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Testing A Methodology to Assess Fluctuations of Coastal Rocks Surface Temperature

Marta Pappalardo * and Martina D'Olivo

Department of Earth Sciences, Pisa University, Via S. Maria 53, 56126 Pisa, Italy
* Correspondence: marta.pappalardo@unipi.it

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Abstract: The aim of this work is testing a cheap and user-friendly methodology suitable for studying temperature fluctuations of coastal rocks' surfaces. An infrared thermometer was used, that permits a contactless measurement of the average surface temperature of a patch around a measuring point. Temperature was measured in an array of selected plots every 45 min from dawn to sunset in a 20 m^2 study area along the rocky coast of Calafuria (NW Italy). During the experiment daily temperature in all plots was minimum at dawn and quickly reached its peak value shortly after sun culmination; subsequently, it underwent a small-gradient decrease until sunset. In connection with temporary sun-shading and wind gusts relevant short-term rock surface temperature fluctuations were recorded. Considering mean daily temperature in each plot, it proved to be positively correlated with distance from the shoreline. As regards daily temperature range, its amplitude progressively increased moving farther from the shoreline. The measuring points located where the rock is extensively covered by barnacles experience a temperature magnification effect, possibly due to a micro-greenhouse effect triggered by the production of carbon dioxide by this biota. The entity of measured daily temperature fluctuations is ca. one order of magnitude greater than air temperature fluctuations measured at the same elevation in the closest meteorological station. The results of this work highlight that the infrared thermometer is an effective tool to measure rock surface temperature along rocky coasts, capable of detecting temperature fluctuations more effectively than traditionally employed data loggers. Moreover, this work emphasizes the relevance of temporary sun-shading and wind gusts in triggering short-term rock surface temperature fluctuations, potentially capable of enhancing thermal fatigue and foster surface rock breakdown.

Keywords: infrared thermometer; thermoclastism; rocky coasts; NW Italy

1. Introduction

Temperature fluctuations in rocks' surface trigger thermoclastism [1]. This is a type of rock weathering fostered by mechanical stress due to changes in volume of minerals or mineral grains in response to repeated heating and cooling. In inhomogeneous rock textures, different mineral types respond differently in terms of volume changes to the same thermal stress. Moreover, having rocks bad thermal conductivity, the surface of rocks responds quickly to sun heating, whereas the interior substantially maintains its temperature during short-term temperature fluctuations. Further mechanical stress, thus, affects the surface layer relative to the inner part of the rock. Eventually stress leads to the formation of cracks and finally to rock shattering [2].

Thermoclastism is traditionally considered an effective weathering agent especially in desert environments [3], in cold regions, where the role of thermal fatigue is recognized in association with frost shattering [4–6], and even in extraterrestrial contexts [7], but its relevance under different morphoclimatic conditions, and particularly in coastal environments, is poorly considered [8]. The indirect effectiveness of temperature changes is recognized for example in some genetic theories of honeycombs and tafoni. According to [9] temperature ranges inside tafoni is lower than outside them, and this promotes chemical weathering inside basins. The role of temperature as a rock shaping agent along the coast deserves, instead, to be investigated, in order to quantitatively demonstrate if its effectiveness is negligible compared to that of other weathering factors [10]. Moreover, it would be relevant to test if mechanical stress promoted by a great number of cycles of heating and cooling is more effective then that triggered by less frequent thermal excursions of greater amplitude. Understanding how different rock-types respond to thermal heating is important in order to improve our knowledge of landforms-shaping processes but may also be helpful for applications in the fields of materials science and of cultural heritage management.

Geomorphological research in the field of thermoclastism widely relies on laboratory experiments [11]. Underrepresented are those experimental designs planned directly in the field, with few notable exceptions [12–14]. The instruments that are commonly employed are temperature sensors, frequently coupled with data loggers for recording temperature over time at defined intervals; sensors can be built in or external to the data logger. There are a number of devices, (e.g., iButton®s, HOBO®s, etc., in which the sensor is sheltered by a plastic or metal casing. In the second case the sensor can be a thermocouple or a thermistor, provided with a probe with a termination of different possible size and shape that is put in direct contact with the surface to be measured. In both cases the thermometer is directly in contact with the surface or with the air cushion immediately above it.

