}, varied from between 12 and 268 hours.

Similarly to the analysis with δ = 1, with δ = 2 the greatest number, about 44%, were in class 18. There were no plateaus with EMC < 6 and only one in class

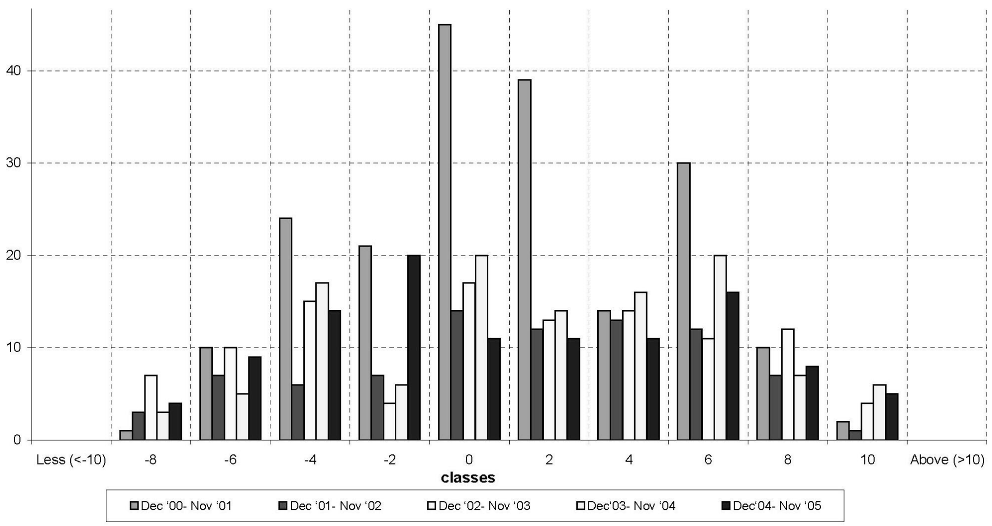

Figure 7 *Orsanmichele: distribution of the slope classes in the different periods, with* T_{min} *= 12 hours and* $\delta = 1$.

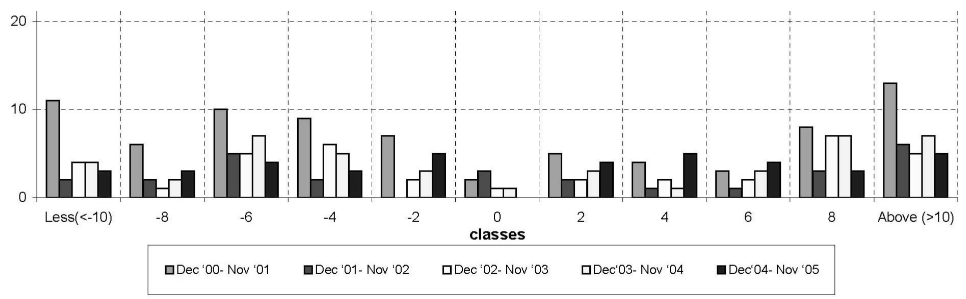

Figure 8 *Orsanmichele: distribution of the slope classes in the different periods, with* T_{min} *= 12 hours and* $\delta = 2$.

EMC > 26 in this period. The duration of the plateaus ranged between 12 and 780 hours and the most frequent was the class 72 (24% of the total). It is observed that plateaus identified in San Donato are generally shorter than those of the Orsanmichele, for both choices of δ.

The ramps are distributed in quite the same way for both the values of δ: between classes –4 and 4 for $\delta = 1$ and between classes –4 and 6 for $\delta = 2$; in particular, most of the ramps are in classes 0 and 2 (89% for $\delta = 1$ and 60% for $\delta = 2$). The ramp magnitude between two adjacent EMC plateaus is often small in this church.

For both δ values, the slopes are scattered in all the classes, with the maximum number of elements in class 0. Also in this case it is possible to observe that the ramps, in absolute value, increase for $\delta = 2$.

