STUDY OF THE MICROCLIMATE OF THE HALL OF THE GIANTS IN THE CARRARA PALACE IN PADUA

Dario Camuffo and Adriana Bernardi

Summary—*The Hall of the Giants (Sala dei Giganti) in the former Carrara Palace, now part of the University of Padua, Italy, contains sixteenth-century frescoes which are subject to soiling by airborne pollutants and to mechanical stress due to heating/cooling cycles. Field surveys were undertaken in the Hall to measure the microclimate and the distribution of suspended particulate matter at different times of year: winter, summer and autumn. By analyzing maps of thermohygrometric cross-sections of the Hall, several factors which disturb the indoor microclimate were identified: solar radiation, which causes seasonal and daily warming cycles; radiators which are controlled by a thermostat and a timer, thus generating discontinuities in the heat supply; the use of the room for lectures and concerts; human activity in adjoining rooms; old windows with leaded glass panes which are very large so that thermal conductivity is high and insulation is poor; external air which enters between the roof and the ceiling through ventilation apertures and then penetrates through fissures in the coffered ceiling; and the daily use of a vacuum cleaner, which dramatically increases the concentration of suspended particulate matter. Actions to be taken in order to mitigate the adverse factors are discussed.*

Introduction

The Hall of the Giants (Sala dei Giganti) is one of the most famous historic rooms in Padua, Italy. It is part of the palace that formerly belonged to the Carrara family, one-time rulers of the city. The building was erected in 1345 and the ceremonial room, frescoed with figures of the Roman Emperors from which it takes its name, was built in 1370. After a fire in 1540, the room was re-frescoed by D. Campagnola, S. dall'Arzere and Gualtiero Padovano who copied the original frescoes fairly faithfully. The building is now the property of the University of Padua and the room is mostly used for lectures and concerts.

The hall is on the first floor, oriented east-west (Figure 1). It is 36·77m long; the eastern side, 10·63m wide, is constituted by an enormous three-mullioned window (an external view of these windows is shown in Figure 2), and the same on the western side, which is 15·73m wide. The north wall has a door in the middle, generally closed, which connects the Hall with the main entrance of the Faculty of Letters, always populated by several students so that it contains a lot of carbon dioxide and water vapour; the south wall has two doors near the ends, connecting with a corridor which is more exposed to the outside and can, therefore, be a source of cold air currents in the winter. The height of the ceiling in the Hall is 8·6m. Over the coffered ceiling there is a small loft, with some small open windows just below the roof.

As well as the orientation of the Hall, its architectural structure and internal characteristics can play a determining role in the evolution of the microclimate. Inside the Hall there are 10 radiators, six of which work and are arranged in groups of three under each window; four have been disconnected and are situated near the main north and south walls. In winter, the radiators are heated, which gives rise to convective cells and consequent atmospheric instability with the resulting mixing of the internal air. Even the radiators which are left switched off are connected to the central heating system, and there is still some passage of warm water through them.

In the middle of the room there is a system of chairs arranged almost symmetrically in front of a stage in the centre of the south wall, in blocks of rows. When investigating the microclimate of the lower layers of the environment, their presence must be taken into account. They may, in fact, be a guide to any possible infiltration of cold air. They may also limit the lateral extent of the convective cells that develop from the floor which has been heated by sunlight, and intercept any solar radiation so that the rear of the Hall is in shadow, thus accentuating the areas subjected to solar heating or otherwise.

The lamps are in the middle of the room, about 6m from the floor. The light intensity is weak and the heat dissipated is not great; as a consequence, the convective cells generated in the air above them are not powerful, and do not greatly influence the atmospheric levels below. In fact, the vertical thermal stratification of the air causes continuous atmospheric stability and tends to suppress any turbulence that starts up.

The ceiling must not be neglected as a source of internal mixing of the air, caused by descending

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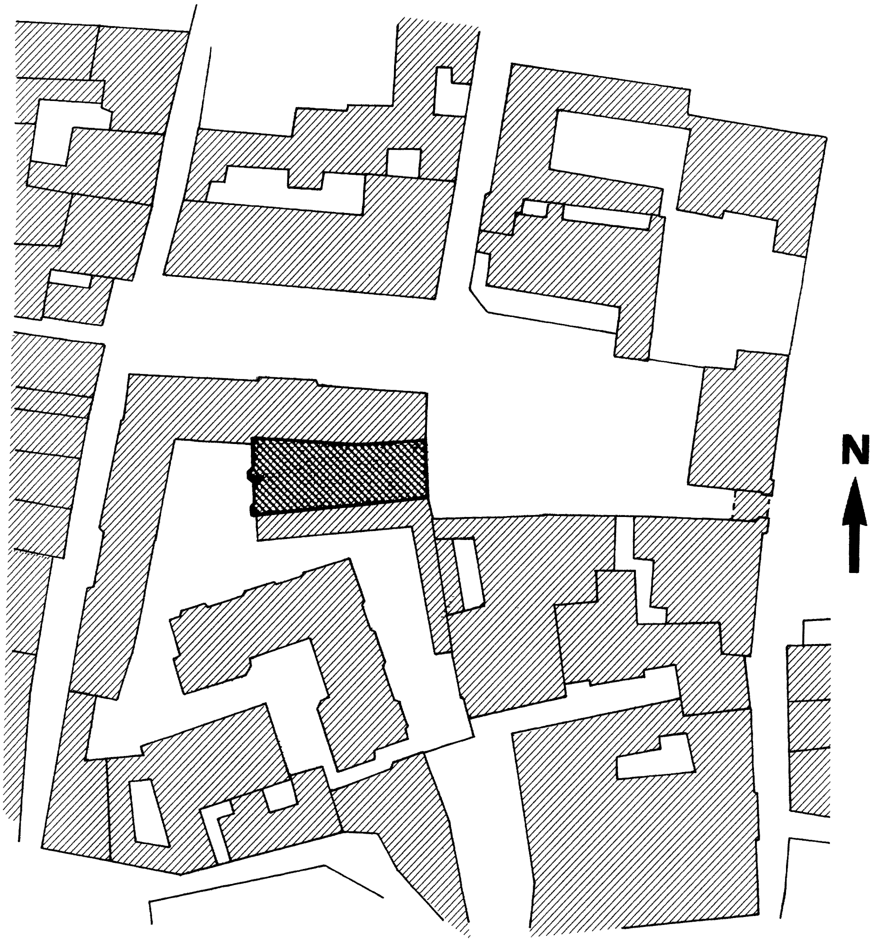

