energies

MDPI

Article

Optimizing Ventilation Strategies for Thermal Comfort in Mediterranean Schools: A Dynamic Modeling Approach

Paolo Maria Congedo , Andrea Palmieri and Cristina Baglivo *

Department of Engineering for Innovation, University of Salento, 73100 Lecce, Italy; paolo.congedo@unisalento.it (P.M.C.); andrea.palmieri@unisalento.it (A.P.)
* Correspondence: cristina.baglivo@unisalento.it

Abstract: Schools, key symbols of progress and innovation, require particular attention regarding energy efficiency, which is considered a strategic priority in sustainable development policies. Improving energy efficiency in schools reduces costs and environmental impact while educating students and the community about sustainability. Ensuring good air quality and thermal comfort is also crucial for student well-being and performance, resulting in improved productivity, health, and concentration. This study shows that proper ventilation in schools can maintain thermal comfort by exploiting the heat loads generated by the environment and equipment. Yearly and hourly analyses were conducted in terms of internal operative temperature on a simplified school prototype located in a Mediterranean city following the UNI EN ISO 52016 standard. Thermal comfort was evaluated in accordance with the UNI EN 16798-1 standard and tested for different air exchange rates. The results showed that the heating system would typically operate for about 1000 h per year, excluding holiday periods when teaching activities are suspended. With the implementation of a suitable ventilation system, however, the need for a heating system could be removed.

Keywords: schools; thermal comfort; internal temperature operative; ventilation; air changes; climate change; energy efficiency; public buildings; Mediterranean climate; hourly analysis

check for updates

Academic Editor: Ioan Sarbu

Received: 12 February 2025
Revised: 16 March 2025
Accepted: 18 March 2025
Published: 20 March 2025

Citation: Congedo, P.M.; Palmieri, A.; Baglivo, C. Optimizing Ventilation Strategies for Thermal Comfort in Mediterranean Schools: A Dynamic Modeling Approach. *Energies* **2025**, *18*, 1542. https://doi.org/10.3390/en18061542

1. Introduction

Energy efficiency in public buildings, particularly schools, has become a priority in environmental policies and sustainable development strategies. Schools, as places of education for future generations, also serve as symbols of progress and innovation. Improving their efficiency not only reduces operational costs and environmental impact but also provides an educational opportunity to raise awareness among students and communities about sustainability.

In many countries, a significant portion of school buildings was constructed in the second half of the 20th century [1,2], a period marked by extensive school complex development. In Europe, between the 1950s and 1970s, numerous school complexes were built, many of which are now obsolete, especially in the Mediterranean regions [3]. In Italy, 67% of the school building stock predates 1974, before the introduction of the first energy efficiency regulations. Additionally, only about 8% of school buildings have been constructed in the last two decades [4]. In regions with hot climates, many schools no longer meet modern sustainable design criteria, leading to uncomfortable indoor environments exacerbated by climate change [5]. Managing energy costs in school buildings in

Mediterranean countries is a complex issue, but innovative solutions, such as optimizing the building envelope and managing air exchange, show that it is possible to reduce consumption without compromising indoor comfort [6].

Changes in global weather patterns, including the increase in heat waves across the Mediterranean area [7,8], make it essential to ensure adequate thermal comfort in school buildings. Children, who are particularly vulnerable due to their developing immune systems, are highly sensitive to indoor environmental quality [9]. Since they spend most of their day in classrooms, it is crucial to ensure that these spaces are healthy and safe. Maintaining good indoor air quality (IAQ) and optimal thermal comfort is essential for both the student's and teacher's well-being and academic performance [10–13].

Ventilation plays a key role in school environments by reducing the spread of pathogens [14], enhancing IAQ [15], and thermal comfort [16]. Ventilation strategies fall into two main categories: natural and mechanical. Natural ventilation relies on physical principles such as convection and wind pressure to ensure air exchange, while mechanical ventilation uses artificial devices to provide consistent and controlled air renewal [15]. However, natural ventilation, which is widely used, has limitations due to climate conditions, outdoor pollution, noise [8,17], and building geometry. Therefore, it is necessary to design ventilation systems that ensure both comfort and air quality while minimizing energy consumption [18]. An optimal system not only removes contaminants but also supplies fresh air, improving indoor environmental quality [19,20].

Recent studies have highlighted the effectiveness of optimal methodologies for retrofitting existing school buildings to enhance their energy performance [21,22]. These approaches are crucial for ensuring cost-effective interventions that improve both energy efficiency and environmental sustainability [23]. In England, for example, energy efficiency in schools is part of a national plan to reduce carbon emissions [24]. The challenge lies in balancing affordability with optimal comfort while maintaining high performance. The study [25] found that, even after renovations, schools in hot climates may still experience long-term thermal discomfort. In the coming years, an increase in indoor operative temperature (TOP) in classrooms is expected, leading to higher cooling demand. Study [26] investigates how integrating future weather forecasts into building assessments can enhance resilience and energy efficiency by analyzing the impact of future climate conditions on energy demand, costs, and comfort across different climate zones. Study [27] explores how building function, orientation, and thermal insulation levels influence energy efficiency and occupant thermal comfort, using dynamic models for an educational facility in Kyiv. The findings indicate that increasing thermal resistance to Swedish standards and introducing intermittent heating and ventilation strategies can reduce energy consumption by up to 42%, with electric heating used during transitional periods to maintain comfort.

This work examines different ventilation and air exchange strategies to maintain thermal comfort and indoor air quality. Dynamic simulation models, based on the UNI ISO 52016-1:2018 standard [28], were applied to a prototype school building located in Lecce, a city with a Mediterranean climate. This approach allows for the analysis of operative temperature under various ventilation scenarios and helps identify the most suitable solutions for schools located in warm climates. In conclusion, this study highlights the importance of an integrated approach to indoor climate management, promoting solutions that ensure thermal comfort, sustainability, and cost-effectiveness.

2. Materials and Methods

The principal steps followed for the implementation of this work are presented below:

- Climate Classification and Heating Regulations for the School Building in Lecce (Section 2.1)

Analysis of the climate of the city of Lecce (southern Italy) where the school is located, characterized by a Mediterranean climate. The focus was on the national regulations in force for this climatic zone.

- Layout of the Prototype Primary School Building (Section 2.2)

Presentation of the school prototype used for the analysis. This prototype has a simple design and complies with national current regulations for school buildings. Its structure complies with the latest energy standards for the relevant climate zone.

- Dynamic Thermal Assessment of the School Building Using Termolog EpiX 15 (Section 2.3)

Hourly and annual operative temperatures for various air exchange scenarios were calculated using UNI 52016 standards with Termolog EpiX 15 software. Each scenario was analyzed to evaluate thermal comfort throughout the year.

2.1. Climate Classification and Heating Regulations for the School Building in Lecce

The school building under study is assumed to be located in the city of Lecce, in south-eastern Italy. Lecce has a Mediterranean climate with mild winters, warm springs, hot summers, and hot autumns, with annual precipitation under 500 mm. According to Köppen's classification [29], Lecce is a warm-summer Mediterranean climate (Csa). Figure 1 illustrates the annual external temperature trend and marks the school vacation periods scheduled for 1–8 January, 6–8 April, 10 June–15 September, and 23–31 December. The days on which holidays begin and end may, of course, vary slightly over the years. The days presented here are indicative.

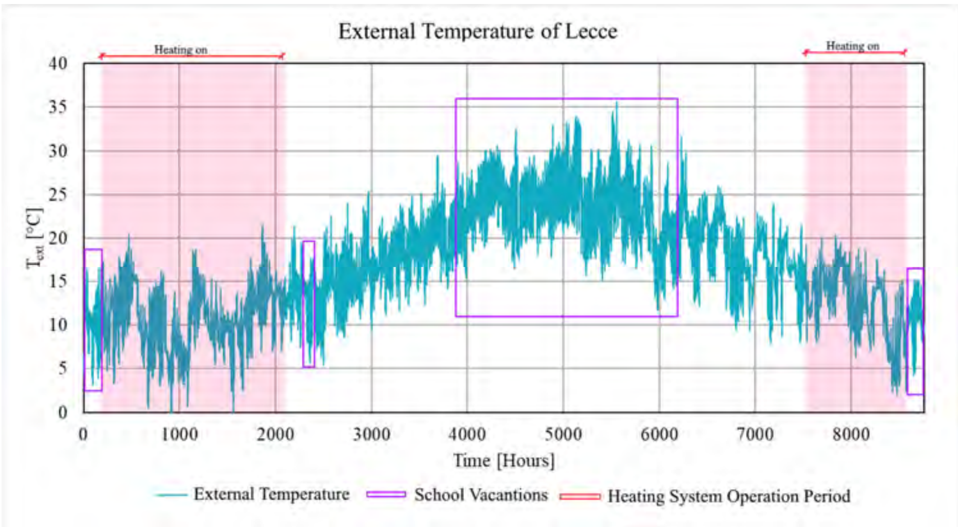


Figure 1. Annual external temperature of the city of Lecce, with indications of heating on and school vacation periods.

According to the Italian climate classification [30], Lecce falls under national climate zone C, based on Heating Degree Days (HDD). HDD is calculated as the sum of the positive differences between the indoor temperature (set at 20 °C) and the daily average external temperature across all days of the year. This determines the days and hours of operation of the heating system in climate zone C. The heating of buildings is permitted from 15 November to 31 March for 10 h per day. In this study, the heating system is always considered to be switched off.

2.2. Layout of the Prototype Primary School Building

The prototype building is a primary school for children between the ages of 6 and 10, whose teaching activities are from 8 a.m. to 4 p.m., Monday to Friday. There are estimated to be 20 students per classroom.

The building has a simple square plan with a net area of 332.70 m^2, as illustrated in Figure 2. The area is divided into nine equal thermal zones, each measuring 6×6 m^2, considered as classrooms. The school prototype model is straightforward. However, the selected geometric representation reflects typical classroom layouts, which are generally rectangular, with one or two exterior-facing walls featuring windows and at least one wall adjacent to a heated corridor or another internal thermal zone. The objective of this study is to analyze the thermal loads and comfort conditions within classrooms, which are characterized by high internal heat gains compared to other school areas. The simplification does not compromise the accuracy of the thermal analysis, as it retains the essential thermal interactions relevant to the study.

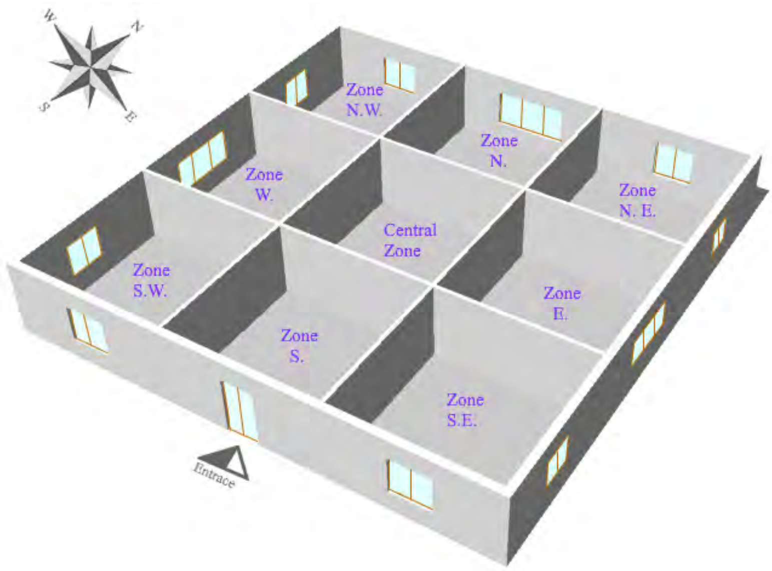


Figure 2. School building prototype model.