The aim of this work is to find out and test a cheap and user-friendly methodology potentially suitable for studying temperature fluctuations of coastal rocks surface. The methodology needs to account for the specific conditions of the environment to test and particularly to yield data with great spatial resolution. Using thermal infrared satellite images was excluded because it does not provide sufficient spatial resolution [15] whereas handheld thermal cameras are exceeding our target budget.

For all the above mentioned reasons an infrared thermometer was employed, provided with a sensor capable of measuring the amount of infrared radiation emitted by the surface and to convert it into a temperature value. The radiation captured comprises also a minor proportion of reflected infrared radiation whose source is the sun (albedo). This instrument seems particularly useful because it permits a contactless measurement of the average surface temperature of a patch around a measuring point. The measure will be equally influenced, thus, by the temperature of each of the mineral grains within the patch. This type of measurement is likely to minimize disturbing factors affecting traditional temperature measuring tools, such as the thermal properties of the materials forming the sensor itself and disturbance due to the air cushion interposed between the object to be measured and the thermometer. Temperature measurements were repeated in order to get a daily record of measurements and to test how short-term fluctuations of boundary conditions, such as cloud cover or wind gusts, may affect the measurement. The test was performed directly in the field, in order to maximize the effect of multiple variables that are effective in the natural environment.

2. Study Area

The experiment was performed along the rocky coast of Calafuria Locality, a coastal sector facing the Northern Tyrrhenian Sea in NW Italy, lying in the flanks of the Apennine Chain (Figure 1).

The bedrock is shaped in a siliciclastic turbidite, representing the top formation of the "Tuscan Nappe" of the Apennine Chain [16]. Locally this formation is represented by a sandstone, characterized by rounded grains forming alternating coarse and very coarse layers, with occasional finer (shale) or coarser (conglomerate) beds. The most represented mineral grains are quartz, potassic feldspar and plagioclase; micas and iron oxides are the most abundant accessory minerals. The carbonatic cement does not exceed 10% of the total minerals amount. The bedrock is affected by at least two fault systems. Incoming waves from 240° N prevail, being the coast exposed to SW; maximum coastal significant wave height is 4.5 and waves break mostly 4 m from the shore. Tide is of the semidiurnal type and the tidal range does not normally exceed 40 cm [17].

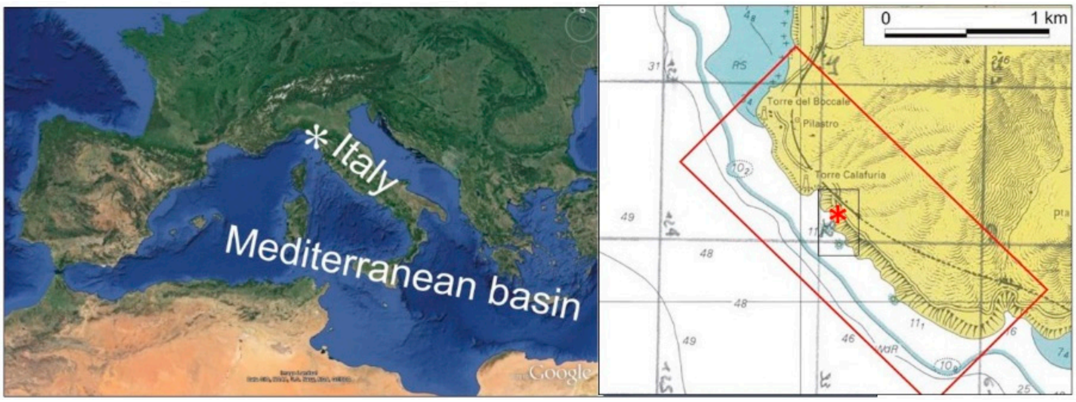


Figure 1. General sketch map and location of the study area (rectangle) and, within it, of the test site (star).