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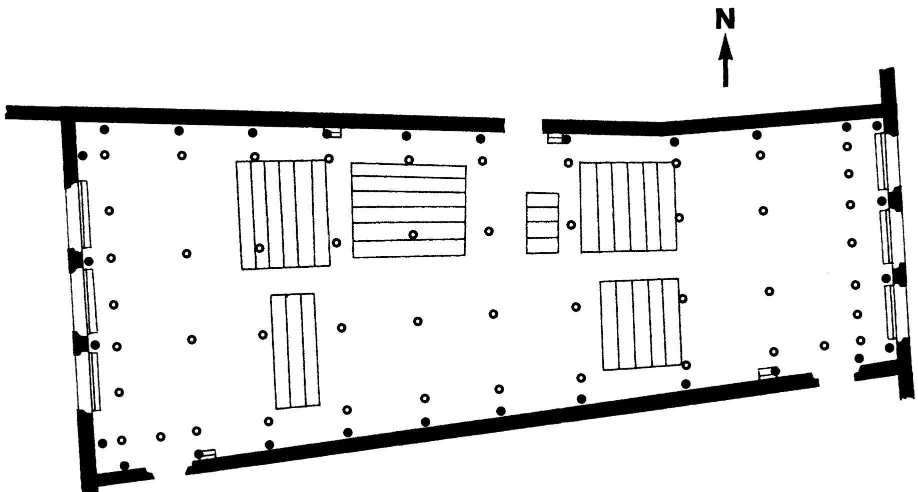

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Figure 1 (opposite) (a) Topography of the city around the Carrara Palace: the Hall of the Giants is indicated with heavier shading. (b) Cross-section of the Hall of the Giants, showing the location of the points where measurements were taken at 1·5m above the floor. Black dots show the location of the observations near the walls (at 2mm and 200mm), white dots show the measurements in the interior of the room. The windows are located on the eastern (see also Figure 2) and western sides; two doors are on the south side and one on the north. Radiators are sited below the windows; another four disconnected radiators are sited on the north and south walls, three of them beside the doors. The banded rectangles inside the room show the position of groups of chairs in rows: the bands show how the rows are distributed.

currents, as shown by the values of the radiant temperatures, which were always lower than the temperatures of the other surfaces during the autumn and winter surveys. Differences of temperature between air and walls may cause blackening of the frescoes, and will be discussed later. During the summer, on the other hand, because of solar heating, the temperature at the ceiling is higher, resulting in interior stability.

During the cold season or at night, the cold air that penetrates the environment below the roof (where small windows are always open) infiltrates between the framework of the coffered ceiling and descends in gusts into the Hall, especially on the west side, where further mixing takes place.

Penetration of solar radiation

In order to evaluate the direct solar energy that enters the Hall and determine which areas of the walls and floor were affected by it, in terms of daily and seasonal cycles, a suitable computer model was made [1–3] following the theoretical calculation of irradiation [4]. Heating the walls and the floor can set up an upward movement of the air masses which, in turn, create an unstable environment that also affects the transport, diffusion and deposition of pollutants. Furthermore, there may be a change in the water content of the micropores in the wall because of heating.

On the floor and the north and south walls are indicated the 'spots' of direct solar radiation which enters in the morning from the east windows and in the afternoon from the west ones. These have been computed for every month and for each hour, but have been summarized in Figure 3 for the equinoxes (Figure 3a), the summer solstice (Figure 3b) and the winter solstice (Figure 3c). The solar radiation enters in the morning but stops at noon when it is parallel to the windows, then enters again in the afternoon. In order to avoid the confusion caused by too many graphs, each figure reports the spots calculated every two hours from the astronomic noon. Only at the winter solstice has an odd time been included, in order to include a second datum. The time has been expressed in Western European Time (WET)*. In each figure the hour is reported on the spots, and the spots from the three windows have been graphically represented with the same shading. When the spots are on the floor, they are represented by parallelograms, but when they hit the north (or south) wall then the shape of the spot changes. When part of the solar beam has been intercepted by external buildings, the missing part of the spots has been indicated with a dotted line. In the calculations, the shape of the room was included exactly and the windows were approximated by rectangles.

Thus, over a period starting from the autumn equinox (Figure 3a) and ending at the spring equinox, the south wall is not subject to any direct sunlight. Direct radiation only reaches the south wall near the summer solstice (Figure 3b) and then only in the early morning (till about 06:30) and late afternoon (from about 18:00 on). The north wall is subject to solar radiation for many hours of the day, depending on the season, through both the east and the west windows. At the equinoxes, in particular, almost the whole of the lower part of the north wall is subject to direct solar radiation. The sunlight reaching this wall tends to diminish gradually towards the summer solstice, when it is practically negligible. From the autumn equinox to the winter solstice (Figure 3c), the part of the wall affected is reduced even further because the incident radiation band is partially intercepted by the surrounding architectural structures.

The interception of the solar beam depends, substantially, on the presence of other buildings, the solar azimuth and its height with respect to the horizon. The interception is greater in winter when the azimuth values are lower. The building adjacent to the east wall reduces the surface of the wall that is affected, but only in the winter months and then only in the early hours of the morning (until about 08:30). As a result, at 08:30, the north wall is only bathed in sunlight in a small area towards the top

*True solar time corrected for the equation of time (which takes into account astronomical disturbances in the apparent motion of the sun) and the change of longitude giving the distance of the site from the reference meridian. For this reason the time in WET has no whole values.

Figure 2 External view of the three mullioned windows on the eastern side of the Hall.

and east. In the succeeding hours, as well as at other times of the year, the beam is limited, almost exclusively, to an area of the floor.