The building does not border on other buildings, and the internal subdivision allows for one class for each exposure. According to the Ministerial Decree of 18 December 1975 (M.D. 18/12/1975) [31], the internal area of the classrooms is 1.8 m^2 per student, with a net height of 3.00 m.

The envelope stratigraphy is set in accordance with the criteria defined by Ministerial Decree 26/06/2015 (M.D. 26/6/2015) [32] for Italian climate zone C, as reported in Table 1. In particular, Table 1 presents the thermal properties of each layer of the components and the resulting set thermal transmittance (U_{set}) and the relative limit imposed by M.D. 26/06/2015 (indicated by U_{lim}). As can be seen, the set value does not fall much beyond the limit value.

As shown in Table 2, three types of windows were considered: a French door for the south-facing area, central windows for the west, east, and north areas, and two lateral windows for the southwest, northwest, northeast, and southeast areas. All windows are equipped with low-emissivity double glazing (4-12-4) and Argon-filled cavity.

The frame is made of Polyvinyl Chloride (PVC) with three chambers and a plastic spacer. The shading consists of white aluminum horizontal blinds. In the simulations, the blinds were not considered lowered during class hours.

Table 1. Opaque envelope stratigraphy.

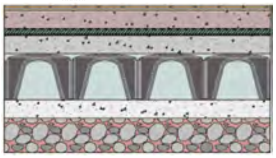
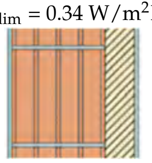
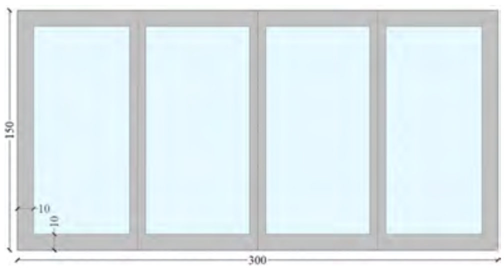
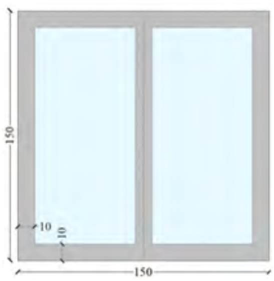
Component	Layers	d [mm]	ρ [kg/m^3]	λ [W/mK]	C [kJ/KgK]
Below ground floor U_{set} = 0.764 W/m^{2}K U_{lim} = 0.84 W/m^{2}K 	Internal adductance			5.88	1
	Floor tiles	10	2300	1.0	0.84
	Cement mortar	10	2000	1.4	1
	Ordinary concrete screed	80	1700	1.1	1
	Vapor barrier	0.5	360	0.4	1.5
	Extruded polystyrene (XPS)	20	24	0.032	1.45
	Bituminous waterproofing membrane—RADON barrier	5	1200	0.2	1
	Reinforced concrete	80	2400	1.91	1
	Underfloor cavity with ventilated cavity	200	1.2	1.39	1
	Lean concrete	80	2200	1.0	1
	Coarse gravel without clay	150	1700	1.2	0.84
Roof U_{set} = 0.317 W/m^{2}K U_{lim} = 0.33 W/m^{2}K 	Internal adductance			10	1
	Internal plaster	10	1400	0.7	1
	Slab blocks with lightening elements in place	260	1800	0.743	1
	Vapor barrier	0.5	360	0.4	1.5
	Extruded polystyrene (XPS)	80	24	0.032	1.45
	Bituminous waterproofing membrane	5	1200	0.17	1
	Concrete	100	1800	0.94	0.88
	Concrete substrate—cement mortar	10	2000	1.4	1
	Ceramic tiles	10	2300	1.3	0.84
	External adductance			25	1
External wall U_{set} = 0.308 W/m^{2}K U_{lim} = 0.34 W/m^{2}K 	Internal adductance			7.69	1
	Internal plaster	10	1400	0.7	1
	Brick blocks	250	1000	0.4	1
	Expanded Polystyrene (EPS)	80	24	0.033	1.45
	External plaster	10	1800	0.9	1
	External adductance			25.0	1

Table 2. Thermal characteristics of French door, central and lateral windows.

French Door	Central Window	Lateral Window
$U_{w,set}$ = 1.926 W/m^{2}K $U_{w,lim}$ = 2.200 W/m^{2}K	$U_{w,set}$ = 2.009 W/m^{2}K $U_{w,lim}$ = 2.200 W/m^{2}K	$U_{w,set}$ = 2.004 W/m^{2}K $U_{w,lim}$ = 2.200 W/m^{2}K
		

As previously mentioned, the simulations focus on calculating the internal operative temperature in a free-floating regime; the heating and cooling systems are not considered.

2.3. Dynamic Thermal Assessment of the School Building Using Termolog EpiX 15

The school building is thermally assessed using Termolog EpiX 15 software [33]. Termolog is a modular software certified by the Italian Thermo-technical Committee (CTI). The software is equipped with an hourly dynamic calculation engine [34] and allows for a precise evaluation of the hourly energy balance and the building response to external and internal climatic conditions in accordance with UNI EN ISO 52016:2018, with a particular focus on operative temperature. The dynamic analysis is based on parameterized RC (Resistance–Capacity) models, where each heat-losing element is represented by its own equivalent circuit. For each hour, the envelope energy balance is calculated on the basis of different boundary conditions and usage profiles, the data required at each calculation step are:

- cooling and heating temperatures (set point and set back);
- occupancy profiles and internal contributions due to the presence of people, machines, and lighting;
- hourly air exchange of the envelope;
- hourly internal vapor production;
- hourly usage profiles of movable shading devices on windows.

The UNI EN ISO 52016:2018 standard accurately represents the building response to both external and internal climatic conditions. Specifically, these calculations generate an hourly plot of the operative temperature throughout the year.

Standard UNI 10375:2011 [35] defines TOP, expressed as follows:

$$TOP = (h_r T_{mr} + h_c T_{db})/(h_r + h_c) \quad (1)$$

where:

- h_r is the linear radiative heat transfer coefficient [W/m^{2}C];
- T_{mr} is the mean radiant temperature [°C];
- h_c is the convective heat transfer coefficient [W/m^{2}C];
- T_{db} is the dry bulb temperature [°C].

The analysis of internal operative temperature in Termolog EpiX 15 is performed under a free-floating regime on an hourly basis throughout the year. Specifically, the indoor operative temperature is tracked in relation to air exchange rates, labeled as “Combo”, followed by the respective number of air exchanges. For instance, in “Combo 01”, the indoor operative temperature values are derived with one air exchange per hour, while in “Combo 02”, the values correspond to two air exchanges per hour. The study covers combinations ranging from a minimum of 1 to a maximum of 10 air exchanges per hour, with the number of students in the room kept constant.

Ventilation rates close to 2 vol/h were considered in order to assess temperature trends under conditions of low occupancy of the classroom, as might occur during extracurricular activities, intervals between lessons or in the first and last hours of the school day. In addition, these values make it possible to examine the thermo-fluid dynamic behavior in situations where air exchange is intentionally reduced to improve energy efficiency or to limit heat loss in the colder months. Analyzing these scenarios provides a better understanding of the role of ventilation in maintaining thermal comfort and air quality while still ensuring acceptable conditions for occupants.

In Table 3, considering the different ventilation combinations, the values of heat loss power by transmission φ_t [W], heat loss power by ventilation φ_v [W], reheat thermal power φ_{rh} [W], and the total thermal load φ_{hl} [W] of the entire building are reported.

Table 3. Thermal loads of the entire building under different ventilation combinations.

Combo	Thermal Power Transmission φ_t [kW]	Thermal Power Ventilation φ_v [kW]	Reheat Thermal Power φ_{rh} [kW]	Total Thermal Load φ_{hl} [kW]
1	6.39	7.97	5.83	20.19
2	6.39	14.58	5.83	26.80
3	6.39	21.19	5.83	33.40
4	6.39	27.80	5.83	40.01
5	6.39	34.41	5.83	46.62
6	6.39	41.02	5.83	53.23
7	6.39	46.89	5.83	59.11
8	6.39	54.24	5.83	66.45
9	6.39	60.11	5.83	72.33
10	6.39	67.45	5.83	79.67

The influence of different air changes through the ventilation system strongly influences thermal comfort. According to UNI EN 16798-1:2019 [35], thermal comfort quality levels classified according to the intended use of the building must be guaranteed in the rooms: high, moderate, medium, and low. In the case of a primary school, it is essential to maintain a high environmental quality.

In the absence of heating and/or cooling systems, the assessment of thermal comfort can either follow the guidelines for mechanically ventilated buildings or use a method that considers occupant adaptation effects. During the winter months, to ensure adequate thermal comfort, the indoor operating temperature should be maintained between 21 °C and 23 °C. During intermediate periods (spring/autumn) and during summer, the standard defines the thermal comfort zone through two equations that establish upper and lower limits, as reported below:

$$\text{category I}: \begin{cases} \theta_0 = 0.33 \cdot \theta_{rm} + 18.8 + 2 & \text{Upper limit} \\ \theta_0 = 0.33 \cdot \theta_{rm} + 18.8 - 3 & \text{Lower limit} \end{cases} \quad (2)$$

where:

- θ_0 is indoor operative temperature [°C];
- θ_{rm} is weighted average external temperature [°C].

3. Results and Discussion

This section presents the trends of the internal operative temperature as a function of different ventilation scenarios for air exchange across all zones. Figures 3–5 graphically depict the annual trend of internal operative temperature, highlighting periods of non-teaching activity in blue.

Influence of Different Air Changes on Thermal Comfort for Each Month

Figures 6 and 7 show the variation of the indoor operative temperature in relation to air exchange rates in Zones N and S, from January to March, considering only the teaching hours (from 8:00 a.m. to 4:00 p.m., Monday to Friday).

