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# Core of Sustainability Education: Bridging Theory and Practice in Teaching Climate Science to Future Mathematics and Physics Teachers

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**Abstract:** We present a thoughtfully curated collection of laboratory demonstrations, simulations, and straightforward experiments that explore the fundamental processes underlying greenhouse effect (GHE), climate, atmospheric physics, and Earth's energy balance. The objective is to connect theory and practice in climate science education and address common student misconceptions. The activities are structured to guide students in constructing simple models of Earth's radiative equilibrium. Experimental activities cover essential concepts such as the electromagnetic spectrum, radiation–matter interaction, thermal radiation, and energy balance. Physical experiments include visualizing the spectrum with a homemade spectroscope and an infrared (IR) thermal camera, studying absorption and selective transparency when light interacts with different materials, measuring the power emitted by a heated filament, and using simple models, such as black and white discs or a leaking bucket, to understand radiative equilibrium and steady states. This sequence was piloted in a physics education laboratory class with 85 university students enrolled in mathematics and physics courses for future teachers. To assess comprehension improvement, pre- and post-tests involving the production of drawings and explanations related to the GHE were administered to all students. These activities also aim to promote critical thinking and counter climate misinformation and denial. The results showed a significant improvement in understanding fundamental GHE concepts. Additionally, a small subset of students was interviewed to explore the psychological and social dimensions related to the climate crisis.

**Keywords:** climate education; greenhouse effect; global warming



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## 1. Introduction

Sustainability education has emerged as a crucial component of modern learning, aiming at equipping individuals with the knowledge and skills necessary to address pressing environmental challenges. The importance of sustainability education [1–3] lies in its potential to foster a generation of informed and proactive citizens who can drive the transition toward a more sustainable future. However, this endeavor is fraught with challenges, including the need for interdisciplinary approaches, the integration of sustainability into existing curricula [4,5], and the cultivation of a global perspective.

Central to sustainability education is the focus on global warming, a defining issue of our time that underscores the interconnectedness of ecological, social, and economic

systems. By emphasizing climate issues [6], sustainability education not only highlights the urgency of action but also inspires innovative solutions that are essential for the well-being of our planet and future generations [7].

Thus, within the broader framework of sustainability education, climate change education—focusing specifically on understanding the causes and addressing the impacts of the climate crisis—emerges as a key component in education for sustainable development [8]. This form of education encompasses all frameworks aimed at raising student awareness of the climate issue, promoting societal efforts toward mitigation and adaptation, and equipping students with the scientific knowledge, skills, values, and reflective attitudes needed to act as agents of change [9]. In CE, a central role is played by building critical thinking skills for a critical and conscious approach to information (including misinformation) [10] and by developing the ability to form conscious, critically reflected, and argumentatively sound opinions and judgments, e.g., on climate protection measures. By integrating climate-specific knowledge and skills, sustainability education empowers individuals to become informed and engaged citizens capable of contributing to a climate-resilient and sustainable future. It encompasses scientific literacy about the climate system, the impact of human activities, and the social, economic, ethical, and political dimensions of the issue, thus empowering learners to become agents of change.

Global warming and, more generally, climate change are topics of increasingly animated and widespread debate at various levels of competence and semantics [11]. This problem is obviously of universal interest and, as such, has no political or geographical boundaries: all of humanity is involved and should potentially participate in activities aimed at monitoring and containing the evolution of these changes of physical and chemical origins [12]. The discussion is everywhere—in families, on talk shows, internet sites, groups, blogs, in governments, laboratories, and schools of all kinds. It is appropriate and important that this happens: the first cure for the problem is through consciousness and social awareness of the enormous impact that the atmospheric dynamics of our (unique) planet will have and, to an ever-greater extent, is already having on our lives, our economy, trade, nutrition, health, and everything we know [7,13].

In addition to these considerations, which are, all in all, obvious, it is essential to draw attention to the necessity of conveying appropriate and reliable information in this field by strictly adhering to the communication languages and methodologies of the scientific method. Issues concerning global warming must clearly be associated with relevant chapters of scientific research relating to the sciences of the atmosphere. As such, they must be addressed using formal tools and both theoretical and experimental investigation techniques that follow precise operational protocols [14]. If it is true that initiation to laboratory practice takes place at the level of secondary schools, it is only at the level of university studies that the approach to scientific investigation finds its experimental foundation and fulfillment [15]. The exploration of issues related to the physics of the atmosphere is no exception from this point of view: it is based exclusively on the usage of laboratory instrumentation and the timely analysis of observed and measured data. It could be said that—in general but even more specifically in this field of research—a virtuous circle must be established between purpose and methodology. Speaking of an “ethical commitment” of the scientific mission, there are excellent reasons to study the physics of the atmosphere (with all the indispensable disciplinary connections ranging from thermodynamics to statistics, from electromagnetism to quantum physics) as seen above, and this can only be carried out with ideas and practice in continuous reciprocal reinforcement [16,17]. While Earth’s atmosphere is studied in the laboratory, one acquires, at the same time, a wealth of transversal procedural skills widely usable in countless contexts and case studies different from the starting one. For these reasons, we think that

this particular subject of study is well suited as a prototypical topic to be addressed in lab courses for undergraduates and teachers in training.