The direct radiation which hits the walls and the floor is partly absorbed and partly reflected or, rather, diffused. Bearing in mind that the maximum intensity of diffused sunlight is towards where it is reflected, the areas affected by sunlight reflected off the walls or floor were determined by tracing the movement of the solar beams, starting from the areas reached by direct sunlight inside the Hall. An example is shown in Figure 4, which considers two hours, 14:30 and 15:30, during the survey which will be discussed later. The small amount of radiation reflected from the walls generally reaches the floor and only a small part reaches the opposite wall. From this analysis, it was seen that only the western part of the south wall can be affected by light reflected from the north wall which is subjected to the sunlight entering through the window to the west.

The intensity of the solar radiation was not measured during this campaign as it is already known for this region [5–8] and it is easy to compute the incidence of solar radiation on a vertical surface once its direction is known [3, 4]. The main problem caused by direct solar radiation on a fresco is that the plaster first expands and later contracts when the radiative flux stops, subjecting the frescoes to mechanical stress. The amplitude of these heating-cooling cycles depends on the albedo of the wall, which varies from point to point, being determined by the pigment coating and the particles (mainly black soot) deposited on it. In addition to mechanical stress, the heating of the fresco may generate rising air currents, which increase the deposition rate of suspended particulate matter via inertial impaction, as will be discussed later.

Analysis of the microclimate

Field surveys were carried out at different seasons in 1992: in the depth of winter (February) when the external temperature was at its minimum and the heating system worked at maximum power; at the height of summer (July) when the solar radiation and air temperature were at their maximum; and in autumn (November), i.e., in the mid season, slightly after the beginning of the academic year, when activity is more intense. From the climatic point of view, February is without precipitation but foggy,

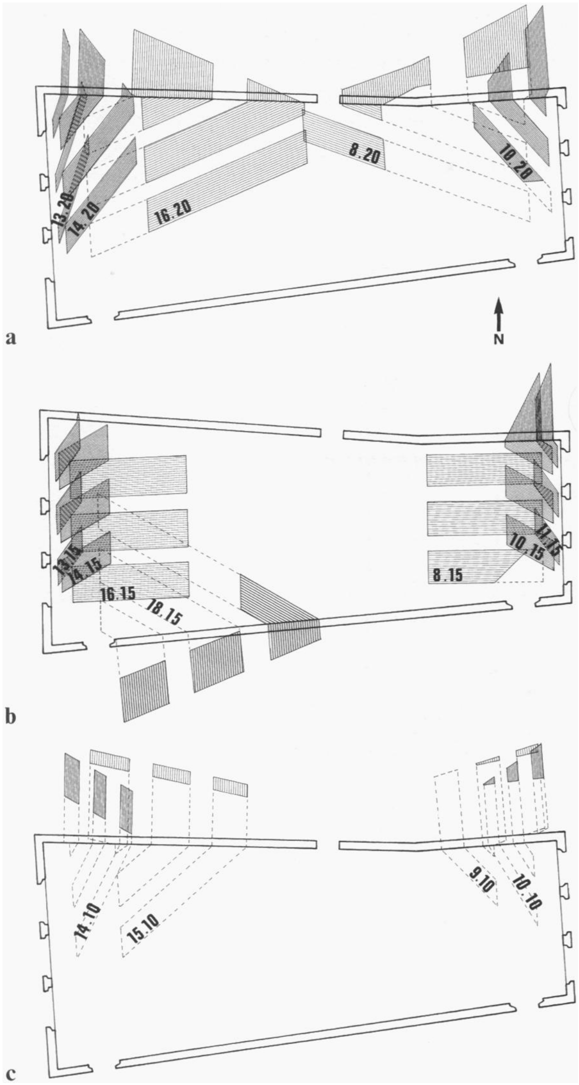

Figure 3 Areas affected by direct sunlight on the floor of the Hall and on the north and south walls, at different times (hours shown by corresponding figures expressed in Western European Time): (a) equinoxes, (b) summer solstice, (c) winter solstice.

July is dry and November is characterized by frequent rainfall [9]; the year 1992 was absolutely normal. As the local climatology is well known and the building is in the same town as the CNR Institute, it was easy to choose typical days for the field surveys. The microclimate campaigns consisted in measuring for one week the evolution over time (with special reference to daily cycles) of the main thermohygrometric parameters, i.e., the temperature of the air, walls, floor and ceiling, specific humidity (SH), relative humidity (RH) and dew-point (DP). Given the large dimensions of the room and the impossibility of attaching contact sensors to the frescoes, an automatic station continually monitored the surface temperatures using infrared thermometry (six radiometers monitoring the ceiling, the floor and the four walls, to an accuracy of $\pm 0{\cdot}5°C$); atmospheric thermal stability and vertical gradient of the other thermohygrometric variables were measured with a 6m pole, equipped with psychrometers at 2, 4 and 6m. The psychrometers were commercial instruments, with the dry and wet temperatures measured by thermistors, protected by a reflective metal shield against disturbing external infrared radiation. The psychrometers were checked in the laboratory and improved, in order to get an overall accuracy of $\pm 0{\cdot}02°C$. In room conditions, an error of 0·1°C in the temperature reading causes an error of less than 1% RH, $0{\cdot}1 gkg^{-1}$ SH, 0·1°C DP.

In addition to the vertical profile, the temperature and humidity distributions were measured in a horizontal plane, at 1·5m from the floor. This horizontal cross-section shows the air/wall interactions, the space gradients and their temporal evolution. As it was essential to avoid intercalibration errors, the same fast-response instrument was used (a precision psychrometer built in our laboratory, with the same accuracy as those mentioned above, but faster response; the time constant in air was 6s). It was moved manually from each point to the next one. The grid of the measuring points (Figure 1b) was composed of two interconnected series of data: a first series of 48 points at the same height, measured at regular intervals close to the walls, i.e., 24 points at 2mm from the surface and 24 at 200mm, in order to detect the gradients near the walls and the exchanges of heat and water vapour; the second

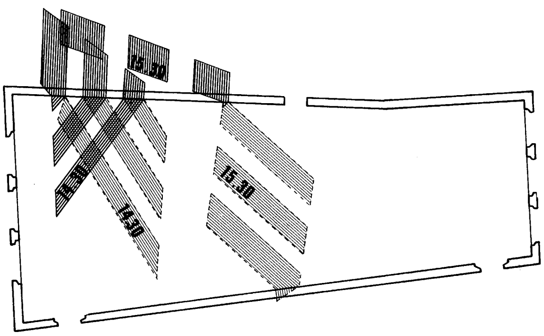

Figure 4 The areas on the floor and on the north wall affected by direct sunlight (heavier shading) and reflected off the wall onto the floor (lighter shading) on the afternoon of 15 February, at 14:30 and 15:30.

series was chosen to show the temperature and humidity distribution inside the room, and was composed of 48 other points, distributed in 10 transverse lines of four equispaced points plus eight to monitor the air entering from the doors and the windows. The series of measurements was repeated every two hours. The principle of this method has already been presented [1, 2, 10, 11].