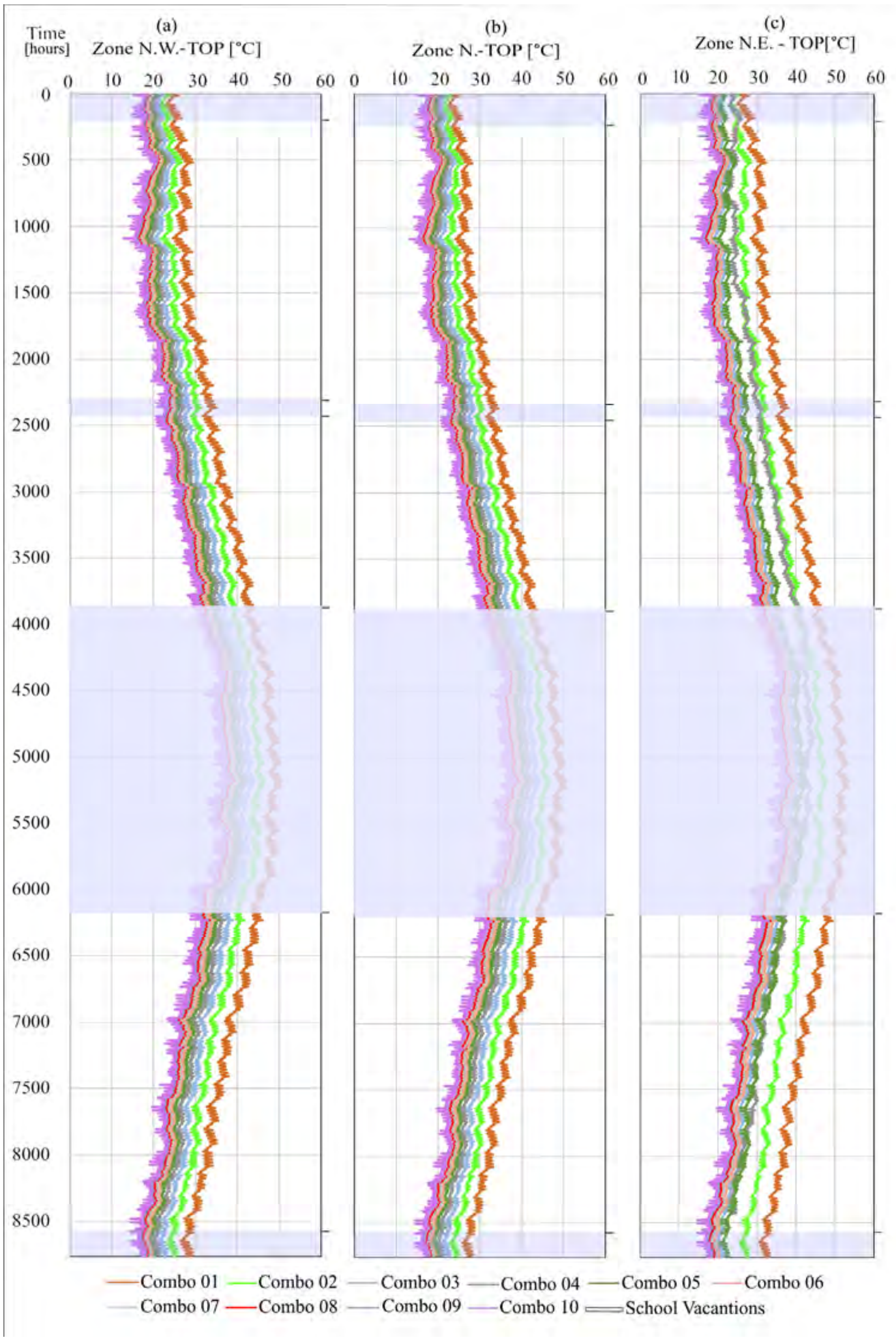


Figure 3. Indoor operative temperature. (**a**) Zone N.W., (**b**) Zone N, and (**c**) Zone N.E. (number of combo corresponds to the number of air volume change a hour).

Each colored point represents a specific combination of air exchanges required to maintain the temperature between 21 °C and 23 °C (as indicated by the green area). The alternating colors indicate moments when the previous air exchange rate was insufficient, requiring a new combination to maintain the temperature within the comfort range.

Although DPR/1993 [30] requires heating systems to be active during these months, the simulations assume that the heating system is switched off, as the aim is to assess thermal comfort based solely on changes in air exchange.

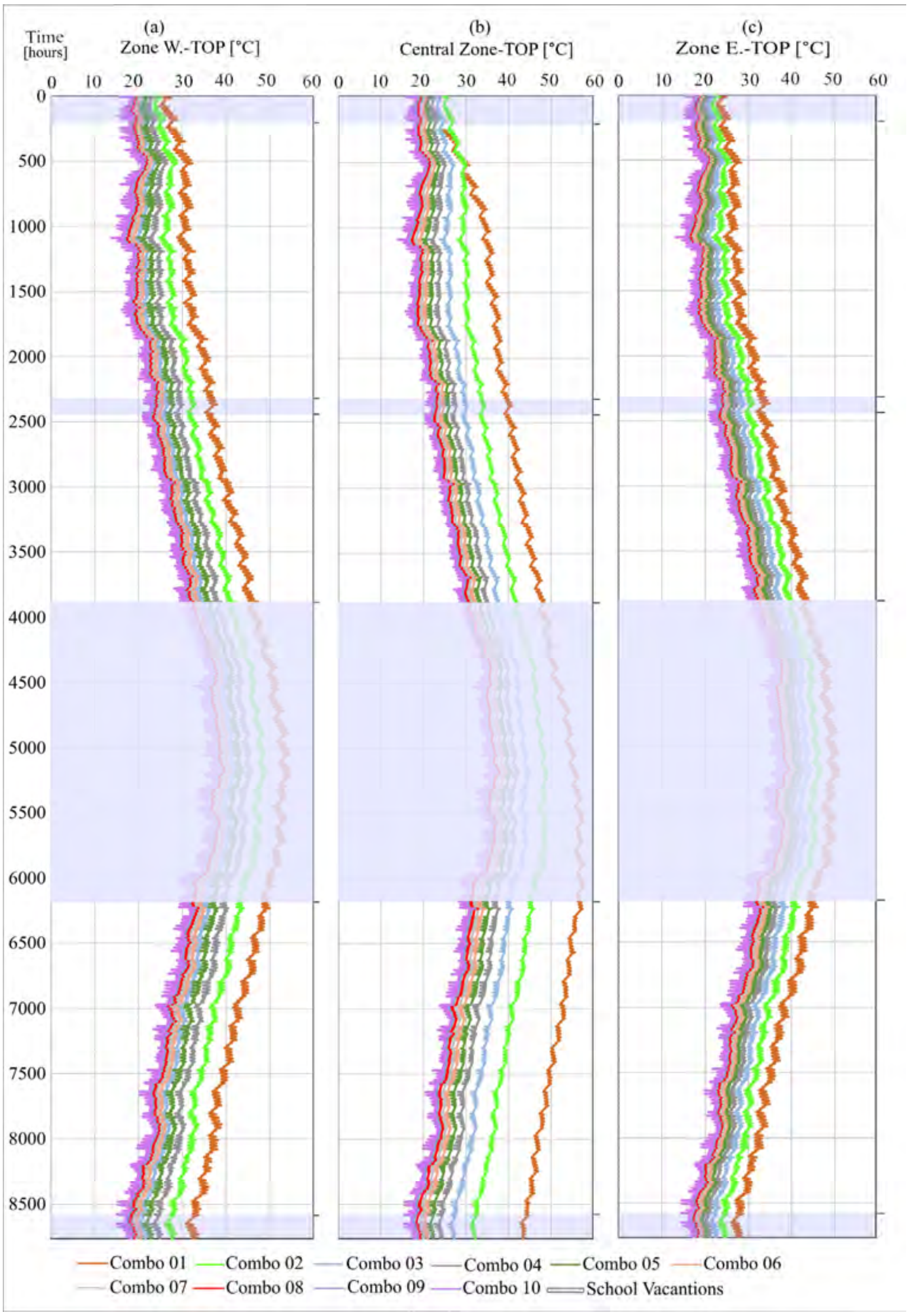


Figure 4. Indoor operative temperature. (**a**) Zone W., (**b**) Central Zone, and (**c**) Zone E.

However, the graph shows that by adjusting air exchanges, it is possible to maintain thermal comfort without using the heating system.

The graph in Figure 6a shows the trend of indoor operative temperature in Zone N during January, limited to school hours, starting from 9 January (the first day after the winter break), corresponding to the 200th hour of the year. In January, it is possible to achieve an operative temperature between 21 °C and 23 °C for all teaching hours by alternating air exchange combinations from Combo 03 to Combo 05. Meanwhile, the graph in Figure 7a, related to Zone S, shows the indoor operative temperature trend for January. In this case, unlike the north-facing room, different air exchange combinations are required, specifically from Combo 03 to Combo 06.

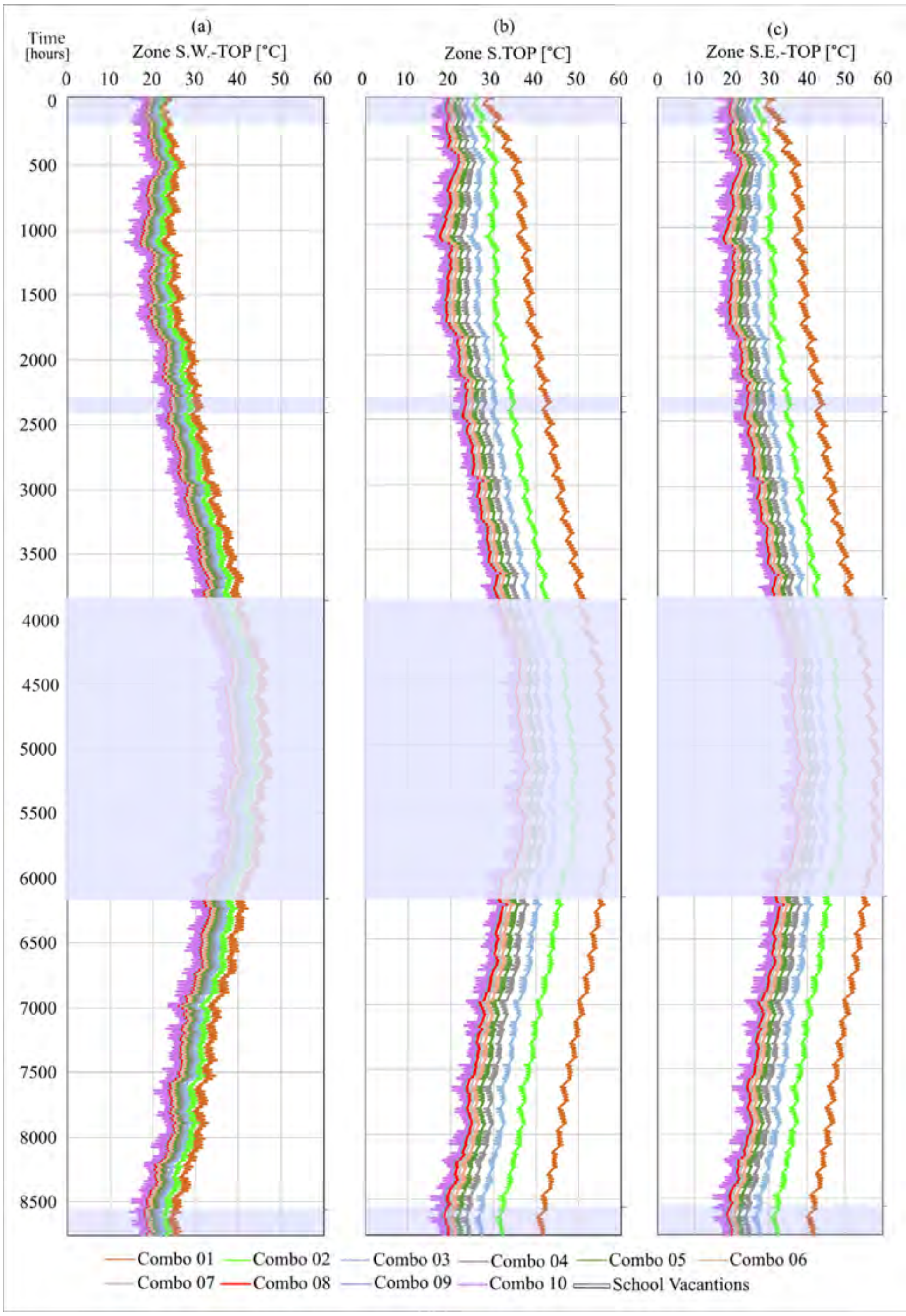


Figure 5. Indoor operative temperature. (**a**) Zone S.W., (**b**) Zone S, and (**c**) Zone S.E.