Desert area

The data collected (from 2003 to 2005) in the historic building situated in a desert area are made of three sets, one-year long. In the three periods analyzed, choosing $\delta = 1$ and $T_{min} = 12$ hours, about 140 plateaus were identified for each year.

The frequency distribution of the plateaus based on EMC values shows that the majority of elements belong to class 6 (more than the 83% of the plateaus). In the period analyzed, there were no plateaus for EMC > 9. The duration of the plateaus obtained with these δ and T_{min} parameters varies between 12 and 348 hours. Analyzing the frequency distribution of the plateaus according to duration, class 24 is the most populated (about 25% of the total). Consequently, most of the ramps are small: at least 95% of them belong to classes 0 and 2, for each considered period. For the three analyzed periods, it is possible to observe that the ramps are generally scattered between classes –6 and 6 with peaks in central classes.

Using $\delta = 2$ and $T_{min} = 12$ hours the procedure identified, for each year, a smaller number of plateaus (about 24) that usually had a longer duration (range between 14 and 1380 hours). As in the analysis using $\delta = 1$, the majority of the plateaus (more than 66%) are in class 6; there are no plateaus for EMC > 10. Almost all of the ramps were between the –2 and 2 classes. For this choice of δ, the slopes were scattered among all the classes, with peaks in central classes.

Garden of former Convent of Quaracchi

The analysis carried out on the data from Quaracchi shows for both δ values, with $T_{min} = 12$ hours, few stable periods, most of which were of short duration. In particular, using $\delta = 1$ at least 90% of the plateaus lasted less than 24 hours in almost all the periods considered. Only in 2002 did 15% of the plateaus show a duration of more than 24 hours.

The rainy periods and relative humidity of the air close to 100% on several nights create the conditions for the existence of many plateaus with EMC greater than 26% (Figures 9 and 10).

The Quaracchi microclimate is characterized by very high EMC values and by short plateaus (less than

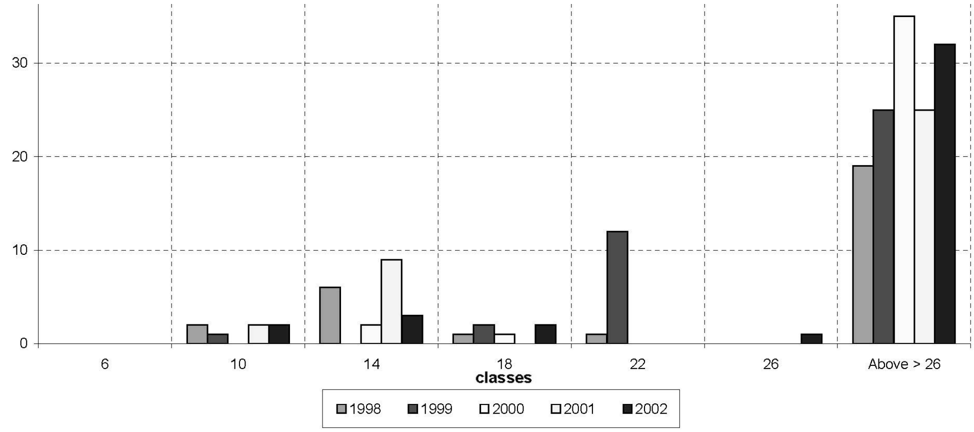

Figure 9 *Garden of Quaracchi former convent: classification of the magnitude of plateaus, with* $\delta = 1$ *and* $T_{min} = 12$ *hours, for each period.*