Spot measurements were performed with a hot-wire anemometer in order to check the presence of convective movements and whether they were turbulent.

Winter measuring survey

Sources of internal heating are one of the most influential factors in the microclimate of a closed environment during winter. The degree to which these affect the climate is underlined by the steep gradients shown in the maps, which correspond to the radiators that are found under the windows; the temperature oscillations are caused by the regulation of the heating by means of a thermostat and a timer.

Two of the immediate effects to which any surface above a radiator is subjected are that the part touched by the ascending flow is blackened and convective cells are started up in the surrounding area with the corresponding downward currents along the cold walls, with subsequent blackening because of thermophoresis and inertial impaction [9]. Similar effects, even though they are less, are caused by the radiators even when the valves are closed, because the walls are affected by the pipes carrying hot water.

Looking at the thermohygrometric maps, the seats which interrupt the continuity of the Hall tend to limit the size of the convective cells within those spaces where the environment has been subdivided and set up the geometric trends of the isolines that reproduce them.

The temperature maps (Figures 5a, 5b, 5c) show steep temperature gradients with marked maxima and minima at any time of the day. In particular, there are high temperature maxima near the radiators under the large windows on the east and west walls, above all during the first half of the day and after 18:00 when the heating system is switched on again. At the same time, infiltration of cold air through the windows causes marked temperature minima that alternate with the maxima resulting from the presence of the radiators. A very extensive area of cold air is present practically all day towards the northeast corner of the Hall. This area is due to a descending current of cold air from cracks in the coffered ceiling (as was verified when the ceiling was examined) which tends to spread. Other temperature minima can be found in the other half of the Hall, towards the west wall. These are caused by other cracks in the ceiling and are particularly evident in the early hours of the morning and in the late afternoon when the outside temperature is lower. Other infiltrations of colder or warmer air can be seen at the two doors in the south wall which lead into the south-running corridor. All these infiltrations of external air cause disturbance and partial mixing; some mixing is due to rivulets of cold air sinking from the ceiling, and some is organized in convective cells which affect large parts of the Hall.

There is considerable homogeneity in the water vapour content of the Hall; the internal gradient is rather modest and runs parallel to the west-east axis, with a maximum value in the west and with only a slight deviation, which is practically negligible due on the one hand to evaporation from the walls when the radiators are switched on and on the other, more simply, to infiltration of external air through the doors or the cracks in the ceiling and windows. During the day, the average specific

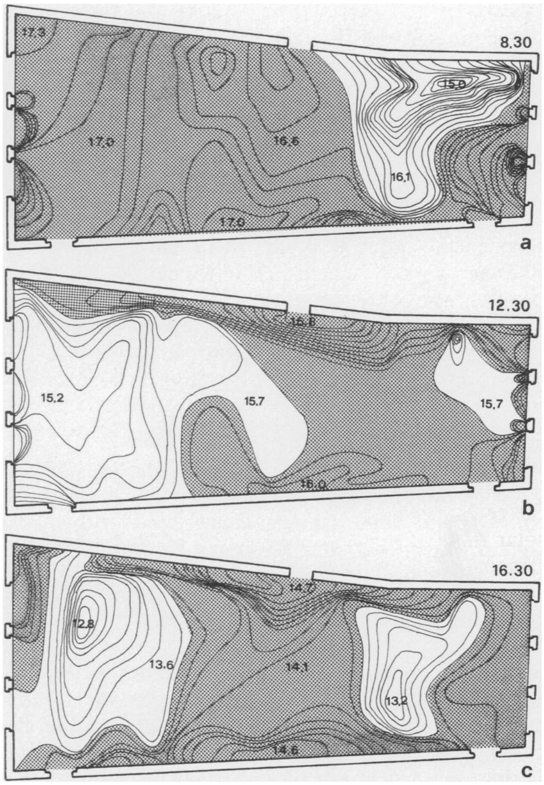

Figure 5 Horizontal cross-section of the distribution of the air temperature at (a) 08:30, (b) 12:30, (c) 16:30 on 7 February.

humidity (SH) tends to increase. At times, this is linked to infiltration of warm damp air through the north door connected with the main hallway and at times to the fact that the Hall is used for university lectures which involve the presence of several students (Figure 6a). This increase in the SH can be seen, above all, in the eastern half of the room, which appears divided into two parts. Towards the evening, when the doors are closed and the radiators switched on again, the environment becomes very stable, in hygrometric terms, and the gradient essentially runs along the main axis of the Hall.

In the early part of the day, the average RH value is about 50% (Figure 6b). As the day wears on, these values tend to increase until they reach about 60% (Figure 6c); they then decrease once more towards the evening, dropping to about 45%. When the SH becomes uniform, any variation in RH depends on changes in temperature. Better heat regulation and possible sources of infiltration of air from the outside can, therefore, considerably reduce the RH oscillations. Large oscillations in the RH values are not advisable because they generate adsorption/desorption cycles which cause the plaster to expand and contract, subjecting the frescoes to mechanical stress. The maximum RH values were found most frequently towards the west wall. The average temperature of the Hall is always well above the dew-point (on average 9°C).