Figure 6b shows the trend of indoor operative temperature in Zone N during February. In this month, Combo 03 and Combo 04 are necessary to maintain the indoor operative temperature within the thermal comfort range. However, the only hours when the lower comfort limit is not reached occur at 4:00 p.m. on 6 February, when the indoor operative temperature drops to 20.92 °C, and at 9:00 a.m. on 15 February, with a temperature of 20.73 °C. These values, although slightly below the limit, can still be considered very close to the lower boundary of the thermal comfort range. In Zone S, on the other hand, the previous combinations ensure thermal comfort throughout all the teaching days and hours, as shown in Figure 7b.

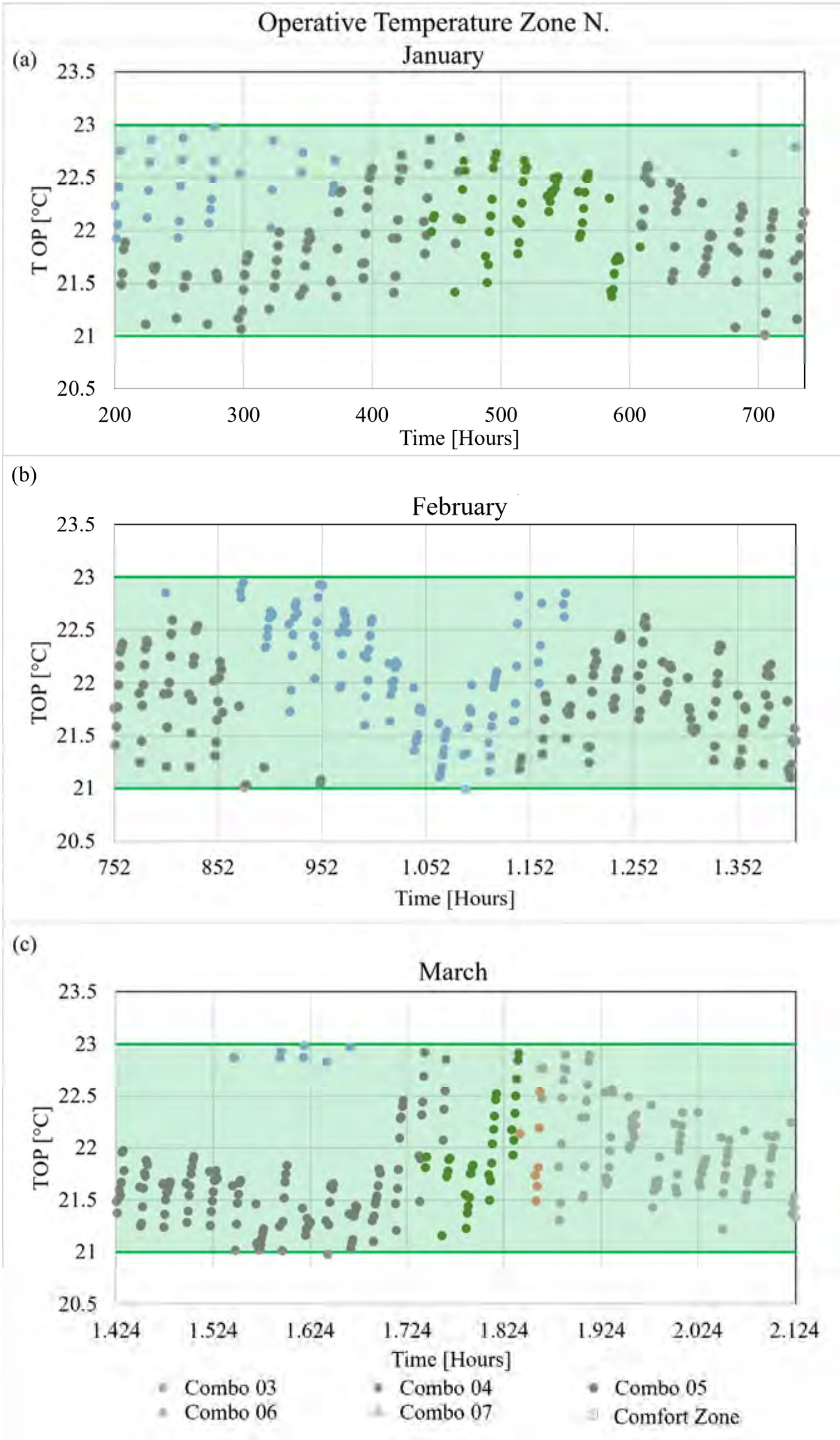


Figure 6. Operative temperature in Zone N for: (**a**) January, (**b**) February, and (**c**) March.

Finally, the graph in Figure 6c shows the internal operative temperature in Zone N during March. In this month, the external temperature is higher than in the previous months, requiring more combinations to achieve internal comfort. Specifically, combinations ranging from Combo 03 to Combo 07 are used. Similarly, Figure 7b, which depicts the internal operative temperature trend in Zone S during March, requires the use of combinations from Combo 04 to Combo 07. The dynamic management of air exchanges during these months allows for the internal temperature to remain within the comfort range of 21 °C to 23 °C.

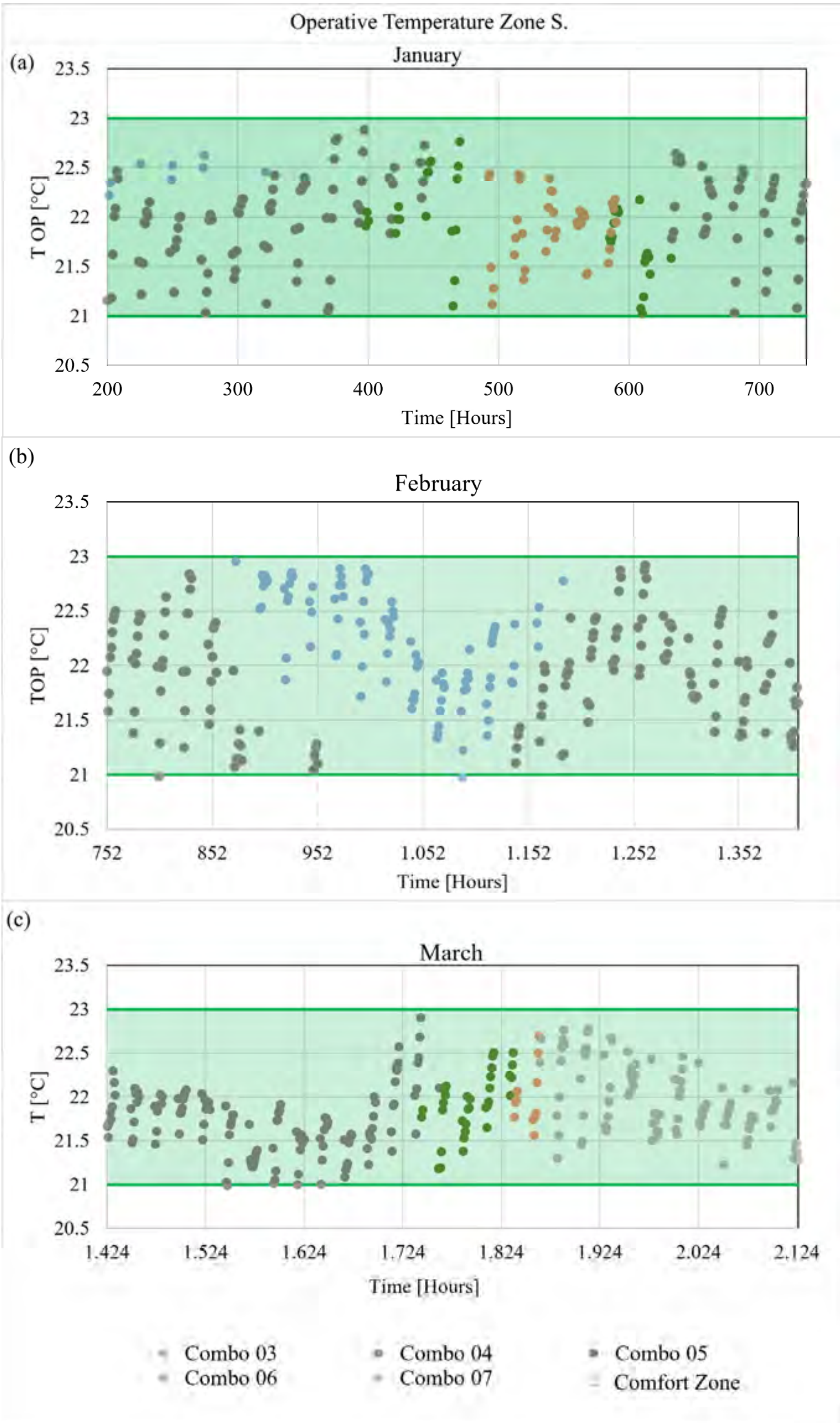


Figure 7. Operative temperature in Zone S for: (**a**) January, (**b**) February, and (**c**) March.

The graphs below illustrate the trend of operative temperature in the two classrooms under study between April and December. In accordance with Presidential Decree 412/1993, the heating system was turned off during this period. Thermal comfort was assessed using Equation (2), in line with UNI 16798 standards, and graphically represented by the green area in the diagrams. Figure 8a,b show the trend of indoor operative temperature in Zones N and S for the month of April. During this period, the optimal combinations to ensure thermal comfort ranged from Combo 08 to Combo 10 for both classrooms, maintaining the operative temperature within the comfort zone for the vast majority of the days analyzed.