3. Materials and Methods

A gently degrading rock slope was selected as a test site within the study area (Figure 1). This landform is the product of ancient quarrying activities (800 BC–1600 AD), but it is currently affected by different types of weathering [16]. The experimental design (Figure 2) was set creating a network of measuring plots, each 10 × 10 cm wide. Plots were virtually connected through five lines (longshore) and four transects (cross-shore). Distance between plots along lines and transects was 2 m.

Figure 2. Sketch of the experimental design. Numbers 1–5 indicate "lines" (longshore) and letters a–d indicate "transects" (cross-shore). At the intersection between lines and transects the measuring plots are located.

The lowest line (baseline) was placed immediately below the upper edge of the continuous barnacle cover i.e., at the upper boundary of the lower supralittoral zone [18]. The baseline was 1.5 m from the shoreline along the cross-shore profile. The four transects had different average dips and were irregular. Plots along the same line, thus, were not at the same elevation above sea level and did not have exactly the same aspect. In transect a (Figure 2) the plot belonging to line 1 was 3 m higher than the plot in line 5, whereas in transect d the elevation range between plots at the opposite ends of the transect was 1 m. This choice was made in order to test the methodology against typical irregular topography conditions.

Temperature was measured in each plot every 45 min from dawn to sunset (7.30 AM–5.15 PM; 17 November 2018). The weather was sunny and moderately windy, with scattered clouds temporarily sheltering the sun. The instrument employed was an Infrared thermometer DT-8833 supplied by Française d'Instrumentation. The resolution was 0.1 °C and the accuracy 0.5 °C. Emissivity was set at 0.95 based on the approximate energy-emitting characteristics of the material (oxidized granular rock surface), as suggested by the operating manual. The thermometer was directed perpendicularly to the plot surface at a distance of 48 cm from it, so that the size of the tested spot was a circle 3 cm in diameter. A laser beam emitted by the instrument indicates the center of the spot, and this was pointed in the middle of the plot. The measurement was repeated three times consecutively in each spot and the three values were averaged. Data were manually recorded and stored in a Microsoft Excel spreadsheet. Instrument error was calculated combining instrument accuracy (0.5 °C) with the value of 0.6 °C, obtained repeating the measurement three times consecutively in each spot and calculating the maximum variability between values. In data processing instrumental error was considered to be within the standard deviation of averaged values and thus included in it.

4. Results

4.1. Temperature Change during the Day

In Figure 3a,b measured temperatures are plotted against time. Grey bands indicate the timing of the temporary presence of sun-shading clouds.

In Figure 3a each point represents data averaged between transects and then between lines, providing an estimate of the overall rock surface temperature changes through time in the test site. Overall temperature (Figure 3a) gradually increases from dawn, peaking 1.5 h after sun culmination, occurring at 12.04 AM, and then moderately decreases until sunset. Temperature at sunset is 6.5 °C higher than at dawn. The total temperature range is 7.8 °C. During the morning temperature increases with a gradient of 1.3 °C/hour, whereas in the afternoon temperature decreases more slowly (0.3 °C/hour). When the test site is shaded from sunlight, the rock surface experiences a temporary cooling, up to 2 °C, but temperature rises again at previous values when sunshine conditions are restored. At 9 AM the overall temperature experiences a moderate temporary decrease of 0.7 °C, that is the effect of shading of the lowermost plots due to the angle of incidence of incoming rays. Air temperature recorded in the closest meteorological station from which data are available (Bocca d'Arno, 1 m asl) ranges from 16.5 to 14.4 (timing unavailable). Water temperature recorded during the experiment at the nearby mareographic station of Livorno was 18 °C.

In Figure 3b each point in the graph represents averaged data from all plots connected by the same line, i.e., equally distant from the baseline. As the topographic profiles along transects display minor irregularity and overall different elevation range (Figure 2), data in Figure 3b mediate the topographic factor between transects. Distance from the shoreline is maximum in line 1 (8 m) and line 5 corresponds to the baseline, located 1.5 m from the shoreline. A similarity of the trend between the different lines is evident, although temperatures display minor fluctuations that are generally not in phase. The delay of occurrence of temperature maximum for each line relative to sun culmination is for all lines between 41 and 86 min. Some lines (n° 1 and 4) experience a temperature increase featuring a second maximum around 3 PM. During the experiment, though, sun shading occurred between 1.30 PM and 3 PM, thus the subsequent increase of temperature may represent a bias. In most cases, at each measuring time, temperature increases moving farther from the baseline. Distance from the sea seems thus to be a major factor differentiating the records. An exception is represented by line 4, which is located immediately above the upper limit of continuous barnacle cover: In 65% of cases it displays a lower temperature than the one recorded in the plots connected by the baseline (line 5).