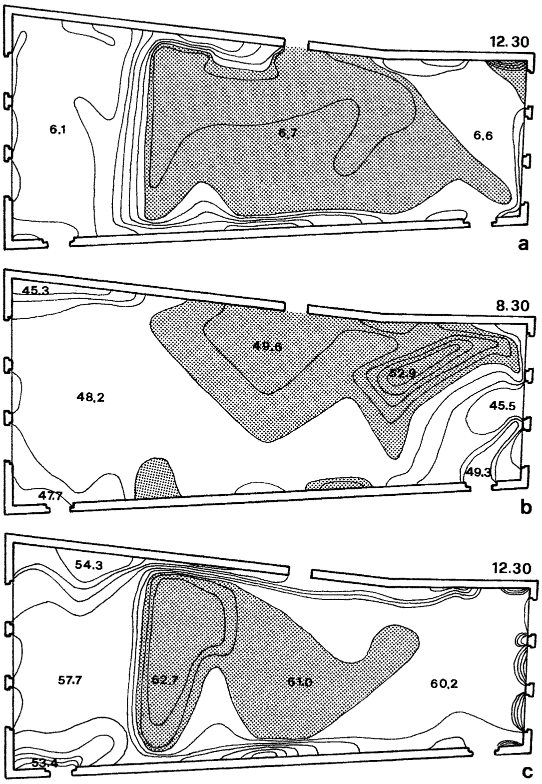

Figure 6 Horizontal cross-section of the distribution of (a) specific humidity at 00:30, (b) relative humidity at 08:30, (c) relative humidity at 12:30 on 7 February.

Summer measuring survey

The presence of isotherms which are more or less perpendicular to the walls in all the maps of the summer survey means that exchanges of heat between air and walls are modest, except when the solar radiation heats the north wall, generating weak ascending currents. During the night and the early hours of the morning, the Hall is divided into two parts (the coldest being in the west) and distinguished by a temperature difference of about 3°C (Figure 7a). The cold in the north-west corner of the Hall is due mainly to infiltrations of air from the ceiling near that corner, as already noted. When solar radiation heats the roof, the warm external air remains in the loft, without penetrating through the coffers of the ceiling. Inside the Hall, a descending current is generated near the cold part of the walls. Infiltrations of air enter through the three doors which are kept open. During the morning, there is an overall rise in temperature, which is even more marked at the east window because of the direct effect of the sun; the same occurs on the west side during the afternoon. As the day wears on, the average temperature continues to rise, especially in the west in the afternoon, which is the last part to be heated. The very large windows tend to transform the Hall into a greenhouse, even when the sky is slightly overcast.

The gradients were steeper in the early mornings, above all near the windows, while they were fairly weak around the middle part of the day. The temperature distribution was clearly affected by the windows and the rows of chairs.

In the morning, the SH gradient was more or less parallel to the main axis of the Hall. The frequency of the isolines gradually decreased with time. In all the maps of the summer campaign, it was seen that when solar radiation heated the brick floor, the latter gave off a considerable amount of water vapour which moved towards the windows, pushed there by the convective cells. Inside the Hall it was noted that there was an infiltration of damp air through the doors, sometimes from the north wall (Figure 7b), sometimes from one of the two doors connected with the corridor on the south (Figure 7c). Anomalies are often found near the north wall where the cold air from the ceiling falls. Steep SH gradients, particularly near the windows and beyond

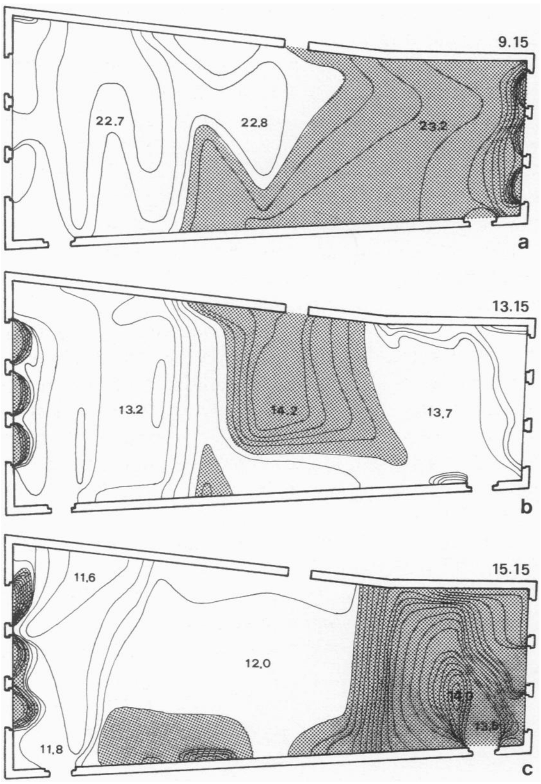

Figure 7 Horizontal cross-section of (a) air temperature at 09:15, (b) specific humidity at 13:15, (c) the same but at 15:15 on 7 July.

the doors, suggest that air is moved from one part of the Hall to the other by convective transport.

As the day wears on, the situation is inverted about the middle of the afternoon. The SH maximum is found in the centre of the Hall, and the minima at the east and west. The SH average value is greatly increased and the maxima are undoubtedly due to the infiltrations from the ceiling which may facilitate the already existing convective movements. In the late afternoon, the distribution tends towards the morning configuration once more, with the maxima towards the west and east windows and the minimum in the centre, favoured by infiltrations of damp air through the doors on the south wall.

The SH anomalies are so marked that the RH distribution is similar to that of SH, with the maxima near the walls in the morning and late afternoon and in the middle of the Hall in the central part of the day. In the morning, the average RH was in the region of 70% and the gradients were rather steep. On average, the air near the walls was rather drier. As time passed, the average value diminished slightly (by 2–3%) and the overall situation seemed much more homogeneous. The minimum RH was found in the centre of the Hall at the north door. Halfway through the afternoon the average RH value tended to vary, sometimes reaching higher values towards the evening, while on other occasions it decreased (by as much as 20%). The average RH value was, however, often rather high.

With respect to the winter survey, the average dew-point spread (DPS) was slightly lower and equal to about 6·5°C. This parameter tended to rise during the daytime, with the heating.

Autumn measuring survey

This survey offers a clear example of how better control of the heating can improve the environmental conditions. In fact, the central heating was no longer controlled by thermostat and a timer with on/off switches but was constantly switched on, with water kept at a lower controlled temperature, which very much contained the air temperature oscillations and, consequently, those of the RH.