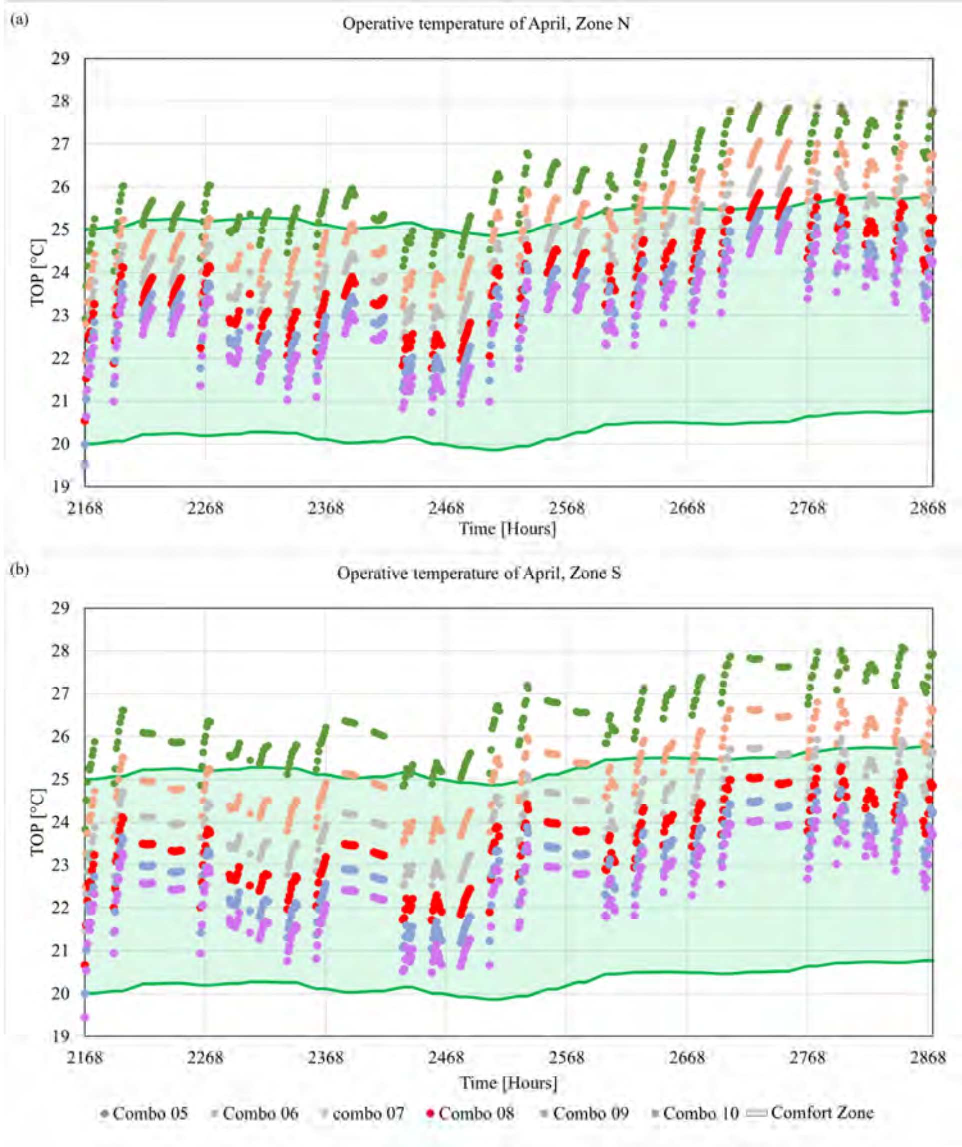


Figure 8. Operative temperature in April for: (**a**) North zone and (**b**) South zone.

A more detailed analysis reveals that, in Combo 07 (Figure 8a), the percentage of hours in which the operative temperature exceeds the comfort zone is 7.04%, mainly concentrated between 24 and 28 April, during specific lesson times. In particular, values above the threshold were recorded on 24 April between 2:00 p.m. and 4:00 p.m.; on 24 and 26 April at 8:00 a.m. and between 1:00 p.m. and 4:00 p.m.; on 27 April at 8:00 a.m. and between 11:00 a.m. and 12:00 p.m.; on 28 April at 8:00 a.m. The time intervals during which the operative temperature exceeds the comfort zone do not follow a regular pattern.

Regarding Combo 08 (Figure 8a), the percentage of hours above the comfort zone drops to 0.37%, occurring only at 4:00 p.m. on 24 April.

In Zone S, Combo 07 (Figure 9b) shows a percentage of hours above the comfort zone of 1.85%, recorded between 25 and 27 April. The critical hours include 25 April at 3:00 p.m. and 4:00 p.m., 26 April at 4:00 p.m., and 27 April at 11:00 a.m. and 12:00 p.m. Similarly, in Combo 08 (Figure 9b), a percentage of 0.37% is observed, coinciding with what was recorded in Zone N, again at 4:00 p.m. on 25 April.

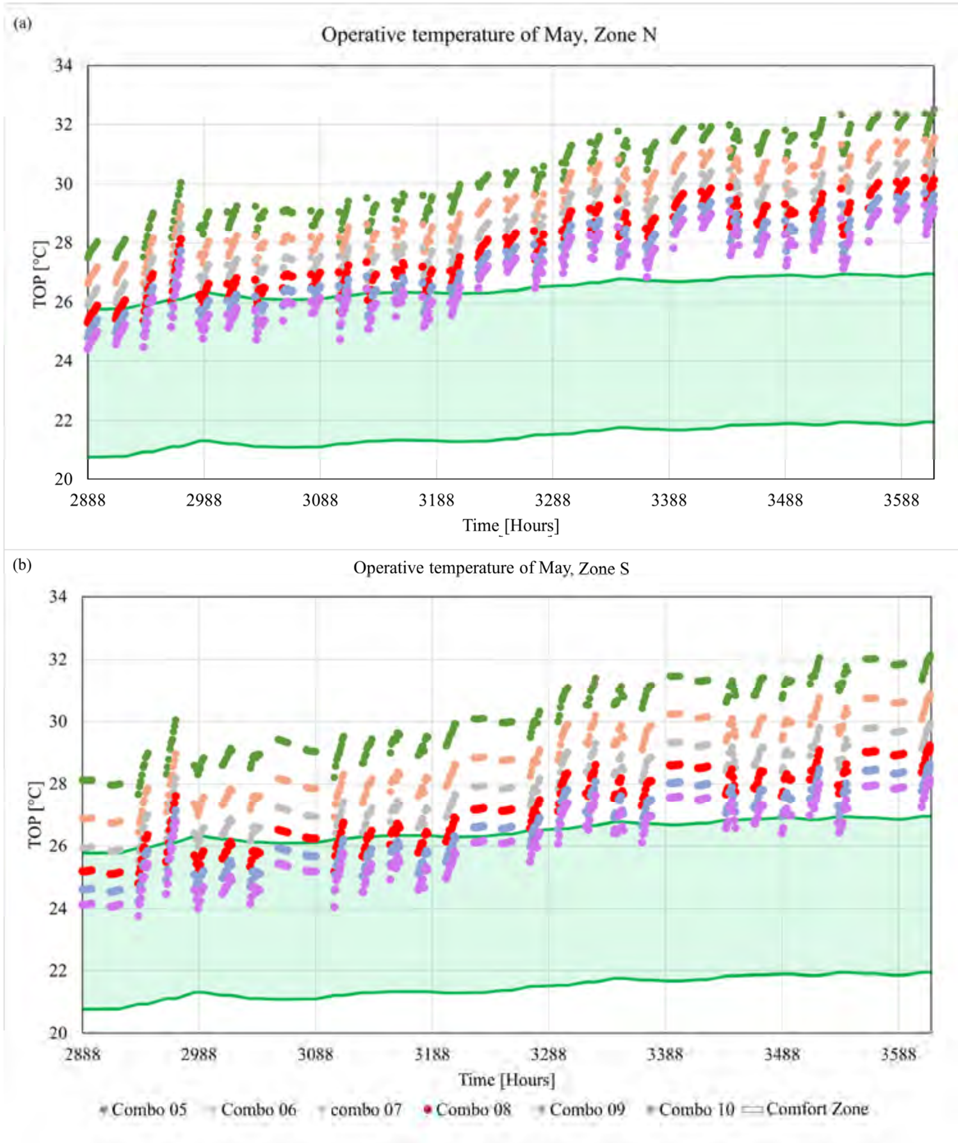


Figure 9. Operative temperature in May for: (**a**) North zone and (**b**) South zone.

Increasing the air exchange rate through ventilation proved effective in maintaining the operative temperature within the comfort zone limits. In conclusion, the analysis suggests that combinations 08, 09, and 10, with optimal regulation of air exchange, ensure optimal thermal comfort in both classrooms during the month of April.

Figure 9a,b show the trend of operative temperatures in May for the classrooms in Zones N and S. Using combination 05, adequate thermal comfort is not achieved on any school day. However, by increasing the air exchange rate, thermal comfort is reached only on certain days and for a limited number of hours, depending on the tested ventilation combinations (Combo 06–10). This phenomenon is primarily due to the rise in outdoor temperatures during the month.

In the Zone N classroom, considering combinations from Combo 06 to 10, the percentages of hours in which the thermal comfort zone is achieved are, respectively: 0.36%, 6.81%, 30.11%, 41.48%, and 52.33%. In the Zone S classroom, for the same combinations, the percentages of hours with adequate thermal comfort are, respectively: 1.75%, 12.19%, 34.41%, 44.44%, and 55.56%.

Figure 10a,b show the trend of indoor operative temperature in relation to the thermal comfort zone in the two classrooms examined, oriented to the north (Zone N) and south

(Zone S), during the teaching hours of the last 12 school days in June (approximately the first half of the month). The graphs clearly highlight that, due to the high outdoor temperatures recorded during this period, the indoor operative temperature never reaches the thermal comfort zone when using only the ventilation system as an air exchange method.