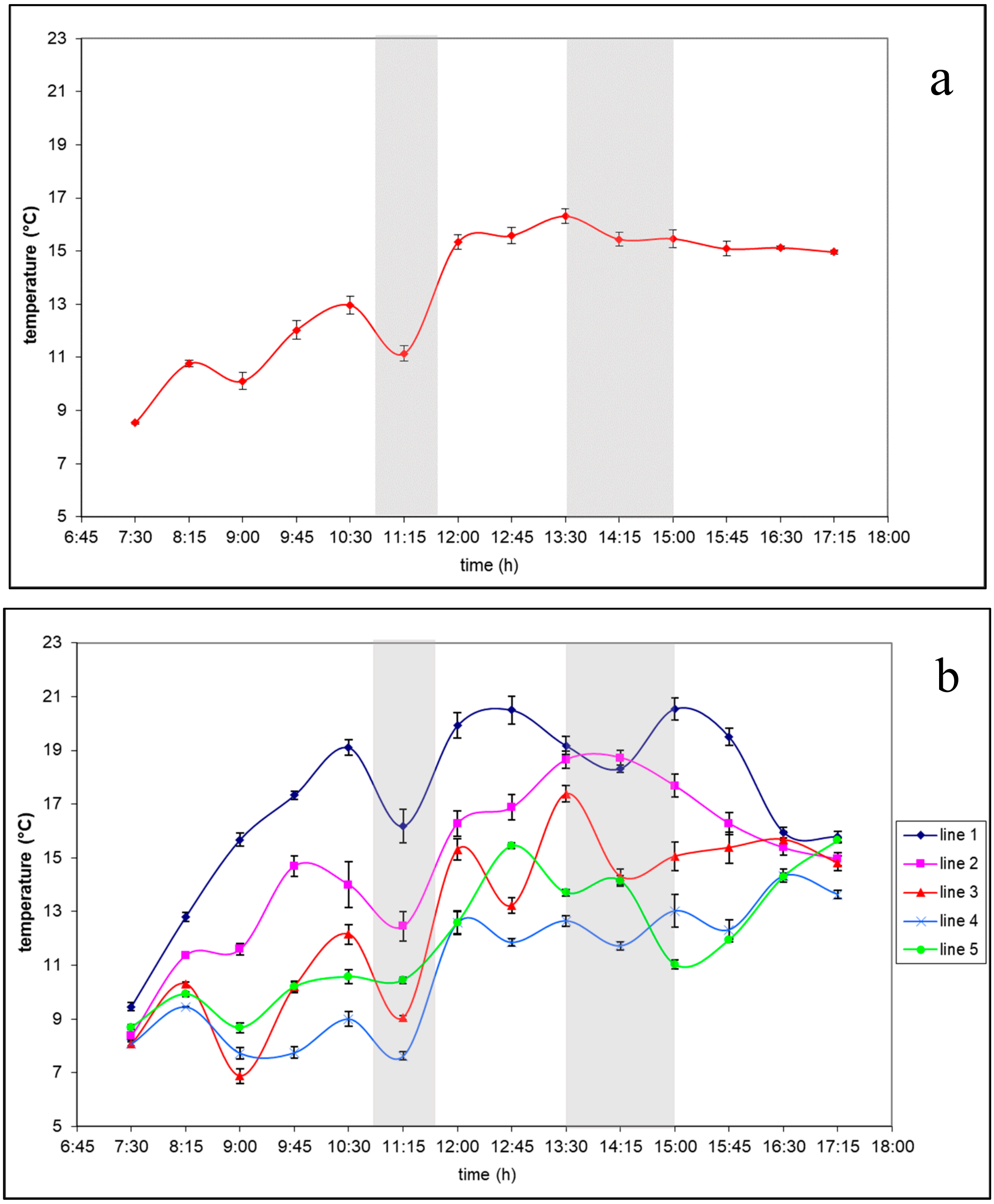
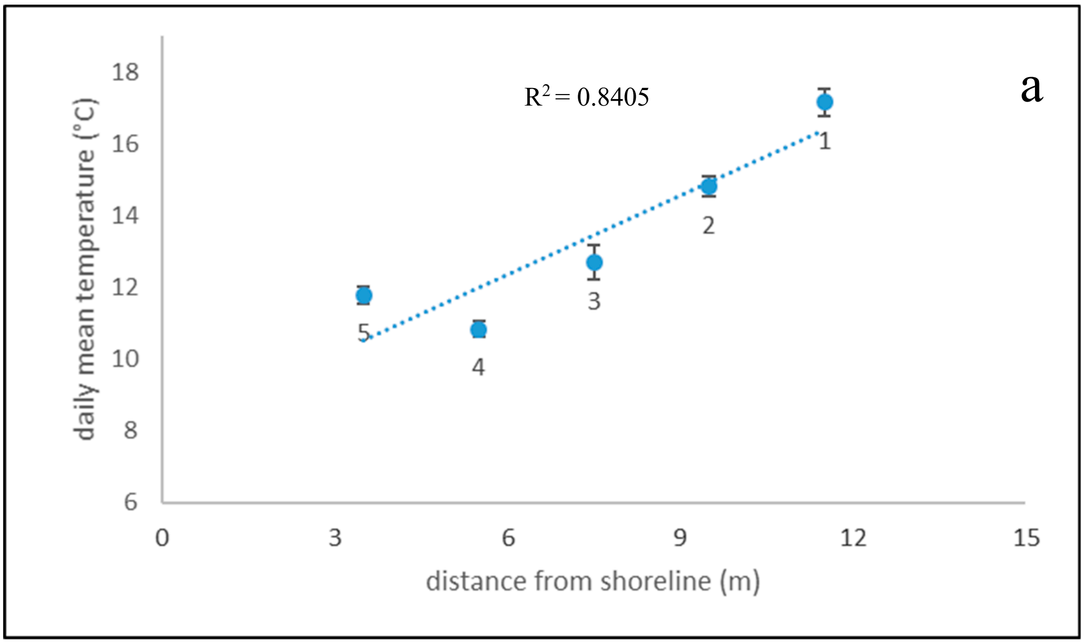