With clear skies, the temperature inside was normally higher during the day because of the greenhouse effect. Inside the Hall the temperature was relatively homogeneous, except in proximity to the radiators and where the solar radiation reached the walls directly. Sometimes there appeared to be a slight gradient, with the temperature gently decreasing from east to west. The isotherms perpendicular to the main north and south walls underlined the thermal balance between the air and the walls. During this survey, the average internal temperature (excluding the anomalies near the radiators on the east and west sides) oscillated between a minimum value of 17·6°C and a maximum of 18·5°C. This was a modest variation when compared to the previous winter survey.

In the early morning, the SH distribution was characterized by the intrusion of dry air penetrating locally through the east and west windows and the north door; this intrusion extended towards the middle of the Hall. At the two sides of the dry central zone, two more humid areas can be found which are associated with the exchange of masses of air through the doors leading into the south corridor. A very damp area can be found near the windows on the west side and then near the opposite ones, on the east, when the wind changes direction. A certain mixing of the air renders the eastern half of the Hall on average humid and homogeneous, while the western half is decidedly drier. In the afternoon, the configuration becomes similar to what it was during the early part of the morning. The temporal distribution of SH was conditioned by the presence of people during lectures and infiltration of air through the doors and from the ceiling. When there were no lectures, and no students in the Hall, there was a constant SH, with an average value of about $7 gkg^{-1}$.

The internal values are subject to slight oscillations between one measurement and another but the average value is more or less the same. The distribution of the RH in the morning is divided into three distinct areas: a drier central sector (53–54%) and two lateral areas which are more humid (57–70%). In the middle of the day, the eastern side is characterized by the maximum humidity. In the afternoon, the configuration is again similar to the morning one, with the minimum RH in the central area. Strong disturbances were always found near the windows and radiators; at times the situation was greatly affected by the airflow through the doors. The main gradients were parallel to the east-west axis.

During this survey, the DPS was similar to the values found during the previous winter survey, reaching an average value of approximately 10·5°C, again suggesting that there is very little condensation on the walls of the Hall.

Analysis of the suspended particulate matter

The suspended particulate matter is mainly composed of black soot particles, generated by the urban traffic. Once deposited, they stick to the surface, obscuring the paintings. Not only is cleaning expensive but also every restoration constitutes an additional stress and a risk factor for the work of art.

It is known that deposition occurs by means of several mechanisms; the main ones are Brownian motion, thermophoresis, diffusiophoresis and Stefan flow, electrophoresis, gravitational settling and inertial impaction [12–14]. Brownian motion is particularly active for fine particles, is independent of surface orientation and is proportional to the square root of the air temperature and to $D^{-2/3}$ where D is the particle diameter. Thermophoresis is proportional to the temperature gradient close to the wall and may favour or counteract deposition, depending on the sign of the gradient. Diffusiophoresis and Stefan flow occur when there is a change in phase of water on the fresco surface, but the field measurements indicated that this can be disregarded. Electrophoresis is more active in dry environments, but the Hall never reached alarmingly low RH. Gravitational settling occurs only on the protruding irregularities of the frescoes and cannot be avoided. Inertial impaction happens in the presence of (micro)turbulence when the inertia force acting on the particles is greater than the viscous force. In the present case, the chief mechanisms that can be controlled and must be studied are thermophoresis and inertial impaction.

The temperature difference between air and walls is responsible for both thermophoresis (either positive or negative) and inertial impaction. When the wall is colder than the air, inertial impaction acts in addition to thermophoresis; when the wall is warmer than the air, inertial impaction acts in opposition to thermophoresis. Inertial impaction follows the formation of an internal free convection layer which develops along the wall surface in the airflow which is formed, i.e., a rising airflow when the wall is warmer and the air close to it becomes lighter than the air at some distance from the wall, or a descending airflow when the wall is colder and the air in contact with it becomes more dense. The motion of this airflow starts in laminar conditions but, after travelling a short distance from the edge of the free convection layer, speed becomes critical and the onset of turbulence is favoured by the roughness or irregularities of the wall. For instance, with a temperature difference of only 0·1°C between air and wall surface, when the airflow has travelled one metre, a speed of $5 cms^{-1}$ is generated inside the free convection layer. Field measurements made with a hot-wire anemometer show that even in these conditions the speed is dominated by well marked fluctuations, characteristic of turbulence. This deposition mechanism is very important: under normal room conditions it blackens the wall surface, resulting in a deposition rate greater than the thermophoretic transport which is originated by the temperature gradients in proximity to the walls [15]. This is particularly true for medium and especially large particles, when the efficiency of thermophoresis decreases whilst that of aerodynamic impaction increases, linked to the mass of the airborne particles. A clear

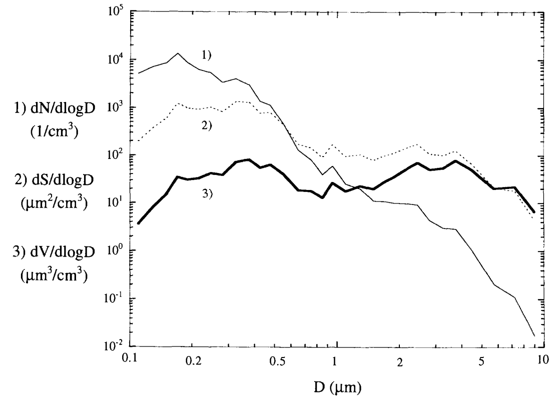

Figure 8 dN(D)/dlnD, dS(D)/dlnD and dV(D)/dlnD versus D at 10:00 on 27 November. Two maxima are evident both for the total volume and the total surface.

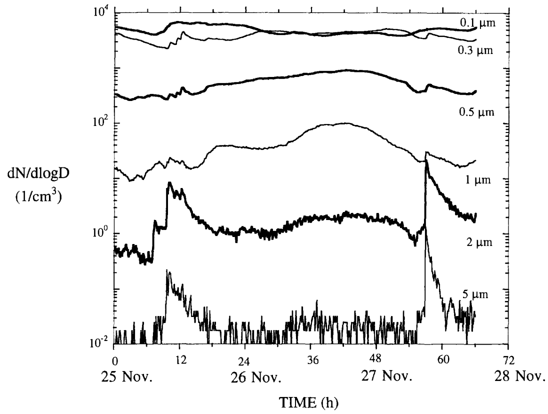

Figure 9 dN(D)/dlnD versus time for the period 25–27 November. Two maxima in the 2 and 5µm concentrations are evident in the mornings of the 25th and the 27th when the vacuum cleaner was used.

idea of the relative importance of the two mechanisms can be obtained by looking above the heaters: the blackening of the wall is much enhanced in the V-shaped regions that form over the wall hooks which support the heater, where the turbulence is greater than in the rest of the rising hot airflow.