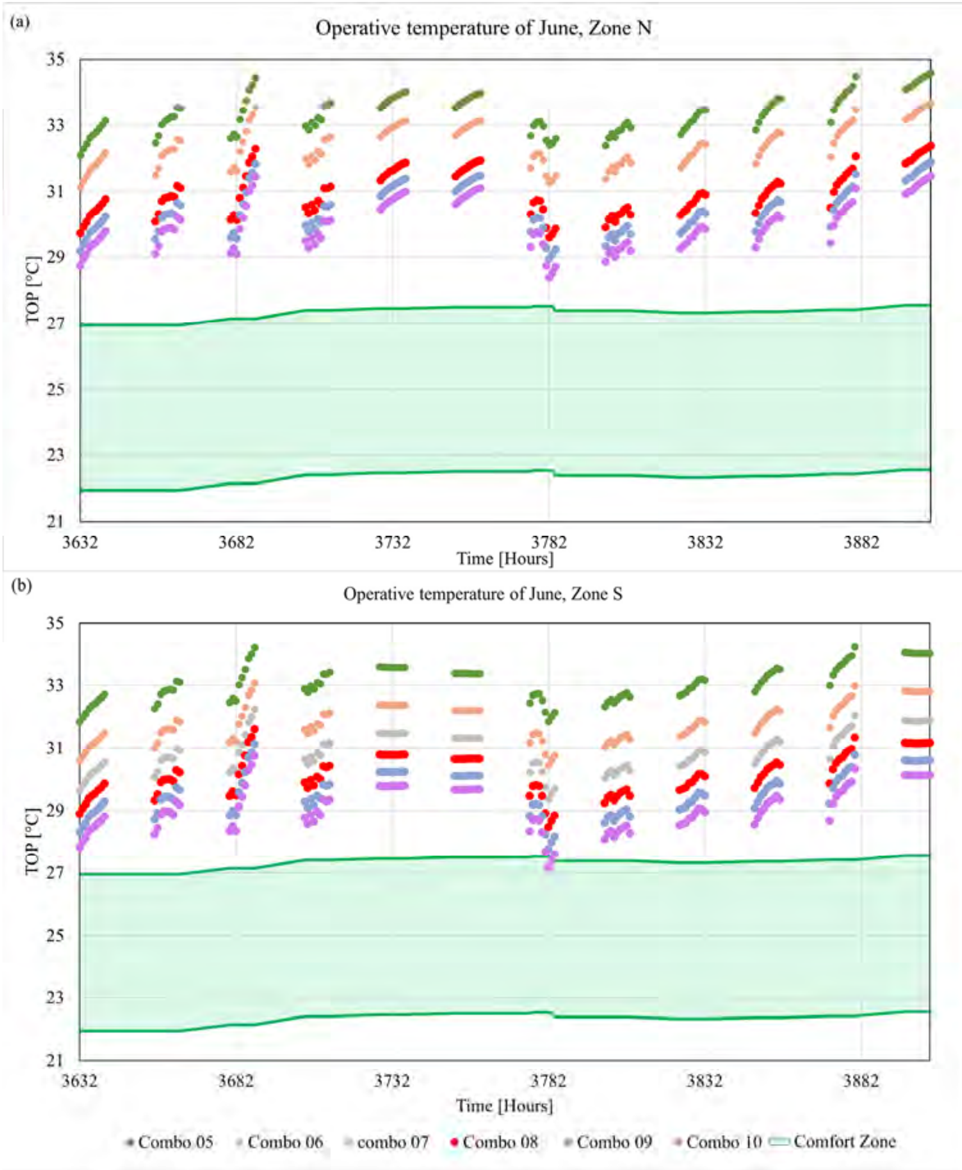


Figure 10. Operative temperature in June for: (**a**) North zone and (**b**) South zone.

The rising summer temperatures, a consequence of climate change, require the adoption of cooling systems, as ventilation alone does not ensure thermal comfort.

Given these conditions, it would be advisable to consider a revision of the school schedule or the implementation of cooling systems and solar shading to improve thermal comfort in the classrooms during the hottest periods of the year.

The analysis of temperatures in September reveals conditions similar to those observed in June. The high outdoor temperatures, still persistent during this period, do not allow for achieving an adequate indoor operative temperature within the thermal comfort zone solely through natural ventilation, as shown in Figure 11a (Zone N) and Figure 11b (Zone S).

In particular, on 25 September, at 11:00 a.m., the ventilation scenario corresponding to combination 10 shows an indoor operative temperature close to the upper limit of the thermal comfort zone (27.32 °C). In the two examined classrooms, values of 27.43 °C for Zone S and 27.54 °C for Zone N are recorded.

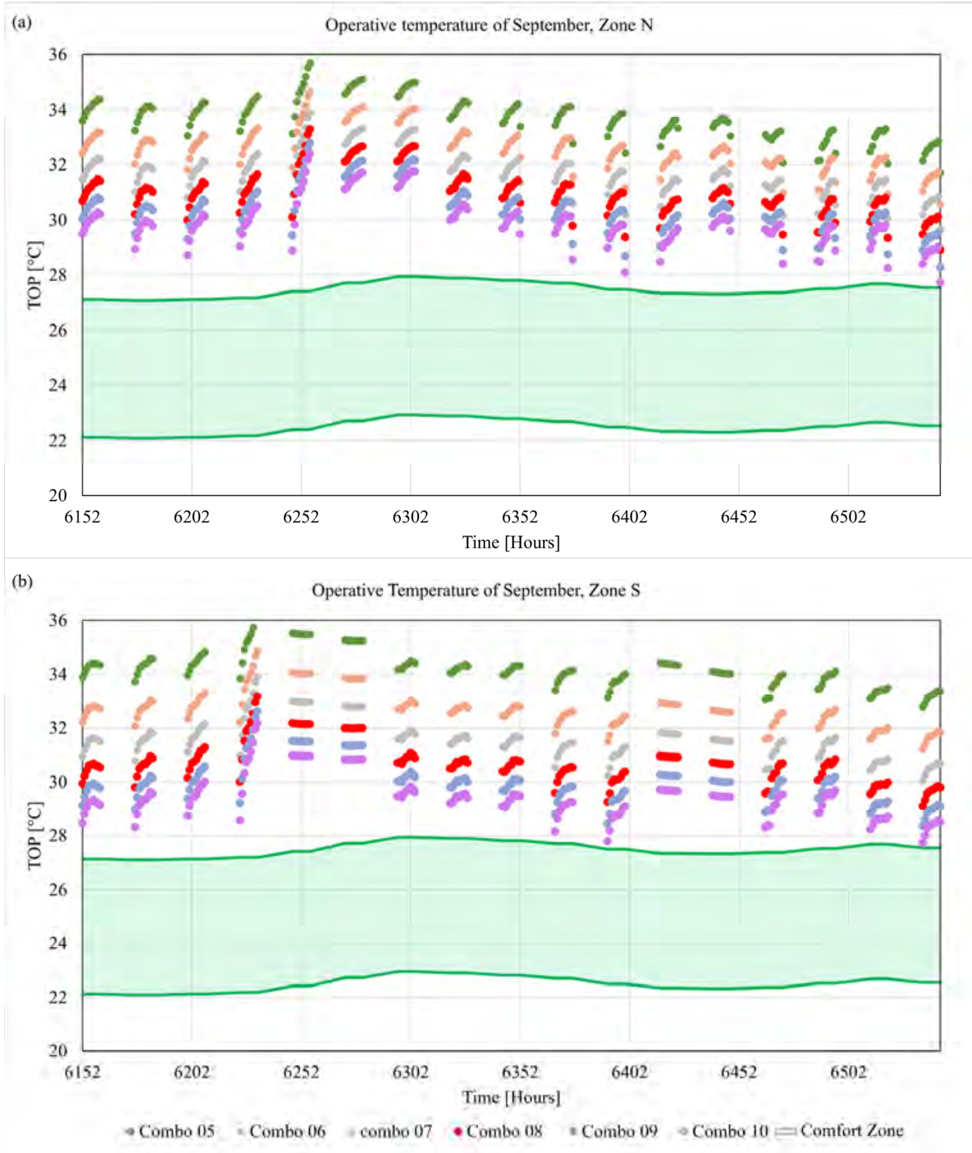


Figure 11. Operative temperature in September for: (**a**) North zone and (**b**) South zone.

Figure 12a,b present the graphs of the indoor operative temperature trends in Zones N and S during the month of October in relation to the thermal comfort zone. The analysis highlights that the use of ventilation to control the indoor operative temperature has proven problematic, especially during the first part of the month, due to the still elevated outdoor temperatures.

Considering combinations 05, 06, 07, 08, 09, and 10 for Zone N, the percentages of hours in which the indoor operative temperature is adequate for thermal comfort are as follows: 0%, 13.26%, 36.92%, 53.40%, 60.93%, and 69.53%. For Zone S, the percentages are as follows: 0%, 9.67%, 32.97%, 53.05%, 62.72%, and 70.25%.

Figure 13a,b show the trend of internal operative temperature in classrooms exposed to the north (Zone N) and south (Zone S), respectively, in relation to thermal comfort during the month of November. According to Italian regulations, heating can be activated starting from 22 November in climatic zone C. As indicated by the UNI 16798 standard, the thermal comfort zone is defined between 21 °C and 23 °C, represented in the graphs by two horizontal lines (red for the lower limit and purple for the upper limit).

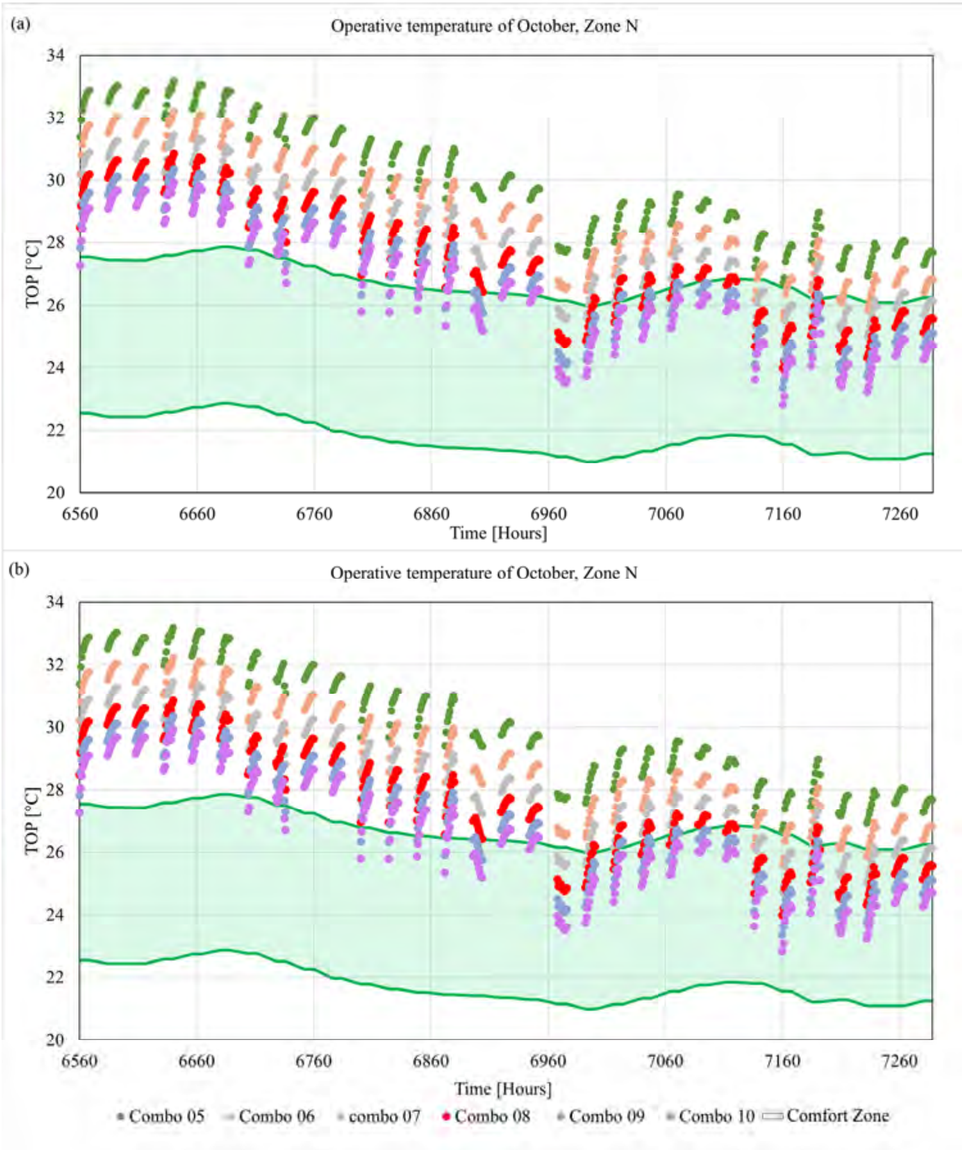


Figure 12. Operative temperature in October for: (**a**) North zone and (**b**) South zone.