Figure 3. Temperatures recorded during the daily experiment are plotted against time. (**a**) Overall temperatures: Data were averaged between transects and then between lines; (**b**) data presented separately for each line; lines are progressively farther from the shoreline starting from line 5 which is the baseline. Grey bands indicate the timing of the temporary presence of sun-shading clouds. Error bars represent the standard error.

4.2. Temperature vs. Distance from Shoreline

In order to examine in more detail the effect of the distance from shoreline on rock surface temperature, the mean of the temperatures recorded along each line during all the experiment time was plotted against the distance from the shoreline of the line itself (Figure 4a). Data were averaged for all transects.



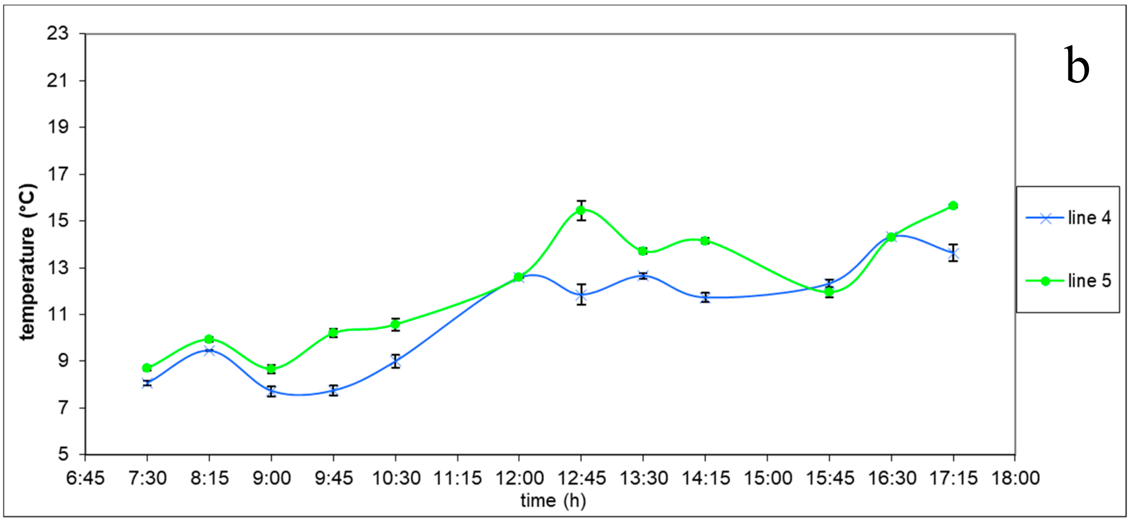


Figure 4. Temperatures related to the distance from shoreline. (**a**) Mean daily data averaged from all plots along one line are plotted against the distance of the corresponding line from the shoreline; (**b**) data recorded during the measuring time span reported separately for lines 4 and 5. Error bars represent the standard error.

Distance from shoreline correlates positively with temperature (Figure 4a), and all points, each corresponding to data averaged from all plots along one line, fit quite closely the regression. Contrarily, line 4 displays a lower temperature than lowermost line 5. In order to better investigate this anomaly in temperature vs. distance correlation in Figure 4b changes of temperature during all the measuring time span are reported separately for lines 4 and 5, and the data recorded during the sun-shading phases have been removed.

4.3. Temperature Range

Temperature range recorded in all plots is represented in Figure 5a. The maximum temperature range was recorded in those plots that displayed the most elevated temperatures (1a,b). The minimum temperature range was experienced by plots 4a and 5b,c, located in the lowest and most shaded part of the test site.