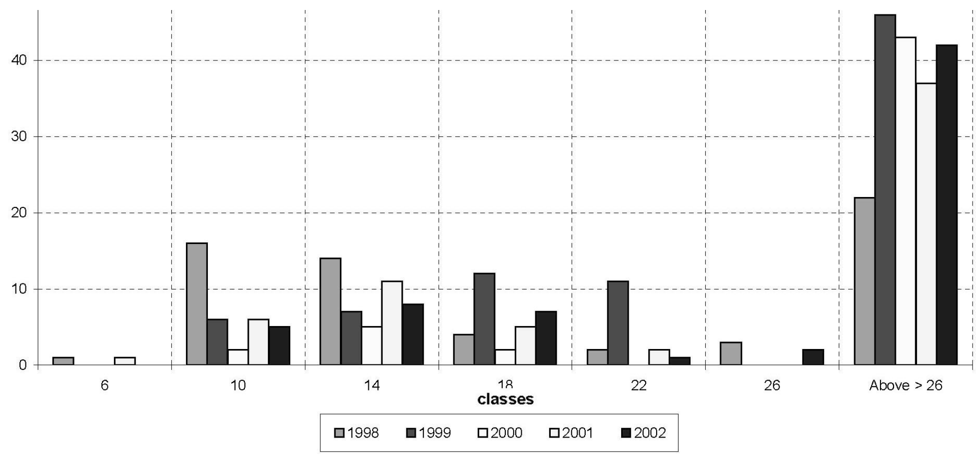

Figure 10 *Garden of Quaracchi former convent: classification of the magnitude of plateaus, with* $\delta = 2$ *and* $T_{min} = 12$ *hours, for each period.*

24 hours). The longer plateaus occur for high values of EMC, in particular on the rainy days of the autumn season. Moreover, the greater is the ramp magnitude, the longer is the duration (more than 12 hours).

Comparison attempts

The multivariate statistical method previously described, based on principal components analysis, was used to compare EMC values and plateaus duration. The method was applied to all the data collected in the four sites and processed in Phase 1.

After normalization of the EMC and of the plateaus duration values, the T_{ij} coefficient was calculated to evaluate how much difference there is in stability (and, consequently, in transience) between the different periods. The method was applied to compare both the microclimatic data sets logged in different sites and the temporal evolution of the data in each set.

Orsanmichele church (δ = 1)

Comparing the plateaus obtained using $\delta = 1$ in Orsanmichele, the periods December 2003–November 2004 and December 2004–November 2005 have very similar T_{ij} values, very close to 1 (Table 1). The other periods are quite distinct both regarding the different characteristics of the EMC and duration plateaus and component variances. In particular, the period December 2002–November 2003 is statistically distant from the two successive periods because of the reduced variance of the components.

It can be observed that in the period December 2000–November 2001 the plateaus for Orsanmichele had shorter durations than in the other periods and that the EMC variance was greater in that period (Figure 11), because of the greater number of plateaus (Figure 3). Moreover, in the period December 2001–November 2002 the variance of the duration component is very high (from 12 hours to >5 days).

The high T_{ij} differences in Orsanmichele church, for example, between the 2001 and the 2005 periods (19.40 with $\delta = 1$) is very probably related to the different regime for visitors to the building. In the first year the structure was open for visitors through the main entrance, with the doors regularly wide open, practically just in front (though at a significant distance) of the data-logger. In the following years the building was closed for restoration and the effect on stability, regularly higher, is very evident.

Comparison between Orsanmichele church and San Donato church (δ = 1)

For $\delta = 1$ there are evident differences when comparing the stability periods obtained in Orsanmichele church with those obtained in the San Donato parish church, although the two buildings are both in Florence and not far (about 3 kilometers) from each other. The data recorded in Orsanmichele in the period December 2000–November 2001 presented the most similarity in microclimatic stability with San Donato. In fact, in that year Orsanmichele was reopened to visitors (whereas all the other sites remained open to visitors on a regular basis throughout the years of this study).