For the classroom in Zone N, with ventilation combinations 08, 09, and 10 (Figure 12a), the percentages of teaching hours within the thermal comfort zone are 56.30%, 65.56%, and 62.22%, respectively. For the south-exposed classroom (Zone S), the percentages of teaching hours within the thermal comfort zone for the same combinations (Figure 13b) are 35.56%, 58.88%, and 62.22%, respectively.

Further tests evaluated thermal comfort according to Equation (2) of the UNI 16798 standard, represented by the green area in the graphs. To effectively maintain the internal operative temperature within the comfort zone in Zone N, it is recommended to use ventilation settings Combo 07, Combo 08, and Combo 09 (Figure 13a). Under these conditions, the percentages of teaching hours within the comfort zone are 93.99%, 100%, and 100%, respectively. In Zone S, to manage an internal operative temperature suitable for thermal comfort, it is recommended to use ventilation settings Combo 07, Combo 08, Combo 09, and Combo 10 (Figure 13b). In this case, the percentages of teaching hours within the comfort zone are 87.41%, 100%, 99.26%, and 99.26%, respectively.

In December (Figure 14a,b), both the thermal comfort within the range of 21–23 °C, recommended for winter months, and the application of Equation (2) according to the UNI16798 standard are considered. In general, an increase in the number of air changes per hour allows for the maintenance of an adequate internal operative temperature for thermal comfort.

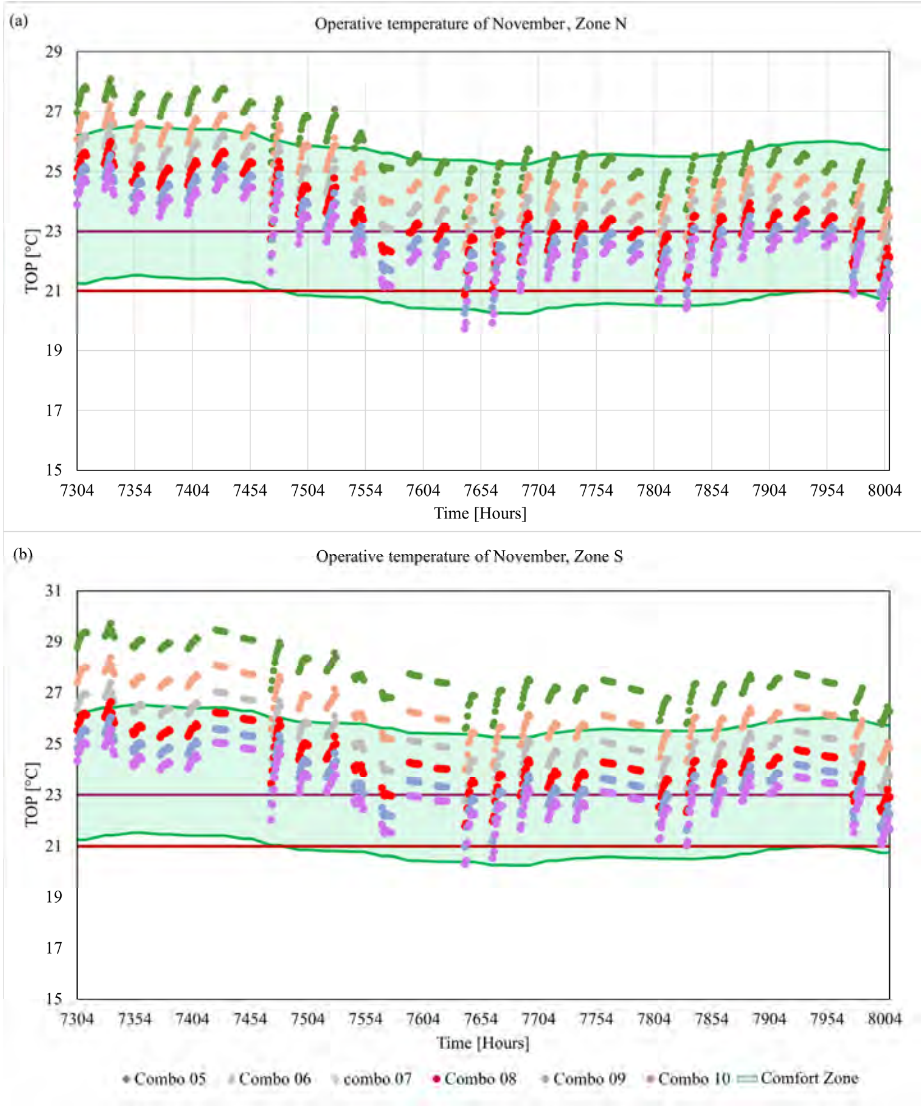


Figure 13. Operative temperature in November for: (**a**) North zone and (**b**) South zone.

Examining the results presented in Figure 14a,b (for Zone N and Zone S, respectively), it is evident that managing the internal operative temperature within the comfort zone is achievable, primarily by using the ventilation settings Combo 04, 05, and 06.

The percentages of school hours during which the internal operative temperature falls within the comfort zone, with a range of 21–23 °C, are 28.28%, 37.87%, and 40.40% for Combo 04, 05, and 06 in Zone N, respectively. In Zone S, the percentages of school hours within the comfort zone for the same combinations are 25.25%, 37.88%, and 40.40%, respectively. Meanwhile, the percentages of teaching hours during which the internal operative temperature is within the comfort zone, as evaluated by Equation (2), are 100%, 99.49%, and 80.30% for Zone N, while for Zone S, they are 90.91%, 100%, and 93.94%, respectively.

It should be noted that the behavior of the internal operative temperature was monitored until 21 December, the last school day before the Christmas holidays.

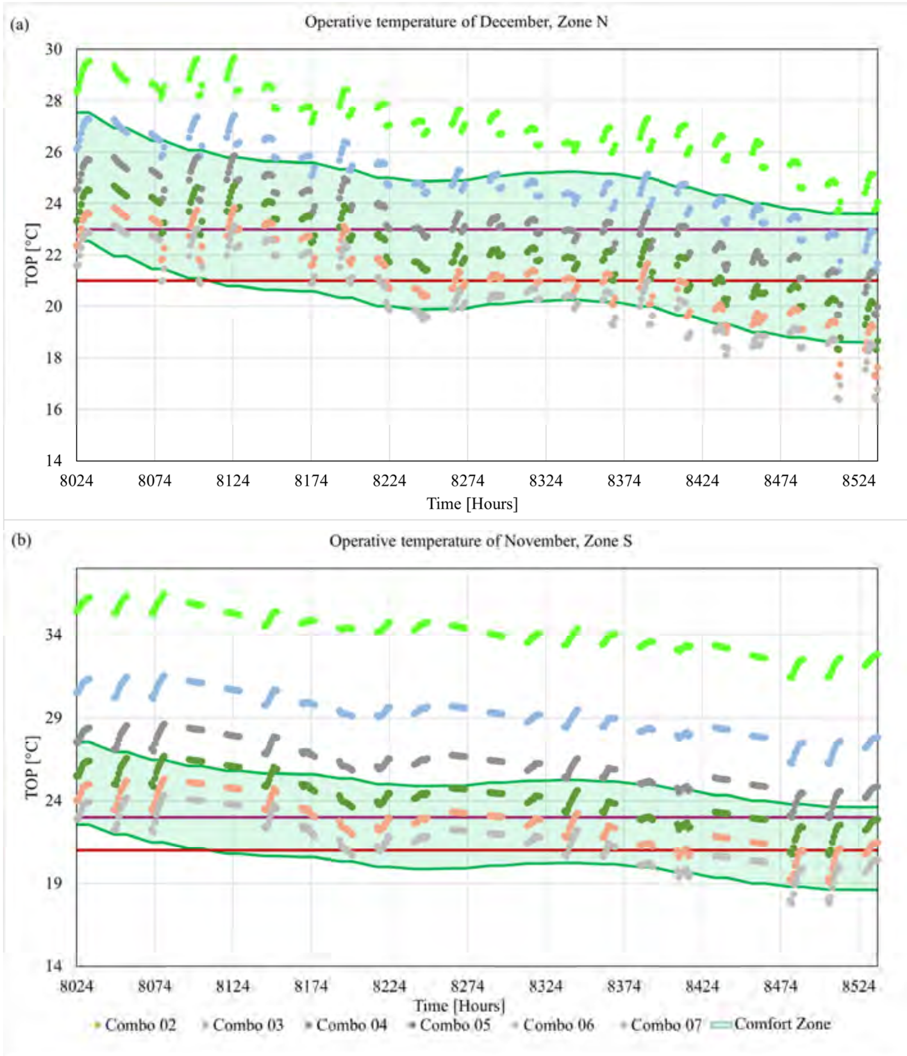


Figure 14. Operative temperature in December for: (**a**) North zone and (**b**) South zone.

Table 4 shows the energy consumption expressed in kWh during the operating hours of the system.

Table 4. Energy consumption.

Combo	Capacity (m^3/h)	Max. Power Consumption (W)	Max. Power Consumption (kW)	Hours of Operation [h]	Daily Energy Consumption [kWh]
1	108	134.26	0.13	8	1.07
2	216	135.90	0.14	8	1.09
3	324	142.23	0.14	8	1.14
4	432	150.00	0.15	8	1.20
5	540	196.95	0.20	8	1.58
6	648	331.21	0.33	8	2.65
7	756	332.85	0.33	8	2.66
8	864	339.18	0.34	8	2.71
9	972	346.95	0.35	8	2.78
10	1080	393.90	0.39	8	3.15

4. Conclusions

This study highlights the importance of an efficient ventilation system for improving the environmental sustainability of school buildings in a Mediterranean climate. In a thermally insulated building, by utilizing the thermal load produced by the occupants and an adequate ventilation system, it is possible to maintain good thermal comfort and indoor air quality without relying on traditional heating systems, thus reducing costs.

The analysis was conducted on a primary school model in Lecce, characterized by a Mediterranean climate. Ten ventilation scenarios (Combo) were evaluated to ensure an adequate indoor temperature for thermal comfort without heating or cooling, through hourly dynamic numerical simulations. The results refer to the North and South classrooms, with average performance.

From January to March, the operative temperature can be maintained between 21 °C and 23 °C with dynamic air exchange management. As external temperatures increase, a higher rate of air exchange is required, while during the warmer months, such as June and September, the installation of cooling systems is suggested.