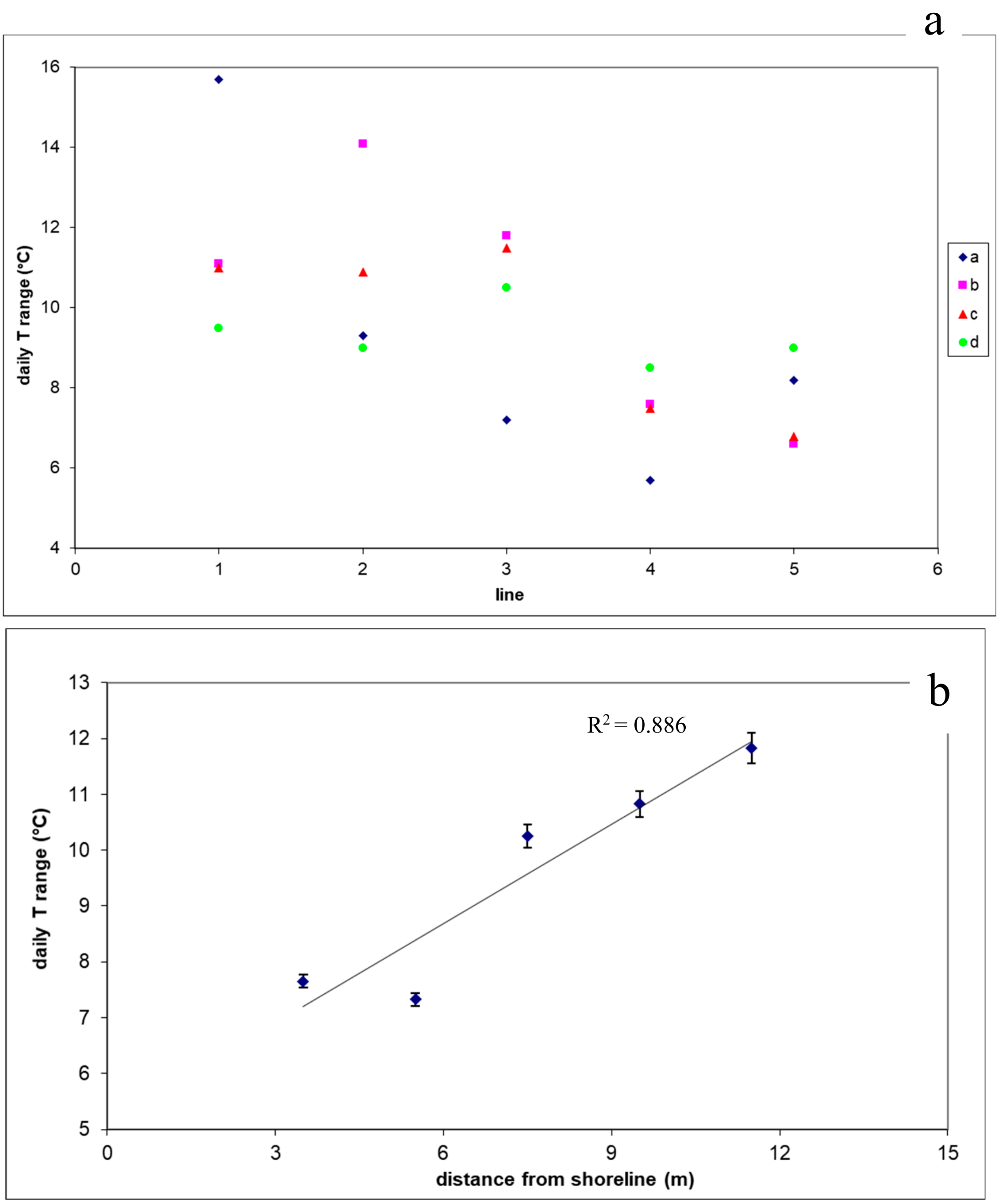


Figure 5. (**a**) Daily temperature ranges recorded in all plots. a–d represent the transects codes; (**b**) daily temperature ranges recorded along each line plotted against distance from the shoreline. Error bars represent the standard deviation.

In Figure 5b the daily temperature range recorded along each line is plotted against distance from the shoreline. Temperature range is positively correlated with distance from shoreline, except for line 4, and all points fit quite closely the regression.

5. Discussion

The infrared thermometer proved to be a cheap and user-friendly tool capable of effectively detecting temperature fluctuations along rocky coasts. As expected [19], the temperature of the rock surface increases gradually during the morning up to ca. 1 h after the sun culmination. Then it decreases during the afternoon with a negative gradient which is 23% of the positive one recorded during the morning. The latter is on average 1.3 °C/hour, which is much lower than 2 °C/min, i.e., the value suggested by [20] as a limit for promotion of irreversible failure. Record provides a qualitative estimate of how much of the radiation absorbed during the morning is released before sunset, and how much it is gradually released during the night. The main factors in influencing the rock heat fluxes, and then its surface temperatures, are suggested to be its specific properties such as thermal capacity and conductivity [21]. The amount of radiation reflected by the rock surface contributes together with radiation outgoing from the rock to the temperature measured by the infrared thermometer. Short-term