The differences evidenced from statistical analysis can be related to:

Table 1 *Values of T_{ij} coefficient providing the statistical estimate of the microclimatic distances between the bivariate sets (EMC, plateaus duration): data collected for Orsanmichele (December 2000–November 2005) and San Donato Church (September 1998–August 1999)*

	Orsanmichele Dec '00–Nov '01	Orsanmichele Dec '01–Nov '02	Orsanmichele Dec '02–Nov '03	Orsanmichele Dec '03–Nov '04	Orsanmichele Dec '04–Nov '05	San Donato Sept '98–Aug '99
Orsanmichele Dec '00–Nov '01		5.51	16.82	11.48	19.40	8.43
Orsanmichele Dec '01–Nov '02	5.51		10.90	4.98	7.22	31.77
Orsanmichele Dec '02–Nov '03	16.82	10.90		6.03	6.28	35.98
Orsanmichele Dec '03–Nov '04	11.48	4.98	6.03		1.41	24.801
Orsanmichele Dec '04–Nov '05	19.40	7.22	6.28	1.41		36.92
San Donato Sept '98–Aug '99	8.43	31.77	35.97	24.801	36.92	

The plateaus are calculated with $\delta = 1$ and $T_{min} = 12$ hours.

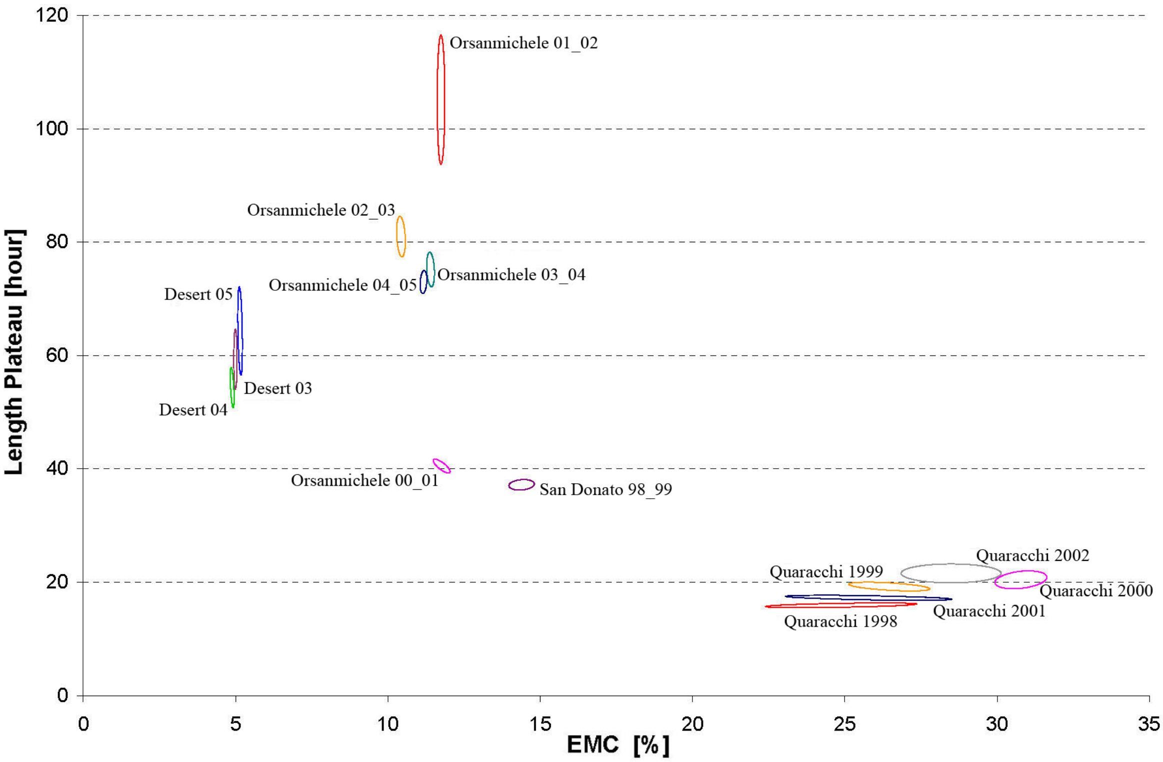

Figure 11 *Ellipse method: analysis of stable periods. Plateaus are defined with δ = 1 and T_{min} = 12 hours.*