The air/surface temperature difference varies during the daytime and is affected by the on/off switch of the heating system and the opening and closing of doors and windows, but dangerous hot-spots form where the wall is hit by solar radiation. The worst condition occurs in winter, when ceiling and walls are colder. The air coming into contact with the cold ceiling reaches a temperature lower than the air below and falls, generating mixing, but much of the cold air flows laterally along the cold walls, forming a global cellular motion with air currents descending on the side and rising in the centre.

A sophisticated instrument, based on the Mie theory of light-scattering by suspended particles [16, 17], analyzes the spatial distribution of the light diffused by a laser beam, counts the particles and subdivides them into 32 intervals which lie in the range between 0·1 and 10µm, on the basis of their optical characteristics. The trend of the spectral distribution of the particle concentration N as a function of particle diameter D is expressed, as usual, as $dN(D)/d\ln D$ and decreases as D increases. Similarly, the total surface S and the total volume V can be expressed as $dS(D)/d\ln D$ and $dV(D)/d\ln D$, respectively. Sometimes the spectral distribution of the total volume $dV(D)/d\ln D$ (less often $dS(D)/d\ln D$) is bi-modal: the main maximum is in the submicronic range; the secondary maximum, if any, is in the micronic range, especially when there is a particle resuspension engendered by people walking about or after the use of a vacuum cleaner (Figure 8). The position and intensity of this secondary maximum are variable, as a consequence of the balance between the actual resuspension and the deposition rate.

The daily trends are variable, especially for the supermicronic particles, which tend to increase during the course of the diurnal hours; this is due to the resuspension of particles when people walk about in the Hall. A marked daily peak is connected with the use of vacuum cleaners for cleaning purposes; vacuum cleaners are effective in swallowing up all the granules and fibres of millimetric size but resuspend the micronic and supermicronic particles already deposited at ground level and are almost wholly ineffective with respect to the finest particles which stick to the floor (Figure 9).

However, when air comes in through the north door from the main hallway, the concentration of suspended particulate matter increases, changing the spectral distribution, due to public activity in the hallway and contact with the outside air.

In winter, when the weather changes from clear skies to haze, the distribution also changes: the finest particles increase by one order of magnitude and the largest ones decrease by one order of magnitude. When there is fog together with high pressure, the ventilation is reduced and this tends to increase the suspended particulate matter. However, the concentration of the larger particles falls because of sedimentation which cannot be counteracted by subsequent resuspension for two reasons: the absence of wind and the wet soil, to which all the particles that touch it stick. Inside the Hall, relatively higher evening concentration values and morning minima would indicate that there is considerable deposition at night.

It is interesting to note that, apart from the induced variation mentioned above, the distribution curves were fairly stationary during the entire period of the survey, which only goes to confirm the importance of an environment where variations in the microclimate are controlled.

Conclusions

The study of the microclimate and the concentration of suspended particles in the Hall of the Giants has shown that parts of the walls are reached by direct solar radiation during the course of the year. The study showed up areas of the frescoes (above all, those on the north wall) that are subject to mechanical stress because of sunlight and it also showed those areas which are subject to greater risk because of deposition processes.

The existing windows are a great source of heat dispersion and permit infiltration of air from the outside, especially when there is wind, because the frames need mending. A second pane of glass should be added, parallel to the existing worked and leaded ones. If the second pane were added to the inside, the exterior of the window would be unprotected; being transparent and seen against the light, the second pane would not be visible from within the Hall (at least during the daytime) or from the outside. If the second pane of glass were added to the exterior, the present leading would be protected but the external aspect would be less attractive, as the new pane would reflect the sunlight outwards. This problem can be solved by using non-reflective glass. Using an optically selective glass, infrared radiation and part of the visible light could be stopped outside, protecting the walls against direct solar radiation and counteracting the indoor greenhouse effect.

An improvement in the winter microclimate, which became stationary and more homogeneous, was made by changing the control of the heat supply. The central heating, which was originally controlled by a thermostat and a timer with on/off switches, was kept constantly switched on, and the water was controlled at a lower temperature, thus avoiding sharp discontinuities in temperature and relative humidity at each switch on or off.

Currently the central heating is provided by two rows of radiators situated under the east and west windows and by a second integrated system consisting of some radiators along the longer north and south walls. While the two rows of radiators under the windows are in a position that does not cause excessive damage, the same cannot be said for those along the long walls, near the frescoes, as they engender soiling and thermohygrometric and mechanical shocks. They should, therefore, be removed.

External cold air is 'showered' by infiltration through cracks in the coffered ceiling. Open windows in the loft are responsible for these infiltrations. These may lead to a certain amount of beneficial ventilation in the daytime in the summer, reducing any overheating, but they cause negative cold inflow during the night and in winter. All the windows in the loft should be closed during the cold season and left open in the summer, but with a protective net so that pigeons cannot enter. Every temperature difference between the loft and the Hall, i.e., at the two sides of the coffers forming the ceiling, causes thermohygrometric and mechanical stress to the wooden panels of the coffered ceiling.

The roof could be insulated beneath the tiles in order to create a more suitable microclimate directly below the roof; this would, in turn, ensure better protection of the existing beams. It would therefore be advisable to insulate the ceiling, too, with mobile heat insulators, to be placed above the beams over the 'floor' of the ceiling.

Using the room (for teaching, lectures, concerts) alters the temperature and specific humidity and, consequently, the relative humidity. The number of people simultaneously present and their residence time should, therefore, be controlled.