fluctuations like those highlighted in connection with temporary sun shading or wind gusts are more likely to be produced by factors implying less inertia in system thermal response, such as albedo. In this preliminary experiment, though, albedo was not measured.

Thermal fluctuations are crucial in causing mechanical stress on rocks surfaces exposed to weathering agents [22,23]. During the experiment temperature range was one order of magnitude greater on rock surface than on air. This demonstrates that the infrared thermometer may detect more correctly the amplitude of daily temperature fluctuations. The effectiveness of short-term shading effects in triggering thermal fluctuations is also demonstrated. In fact, in the morning a temporary sun-shading lasting for ca. 20 min. Causes a temperature decrease of 2 °C in the framework of a general increasing trend. When sunshine conditions are restored, though, the rock temperature increases rapidly up to a value 2.3 °C higher than the one recorded before sun-shading. In the afternoon the effect of temporary sun-shading is more smoothed but similarly causes a temporary increase of the cooling rate. The frequency of temperature fluctuations seems to be a critical factor in fostering thermal fatigue, rather than temperature range amplitude, as demonstrated by [24]. Exposing in the laboratory rock cubes to fixed simulated insolation, they found that mineral stress was maximum a few minutes after/before switching on/off the lamp. Considering that during the day temporary sun-shading may occur frequently, thermoclastism in temperate climates may be a rock breakdown factor that deserves to be better investigated.