- The boundary micrometeorology is different, due to the fact that data were not obtained in the same periods of time.
- The building functions: San Donato continued to be a regularly functioning parish church throughout the years of this study, whereas the Orsanmichele was closed to visitors for many years. Consequently, anthropic influence is very strong in the San Donato church, especially during the holidays. Furthermore, it is noted that this church has a regularly functioning air heating system.
- San Donato is located below road level, an outfall drain passes along the boundary walls and there are two streams at a distance of 300 m: these factors could explain the higher moisture level of the site compared to Orsanmichele.
- The urban heat island effect in Florence: the temperature in the center of town can be 2°C more than in the surroundings [22, 23] and this could interfere with the EMC values.

San Donato data show that the variance of the two components is low, with EMC plateaus comparable in magnitude with Orsanmichele, although with shorter durations (Figure 11).

Desert mountain historical building (δ = 1)

Applying the ellipse method to the plateaus identified using δ = 1 in the microclimatic sets logged in the desert area building, it is evident that the data for the three periods are very similar. In particular the calculated T_{ij} for the years 2003 and 2004 is so close to 1 (1.18) that the sets can be considered almost indistinguishable (Table 2 and Figure 11). The results obtained from Phase 1 show plateaus of medium–long duration (60–80 hours) and a very low EMC (about 6%).

Quaracchi former convent (δ = 1)

The application of the ellipse method to the data sets recorded in Quaracchi shows that the periods, though

Table 2 Values of T_{ij} coefficient providing the statistical estimate of the microclimatic distance between the bivariate sets (EMC, plateaus duration): data collected for a historic building in a desert area (2003–2005)

	2003	2004	2005
2003		1.18	5.37
2004	1.18		3.59
2005	5.37	3.59	

The plateaus are calculated with δ =1 and T_{min}=12 hours.

Table 3 Values of T_{ij} coefficient providing the statistical estimate of the microclimatic distance between the bivariate sets (EMC, plateaus duration): data collected in the Garden of Quaracchi (1998–2002)

	1998	1999	2000	2001	2002
1998		5.24	7.23	4.58	3.22
1999	5.24		3.98	2.09	1.61
2000	7.23	3.98		5.71	1.43
2001	4.58	2.09	5.71		2.30
2002	3.22	1.61	1.43	2.30	

The plateaus are calculated with δ = 1 and T_{min} = 12 hours.

distinguishable, are very similar. In particular, for the 2000 and 2002 data sets, a T_{ij} coefficient of 1.43 has been calculated (Table 3). According to the results obtained from Phase 1, the plateaus have in general short durations (about 20 hours) and a very high EMC, between 22% and 35% (Figure 11).

A similar synthetic chart has been obtained applying the ellipses method to the plateaus identified in the first phase of the methodology using δ = 2.

CONCLUSIONS

As stated in the section on Objectives, Limits and Field of Application, the work reported here has been performed in the framework of standardization studies, aiming to establish criteria for evaluating the suitability of given real microclimates for the conservation of wooden artifacts of cultural importance, from the point of view of preventing decay and/or physical-mechanical damage.

The theoretical bases and the algorithms used to implement them in practice are shown in detail in the sections on The Basics of the Proposed Method, and Description and Implementation of the Analytical Model, Part 1 and Part 2, whereas the section, 'Example', shows in detail the implementation of this method in analyzing four real microclimates, recorded during several years.