Measurement of the particle concentrations indicated that the concentration was substantially constant, except after cleaning, when the use of a vacuum cleaner caused a net increase in the micronic and supermicronic particles, resulting in their resuspension. It is unwise to use this type of cleaner because it can cause an increase in the concentration of airborne particulate matter and, consequently, in the deposition on the walls. It is advisable to use vacuum cleaners with long suction or emission tubes, in order to release the polluted air directly outside.

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Authors

DARIO CAMUFFO, born 1941. Physicist, research director. Since 1969 he has worked at the National Research Council of Italy (CNR), in the field of atmospheric science, climatology and microclimatology; he teaches atmospheric physics at the University of Padua; he is Associate Editor of the journal *European Cultural Heritage Newsletter on Research*, published by the Commission of the European Communities (CEC), and a member of the editorial board of other scientific journals. He is a member of UNESCO commissions for the preservation of monuments, of the Vatican Commission for the Sistine Chapel and of the National Commission for Scientific and Technological Research for the Cultural Heritage of the Italian Ministry for University and Scientific Research. He has been project leader of several research projects for the conservation of the most outstanding monuments. *Address: CNR-ICTIMA, Corso Stati Uniti 4, 35020 Padua, Italy.*

ADRIANA BERNARDI, born 1955. Physicist, researcher. Since 1984 she has worked at the National Research Council of Italy (CNR), in the same group as Dr Dario Camuffo, in the field of microclimatology and conservation. With this group, she has studied several outstanding monuments (Sistine Chapel, Rome; Leonardo's *Last Supper*, Milan; Trajan's and Aurelian's Columns, Rome) and museums (British Museum, London; Uffizi Galleries, Florence; Louvre Museum, Paris) and has actively participated in several research projects supported by the Commission of the European Communities (STEP Programme) for the conservation of the European cultural heritage. She has published several papers on conservation and has been responsible for some research projects. *Address: as for Camuffo.*

Résumé—*La Salle des Géants (Sala dei Giganti), autrefois dans le Palais Carrara et qui fait maintenant partie de l'Université de Padove, en Italie, contient des fresques du XVI^e S. qui sont victimes de l'encrassage dû aux pollutants en suspension dans l'air, et du stress mécanique des cycles chaud/froid. On a donc entrepris un examen de la Salle pour y mesurer le microclimat et la répartition des matières en suspension à différents moments de l'année: hiver, été et automne. En analysant les cartes des cross-sections thermohygrométriques de la Salle, on a identifié plusieurs facteurs de perturbation du microclimat: le rayonnement solaire, qui provoque des cycles de réchauffement saisonnier et journalier; les radiateurs qui sont régulés par un thermostat et une minuterie, produisant ainsi des discontinuités dans l'apport de chaleur; l'emploi de la pièce pour des conférences et des concerts; une présence humaine dans les pièces adjacentes; de vieilles fenêtres aux vitres* *épaisses, si bien que la conductibilité calorique est élevée et l'isolement mauvais; l'air extérieur qui pénètre entre le toit et le plafond par les ouvertures de ventilation et à travers les fentes du plafond à caissons; enfin l'usage journalier de l'aspirateur qui accroît de façon dramatique la concentration des particules en suspension. On discute les options prises pour atténuer ces facteurs défavorables.*

Zusammenfassung—*Der Saal der Giganten (Sala dei Giganti) ist Teil des ehemaligen Carrara Palastes, einem Gebäude, das nun Teile der Universität von Padua in Italien beherbergt. Die dort enthaltenen Fresken des sechzehnten Jahrhunderts leiden unter durch Luftverschmutzung hervorgerufenen Verunreinigungen und sind zudem mechanischen Belastungen durch Heiz- und Kühlperioden ausgesetzt. Untersuchungen vor Ort erbrachten einen Überblick über die mikroklimatische Situation in dem Saal und sollten Aufschluß geben über das Verhältnis der Partikelverteilung in der Luft im Winter, Sommer und Herbst. Mit der Auswertung von thermohygrometrischen Saalquerschnitten konnten mehrere Faktoren ermittelt werden, die das Mikroklima des Saales stören: die Sonneneinstrahlung verursacht saisonale und täglich wechselnde Wärmezyklen; Heizradiatoren werden durch eine Zeitschaltung und zusätzlich über Thermostate geregelt, wodurch Unregelmäßigkeiten in der Wärmezufuhr verursacht werden; Nutzung des Raumes für Vorträge und Konzerte sowie weitere Nutzung der angrenzenden Räume; die alten, bleiverglasten großen Fensterflächen weisen eine hohe thermische Leitfähigkeit auf, während die Isolierwerte niedrig liegen; die Außenluft gelangt durch Lüftungsöffnungen zwischen Dach und Deckenkonstruktion in das Gebäude und dringt durch Riße in der Kassettendecke in den Raum ein; der tägliche Einsatz von Staubsaugern erhöht dramatisch die Partikelkonzentration in der Luft. Es erfolgt eine Erörterung von Möglichkeiten, diese schädlichen Einflüße zu verringern.*

Resumen—*La Sala de los Gigantes (Sala dei Giganti) en el antiguo Palacio Carrara, que ahora forma parte de la Universidad de Padua, Italia, contiene frescos del siglo XVI que se ven afectados por la suciedad de los contaminantes en el aire y por el estrés mecánico causado por los ciclos de calentamiento/enfriamiento. Se llevaron a cabo estudios en la Sala para medir el microclima y la distribución de las partículas en suspensión en distintas épocas del año: invierno, verano y otoño. Al analizar los planos de los cortes transversales termohigrométricos de la Sala, se identificaron varios factores que alteran el microclima interior: la radiación solar, que causa ciclos de calentamiento estacionales y diarios; los radiadores que se controlan por termostato y temporizador, generando así discontinuidades en el suministro de calor; el uso de la sala para conferencias y conciertos; la actividad humana en las habitaciones contiguas; las antiguas ventanas con cristales de vidrio emplomado que son muy grandes y por lo tanto la conductividad térmica es alta y el aislamiento es pobre; el aire del exterior que entra entre el tejado y el techo a través de las aberturas de ventilación y luego penetra a través de fisuras en el techo artesonado; y el uso diario de una aspiradora, que aumenta dramáticamente la concentración de partículas en suspensión. Se tratan las acciones a tomar para mitigar los factores adversos.*