On the whole results obtained in this work are reasonable and mutually consistent. Therefor the infrared thermometer proved to be an effective tool to measure the temperature of coastal rocks surface, and compliment measures of air temperature in field experiments, like the one carried out at Hayley Point, Marengo, Victoria, Australia [14], that used an infrared thermometer to investigate the relationships between surface movement and microclimate.

Moreover, this work highlighted a temperature pattern along the test site that would deserve further investigation. In fact, elevated lines in our experimental design, display higher temperatures and a greater amplitude of temperature range than lower lines (Figures 3b and 5a). This evidence is interpreted as the effect of a better direct exposure to sunlight of the higher plots. The relevance of exposure in constraining rock surface temperature and thermal range amplitude is confirmed also by the fact that along transect a (Figure 2), where difference in height between edge points is greater than in transect d (3 m vs. 1 m), also temperature range between edge plots is greater. Direct exposure to sunlight is thus a major factor controlling instant temperature and temperature fluctuations on coastal rocks surface [25]. This factor is normally neglected in laboratory rock heating experiments, but needs to be considered in the field, where the direction of incoming sun radiation changes continuously on an hourly to seasonal basis. Its role in determining the susceptibility of rocks to thermal strain would require to be better investigated [19]. An alternative or possibly concurrent role could be played by sea spray. It would be interesting to measure if the amount of aerosol driven by sea spray decreases enough along a 10 m cross-shore transect to justify an effect of temperature mitigation due to more humid air closer to the sea.

Another notable result in the experiment carried out in this work that would deserve a specific experimental investigation work is the one shown in Figure 4b. The measuring points located where the rock is extensively covered by barnacles (Figure 6), experience a temperature magnification effect.

Figure 6. One plot of line 5, located within the part of the rock covered with barnacles.

Different hypotheses may be proposed to explain the thermal anomaly of line 5. Some papers suggest that barnacles [13] as well as seaweed canopies [26] reduce surface temperatures of rock and minimize their short-term fluctuations. This is contrary to experimental evidence of this work. Nevertheless, in the cited papers, temperature was tested using thermistor provided with contact probes that in one case were stuck inside the surface layer of the rock and in the other case using iButton® temperature loggers attached to the rock with epoxy. This may have provided temperature records that can be related in the first case to the sub-surface temperature and in the second case to temperature inside the canopy. Our temperature record, instead, is strictly related to the temperature of the rock surface. A hypothesis for the interpretation of our evidence, based on data provided by [17,27] may account for a "micro-greenhouse effect" triggered by the barnacle cover. These biota, in fact, produce carbon dioxide through respiration as well as the processes through which the build their shell.

6. Conclusions

The infrared thermometer proved to be an effective tool to measure temperature of rock surface along the rocky coast of Calafuria (NW Italy). Through a cheap and user-friendly methodology and a simple experimental design this work proved that, in a mid-Autumn day in a Mediterranean study area rock surface temperature daily trend could be determined for the test site. In particular:

- Overall temperature was minimum at dawn, reached its peak value shortly after sun culmination and then underwent a small-gradient decrease until sunset;
- In connection with temporary sun-shading and wind gusts relevant short-term rock surface temperature fluctuations occurred;
- The entity of measured daily temperature fluctuations is ca. one order of magnitude greater than air temperature fluctuations measured at the same elevation in the closest meteorological station;
- Mean daily temperature proved to be positively correlated with distance from the shoreline;
- The amplitude of daily temperature range progressively increased moving farther from the shoreline.

Plots located where the rock is extensively covered by barnacles experienced a temperature magnification effect; it was preliminarily hypothesized that this could be due to a micro-greenhouse effect triggered by the production of carbon dioxide by this biota.

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

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