The following main conclusions can be drawn from the work reported here:

- Transforming temperature and relative humidity data into equilibrium moisture content data has been easily performed by means of an equation, derived from the well-known typical sorption isotherms for wood. Using a single parameter made successive data processing easier to perform and resulting data easier to understand.
- The proposed criteria for describing the temporal evolution of a single microclimatic data set (Phase 1) can be actually implemented by means of appropriate algorithms, and the resulting parameters provide a significant and objective synthetic description of the analyzed micro-environment.
- The descriptive parameters found in Phase 1 for each individual microclimatic data set (resulting from different sites or different periods in the same site) can be efficiently compared by the techniques of multivariate analysis (*principal components*) proposed and implemented in Phase 2.

The proposed characterization can in no way be defined as a 'welfare index' or a 'risk of damage index', since the evaluation of 'good' or 'dangerous' conservation conditions cannot be generalized, but need to be specified by the conservator, who has the full knowledge of the individual artifact to be conserved (structure, materials, state of conservation, past history, etc.). However, it is hoped that this approach will facilitate the work of conservators, providing them with a procedure for characterizing actual or desirable microclimates, in relation to the effects that environmental conditions may produce on wooden artifacts.

Some real microclimatic sets, collected during periods ranging from one to five years long have been analyzed by means of the proposed procedure. The resulting sets of descriptors show a significant difference between the various environments. The proposed method shows good sensitivity to the microclimatic sets, even when belonging to the same location in different years, or when due to different anthropic behaviors, including different visiting patterns of visitors.

Work is still in progress. Among other aspects, further studies and verifications are needed of the actual response (physical or virtual, by means of appropriate modeling techniques) of wooden artifacts placed in selected micro-environments, in order to evaluate how well they relate to the results of this proposed procedure.

Some improvements could allow a better usability and will be the core activity of future developments:

- the release of software routines that can simplify the elaborations of Phase 1 (i.e. the determination of the plateaus and their duration, and the ramps);
- the development of indices able to express more synthetically the microclimatic situation after processing (Phase 1) has taken place;
- the analysis of the physical effects produced on selected objects by climates corresponding to the different areas of the T_{ij} plane (and the ramps); and
- the physical effect of the statistical distances on selected objects, with particular attention to the meaning of the *distance* between the ellipses on the T_{ij} plane.

APPENDIX: OBSERVATIONS ON ELLIPSES METHOD

The ellipses method evidences that if the sets have the same mean point, T_{ij} is null and the two sets are indistinguishable. It is important to underline that a small distance between the average points is not a sufficient condition for $T_{ij} < 1$. T_{ij} is, in fact, directly proportional to CC' (Figure 2) and inversely proportional to the square root of ($CP^2+C'P'^2$), where CP and C'P' are a function of the variances. From a statistical point of view, two sets with very close average points can be considered distinguishable if the total variance of both sets is very small. On the other hand, the two sets are indistinguishable if the total variance has a greater magnitude than the difference between the means. It is worth noting that while this method for evaluating T_{ij} gives responses similar to those resulting from the bivariate Student's t-test regarding the homogeneity or diversity of sets, it also has the advantage of giving a geometrical representation of these parameters. Moreover, this method does not depend on the number of elements in each set and it uses a very simple algorithm; in particular, in the case of a single datum, T_{ij} corresponds to the result of the Student's t-test.

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Résumé *— Cet article décrit une approche méthodologique statistique pour la comparaison de différents microclimats. Cette méthode a été mise au point comme outil pour choisir un nouveau microclimat pour des déplacements temporaires. Au stade actuel de développement, la méthode ne vise pas à être utilisée pour identifier des conditions nocives. La méthode en question est basée sur des indices expérimentaux, indiquant que la sensibilité aux fluctuations environnementales des objets en bois peut différer d'un objet à l'autre, en fonction de plusieurs paramètres physiques et mécaniques. Certains objets peuvent être affectés par des fluctuations qui n'auraient pas d'impact sur d'autres objets. Le paramètre adopté dans ce travail est la teneur en eau à l'équilibre, qui est la teneur en eau qu'un objet en bois aurait tendance à maintenir lorsque placé à humidité relative et température stable pendant une longue période. Il y a lieu de considérer ceci de façon potentielle, car dans un climat fluctuant cette valeur n'est jamais réellement atteinte. La méthodologie comprend deux parties. La première décrit de façon mathématique simplifiée comment le* *climat est subi par des objets de sensibilités différentes. La deuxième analyse la "distance climatique" entre différentes séries de données climatiques, en utilisant la méthode mathématique de l'analyse factorielle en composantes principales, en fonction de la sensibilité préalablement définie des objets . Pour tester la méthode proposée, quatre études de cas microclimatiques sont analysées et les résultats en sont décrits.*