In October and November, the increased air exchange rates improve thermal comfort. In November, the absence of heating requirements highlights the impact of climate change. Ventilation combinations Combo 07, Combo 08, Combo 09, and Combo 10 ensure optimal thermal comfort for 94.8–100% of lesson hours. In December, combinations Combo 04 and Combo 05 are the most effective in maintaining the temperature.

The results showed that a traditional heating system would need to operate for 1071 h annually, but with an adequate ventilation system, it could be entirely eliminated. During periods of extremely high external temperatures, schedule adjustments or the use of passive solutions are recommended to ensure a comfortable learning environment, emphasizing the importance of flexible and adaptive ventilation strategies.

Author Contributions: Conceptualization, P.M.C., A.P. and C.B.; Methodology, P.M.C., A.P. and C.B.; Software, P.M.C., A.P. and C.B.; Validation, P.M.C., A.P. and C.B.; Formal analysis, P.M.C., A.P. and C.B.; Investigation, P.M.C., A.P. and C.B.; Resources, P.M.C. and C.B.; Data curation, P.M.C., A.P. and C.B.; Writing—original draft, P.M.C., A.P. and C.B.; Writing—review & editing, P.M.C., A.P. and C.B.; Visualization, P.M.C. and C.B.; Supervision, P.M.C. and C.B.; Project administration, P.M.C. and C.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Díaz-López, C.; Serrano-Jiménez, A.; Verichev, K.; Barrios-Padura, Á. Passive cooling strategies to optimise sustainability and environmental ergonomics in Mediterranean schools based on a critical review. *Build. Environ.* **2022**, *221*, 109297. [CrossRef]
2. Krawczyk, D.A. Theoretical and real effect of the school's thermal modernization—A case study. *Energy Build.* **2014**, *81*, 30–37. [CrossRef]
3. Romano, R.; Donato, A.; Gallo, P. Retrofit Strategies Optimization Based on Indoor Comfort Analysis Under Real Conditions: The Case Study of the Secondary School ITC Carrara. *Smart Innov. Syst. Technol.* **2022**, *263*, 231–241.
4. Díaz-López, C.; Serrano-Jiménez, A.; Lizana, J.; López-García, E.; Molina-Huelva, M.; Barrios-Padura, Á. Passive action strategies in schools: A scientific mapping towards eco-efficiency in educational buildings. *J. Build. Eng.* **2022**, *45*, 103598. [CrossRef]
5. Serrano-Jiménez, A.; Femenías, P.; Thuvander, L.; Barrios-Padura, Á. A multi-criteria decision support method towards selecting feasible and sustainable housing renovation strategies. *J. Clean. Prod.* **2021**, *278*, 123588. [CrossRef]
6. Congedo, P.M.; Palmieri, A.; Baglivo, C. Climate resilience strategies for schools in mediterranean areas: Is it feasible to condition air merely with ventilation? *Energy Effic.* **2025**, *18*, 24. [CrossRef]

7. Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42539–42559. [CrossRef]
8. Maiques, M.; Tarragona, J.; Gangolells, M.; Casals, M. Energy implications of meeting indoor air quality and thermal comfort standards in Mediterranean schools using natural and mechanical ventilation strategies. *Energy Build.* **2025**, *328*, 115076. [CrossRef]
9. Landrigan, P.J.; A Kimmel, C.; Correa, A.; Eskenazi, B. Children's health and the environment: Public health issues and challenges for risk assessment. *Environ. Health Perspect.* **2004**, *112*, 257–265. [CrossRef]
10. Haverinen-Shaughnessy, U.; Shaughnessy, R.J.; Cole, E.C.; Toyinbo, O.; Moschandreas, D.J. An assessment of indoor environmental quality in schools and its association with health and performance. *Build. Environ.* **2015**, *93*, 35–40. [CrossRef]
11. Jendrossek, S.N.; Jurk, L.A.; Remmers, K.; Cetin, Y.E.; Sunder, W.; Kriegel, M.; Gastmeier, P. The Influence of Ventilation Measures on the Airborne Risk of Infection in Schools: A Scoping Review. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3746. [CrossRef] [PubMed]
12. Jia, L.-R.; Han, J.; Chen, X.; Li, Q.-Y.; Lee, C.-C.; Fung, Y.-H. Interaction between Thermal Comfort, Indoor Air Quality and Ventilation Energy Consumption of Educational Buildings: A Comprehensive Review. *Buildings* **2021**, *11*, 591. [CrossRef]
13. Cabovská, B.; Bekö, G.; Teli, D.; Ekberg, L.; Dalenbäck, J.-O.; Wargocki, P.; Psomas, T.; Langer, S. Ventilation strategies and indoor air quality in Swedish primary school classrooms. *Build. Environ.* **2022**, *226*, 109744. [CrossRef]
14. Srivastava, S.; Zhao, X.; Manay, A.; Chen, Q. Effective ventilation and air disinfection system for reducing coronavirus disease 2019 (COVID-19) infection risk in office buildings. *Sustain. Cities Soc.* **2021**, *75*, 103408. [CrossRef]
15. Pan, C.-Y.; Weng, K.-T.; Hsu, H.-C. Air change per hour improvement for positive and negative pressure mechanical ventilation facilities systems. *J. Build. Eng.* **2024**, *83*, 108414. [CrossRef]
16. Nasrollahi, N.; Ghobadi, P. Field measurement and numerical investigation of natural cross-ventilation in high-rise buildings; Thermal comfort analysis. *Appl. Therm. Eng.* **2022**, *211*, 118500. [CrossRef]
17. Chen, Y.-H.; Tu, Y.-P.; Sung, S.-Y.; Weng, W.-C.; Huang, H.-L.; Tsai, Y.I. A comprehensive analysis of the intervention of a fresh air ventilation system on indoor air quality in classrooms. *Atmos. Pollut. Res.* **2022**, *13*, 101373. [CrossRef]
18. Li, H.; Liu, M.; Kong, X.; Wang, L.; Li, J.; Fan, M. Experimental research on energy utilization, aerosol transmission and thermal comfort under different ventilation strategies: Densely-occupied classrooms as a case study. *Build. Environ.* **2025**, *270*, 112523. [CrossRef]
19. Schulze, T.; Eicker, U. Controlled natural ventilation for energy efficient buildings. *Energy Build.* **2013**, *56*, 221–232. [CrossRef]
20. Wargocki, P.; Porras-Salazar, J.A.; Contreras-Espinoza, S.; Bahnfleth, W. The relationships between classroom air quality and children's performance in school. *Build. Environ.* **2020**, *173*, 106749. [CrossRef]
21. Baglivo, C.; Bonomolo, M.; Congedo, P.M.; Beccali, M.; Antonaci, S. Technical-Economic Evaluation of the Effectiveness of Measures Applied to the Artificial Lighting System of a School. *Appl. Sci.* **2021**, *11*, 6664. [CrossRef]
22. Congedo, P.M.; Baglivo, C.; Seyhan, A.K.; Marchetti, R. Worldwide dynamic predictive analysis of building performance under long-term climate change conditions. *J. Build. Eng.* **2021**, *42*, 103057. [CrossRef]
23. Firman, N.S.; Zaki, S.A.; Tuck, N.W.; Singh, M.K.; Rijal, H.B. A study on adaptive thermal comfort and ventilation in Malaysia secondary school classrooms of tropical climate. *Build. Environ.* **2025**, *273*, 112701. [CrossRef]
24. Karakas, F.; Grassie, D.; Schwartz, Y.; Dong, J.; Bagkeris, E.; Mumovic, D.; Milner, J.; Chalabi, Z.; Mavrogianni, A. A Multi-Criteria decision analysis framework to determine the optimal combination of energy efficiency and indoor air quality schemes for English school classrooms. *Energy Build.* **2023**, *295*, 113293. [CrossRef]
25. Baglivo, C. Dynamic Evaluation of the Effects of Climate Change on the Energy Renovation of a School in a Mediterranean Climate. *Sustainability* **2021**, *13*, 6375. [CrossRef]
26. Ashrafian, T. Enhancing school buildings energy efficiency under climate change: A comprehensive analysis of energy, cost, and comfort factors. *J. Build. Eng.* **2023**, *80*, 107969. [CrossRef]
27. Buyak, N.; Deshko, V.; Bilous, I.; Pavlenko, A.; Sapunov, A.; Biriukov, D. Dynamic interdependence of comfortable thermal conditions and energy efficiency increase in a nursery school building for heating and cooling period. *Energy* **2023**, *283*, 129076. [CrossRef]
28. *UNI EN ISO 52016-1:2018*; Prestazione Energetica Degli Edifici—Fabbisogni Energetici per Riscaldamento e Raffrescamento, Temperature Interne e Carichi Termici Sensibili e Latenti—Parte 1: Procedure di Calcolo. Ente Nazionale Italiano di Unificazione (UNI): Milan, Italy, 2018.
29. Arnfield, A.J. Classificazione Climatica di Köppen. *Enciclopedia Britannica*, 16 October 2023. Available online: https://www.britannica.com/science/Koppen-climate-classification (accessed on 19 December 2023).
30. *DPR 412/1993*; Italian Presidential Decree, Regolamento Recante Norme per la Progettazione, L'installazione, L'esercizio e la Manutenzione degli Impianti Termici degli Edifici ai fini del Contenimento dei Consumi di Energia, in Attuazione Dell'art. 4, Comma 4, della Legge 9 Gennaio. Gazzetta Ufficiale della Repubblica Italiana: Rome, Italy, 1993.

31. *M.D. 18/12/1975*; Italian Ministerial Decree, Norme Tecniche Aggiornate Relative All'edilizia Scolastica, ivi Compresi gli Indici di Funzionalità Didattica, Edilizia ed Urbanistica, da Osservarsi Nella Esecuzione di Opere di Edilizia Scolastica. Gazzetta Ufficiale della Repubblica Italiana: Rome, Italy, 1975.
32. *M.D. 26/6/2015*; Italian Ministerial Decree, Applicazione delle Metodologie di Calcolo delle Prestazioni Energetiche e Definizione delle Prescrizioni e dei Requisiti Minimi degli Edifici. Gazzetta Ufficiale della Repubblica Italiana: Rome, Italy, 2015. (In Italian)
33. Congedo, P.M.; Baglivo, C.; Centonze, G. Walls comparative evaluation for the thermal performance improvement of low-rise residential buildings in warm Mediterranean climate. *J. Build. Eng.* **2020**, *28*, 101059. [CrossRef]
34. *UNI 10375:2011*; Metodo di Calcolo della Temperatura Interna estiva degli Ambienti. Ente Nazionale Italiano di Unificazione (UNI): Milan, Italy, 2011.
35. *UNI EN 16798-1:2019*; Prestazione Energetica degli Edifici—Ventilazione per gli Edifici—Parte 1: Parametri di Ingresso Dell'ambiente Interno per la Progettazione e la Valutazione della Prestazione Energetica degli Edifici in Relazione alla Qualità Dell'aria Interna, All'ambiente Termico, All'illuminazione e All'acustica—Modulo M1-6. Ente Nazionale Italiano di Unificazione (UNI): Milan, Italy, 2019.