Zusammenfassung — *Diese Arbeit beschreibt ein statistisch-methodologisches Vorgehen für den Vergleich verschiedener Mikroklimata. Die Methode wurde als Werkzeug für die Wahl eines neuen Mikroklimas bei temporären Ortsveränderungen entwickelt. Gemäss dem heutigen Stand der Entwicklung ist diese Methode nicht für die Identifizierung schädigender Bedingungen gedacht. Die vorgestellte Methodik basiert auf Experimenten, die zeigen, dass die Sensibilität von Objekten aus Holz gegenüber sich verändernden Umgebungsbedingungen von Objekt zu Objekt unterschiedlich und von vielen physikalischen und mechanischen Paramatern abhängig ist . Einige Objekte werden von Veränderungen betroffen, die für andere nicht von Bedeutung sind. Der in dieser Arbeit angenommene Parameter ist der Gleichgewichtsfeuchtigkeitsgehalt; das ist der Gleichgewichtswert, den ein Holzobjekt bei gleichbleibender Temperatur und relativer Luftfeuchtigkeit über längere Zeiträume zu erhalten tendiert.. Dieser Wert muß als potentiell angesehen werden, da er in einem veränderlichen Klima niemals erreicht wird. Die Methode basiert auf zwei Teilen: Der erste beschreibt einen mathematisch vereinfachten Weg, wie sich das Klima auf Objekte unterschiedlicher Empfindlichkeit auswirkt. Der zweite analysiert die klimatische Distanz zwischen verschiedenen Datensätzen mit Hilfe der mathematischen Technik der Hauptkomponenten-Analyse bezogen auf die vorher definierte Sensitivität der Objekte. Als Test für die Methode werden vier mikroklimatische Fallstudien analysiert und die Ergebnisse beschrieben.*

Resumen — *Este artículo describe un criterio metodológico estadístico para la comparación de diferentes microclimas. Este método se desarrolló como una herramienta para la elección de nuevos microclimas en el caso de desplazamientos temporales. En el actual estado de desarrollo este método no ha sido considerado para la identificación de condiciones dañinas. El método propuesto se basa en evidencias experimentales que sugieren que la sensibilidad de los objetos de madera a las fluctuaciones ambientales puede variar de un objeto a otro, dependiendo de muchos parámetros físicos y mecánicos. Algunos objetos podrían ser afectados por fluctuaciones que no serían significativos para otros objetos. El parámetro adoptado en este trabajo es el contenido de equilibrio de humedad, que es valor de equilibrio al cual un objeto de madera tiende a mantener valores estables de humedad y temperatura durante un largo periodo de tiempo. Ha de considerarse de manera "potencial" ya que en un clima fluctuante nunca llega a alcanzarse totalmente. La metodología se basa en dos partes. La primera describe de una manera matemática simplificada cómo el clima es percibido por los objetos mediante diferentes sensibilidades. La segunda analiza la "distancia climática" entre diferentes grupos de datos climáticos usando la técnica matemática de los principales componentes del análisis, de acuerdo a los previamente definidos valores de sensibilidad del objeto. Como tests del método propuesto se han analizado cuatro casos diferentes de microclima, describiendo los resultados obtenidos.*