Motivated by the above considerations, in the last 15 years, we have been developing and using teaching–learning sequences (TLS) based on experiments designed for undergraduate students, which primarily focused on the physical principles underlying the GHE (whose human-induced increase in the last decades is, of course, the main reason for climate change). The final aim is to use it to reconstruct a basic (but operative) depiction of Earth’s climate [18,19], namely a simplification of the Manabe model (as presented in [20], which is within reach of students but at the same time allows good qualitative predictions of the equilibrium temperature dynamics of the Earth–Sun–atmosphere system and a comprehensive grasp of how rising levels of greenhouse gases impact the atmosphere). Additionally, the influence of feedback mechanisms can be considered. The aim of the present work is to describe in detail this TLS so that it can be reproduced elsewhere. The choice of the topic was driven not only by its underlying physics background but also by the realization that a poor understanding of it is still quite widespread. Research carried out over the years has indeed evidenced how a large number of people, including students at all levels of instruction, have several misconceptions about the workings of the GHE [21–24]. To name just one, the very analogy with an actual greenhouse, which most people have in mind as a consequence of the use of the historically established terminology, is plainly wrong (since the effect of the glass walls on the radiative equilibrium is less important than the fact that they keep the warm air inside the greenhouse). The necessity for a specialized TLS arises because the GHE is challenging to integrate into conventional physics and science curricula. This difficulty is due to its inherent cross-disciplinary nature, spanning multiple traditionally separate areas of physics, and its heavy reliance on concepts taken from other sciences (mainly chemistry and Earth science).

The aims of the sequence are three: besides making students confident in the physics grounds of the radiative equilibrium of the atmosphere and all the relevant physical phenomena that are involved, its heavily experimental character makes it particularly suitable to help them reach the typical goals of laboratory courses. The proposed experiments, in fact, involve relevant phenomena in the physics curriculum, including optics, thermal phenomena, and radiative transfer, in a blended way. Up to now, the sequence presented in this paper has been experimented with 85 undergraduate mathematics and physics students at the University of Trento. A significant additional objective concerns the countering of misinformation and psychological barriers to climate action, which have been integrated into the learning sequence in recent years through an explicit and reflective approach.

The main part of this article, devoted to the description of the physico-chemical grounds of the climate system, is divided into four distinct sections: in the first part (Section 2), we discuss both the theoretical framework that guided the design of the activities and the principles on which the design of the individual activities is based. Then, in Section 3, we present a brief overview of the history of climate models, leading to a brief description of the model we intend to reconstruct in the course of our teaching activity. After isolating the main features of the model and listing all the physical mechanisms and concepts involved, in the third part (Section 4), we will detail the various experimental activities we have developed to enhance students’ understanding of these mechanisms. Since a central role in the GHE is played by the different behaviors of Earth’s atmosphere with respect to visible light and infrared radiation, each physical effect is studied using both types of radiation. The presentation of each activity is accompanied by a discussion of the student’s initial difficulties and the improvements we noted in their understanding of each conceptual area. Finally, in Section 5, we detail the outcomes of the assessments

carried out on the students who engaged in the sequence, specifically concerning the whole phenomenon of GHE.

Although the primary objectives of this work are so internal to the disciplines (physics, chemistry, climate science), it is nevertheless impossible to discuss the greenhouse effect and global warming without addressing the other aspects that characterize the multidimensionality of the climate emergency as a socio-scientific issue [25,26]. For this reason, the countering of misinformation, distrust in science, and psychological barriers to climate action have been integrated into the teaching–learning sequence in recent years through an explicit and reflective approach, prompting students to reflect on the complexity of the problem and its psychological, social, and political implications. Alongside climate models, students were also presented with climate scenarios, perspectives related to energy production and consumption, the main arguments of denialism, and an explicit description of the psychological barriers analyzed in the literature [27]. A brief discussion regarding aspects related to countering misinformation, denialism, and psychological factors is included in the Discussion section, which also presents some considerations made by students at the end of the learning pathway, particularly in relation to the social, environmental, economic, and cultural aspects of these issues, which are specific to sustainability education. Readers who are not interested in the results most directly related to Physics Education Research may skip the discussion of these aspects and proceed directly to Section 6.

## 2. Theoretical Framework

### 2.1. *The Fundamental Principles Guiding the Design of a TLS*

The educational reconstruction of a multifaceted topic such as the GHE and the consequences of its increase for global warming [28] poses serious issues of integration of knowledge since the physical concepts required for a true understanding are multiple and diverse and pertain to different areas of physics [29]. The project of designing a stand-alone university module on this topic must also take into account that the background of participating students will also most likely be diverse, as it can be attractive and useful for students who could also be, tomorrow, teachers of several different subjects [18,19,29]. Lastly, a basic aim of the course is to show and discuss a step-by-step building that passes through several different levels of complexity: in fact, while it is certainly desirable for a student, in particular a physics student, to master a complex model of the greenhouse effect complete with most of its subtleties and higher-order corrections, it is also important that he/she can provide a simplified, but not misleading, account of the core processes which, as a first approximation, contribute to a coherent explanation, for the purposes of teaching and/or public argumentation.

The choice of a teaching–learning sequence of an experimental nature [30–32] is, given these premises, almost obliged in our view [18,19,29]. Indeed, developing concepts through hands-on experimental activities helps maintain the interest of all students, including those who might already possess a solid understanding of the subject. Engaging in lab activities that are new to them can further reinforce their knowledge [33,34]. Conversely, for students who are beginners in a particular area or phenomenon in physics, experiments provide a valuable context for establishing the foundational concepts progressively [35]. It is necessary to alternate and integrate synergistically qualitative and quantitative experiments with theoretical generalizations [36,37].

Preliminary to our design, we performed an in-depth analysis of the scientific content of the greenhouse effect, identifying and classifying into conceptual areas the elementary physical ideas that are necessary to construct the different explanatory models of the GHE at different levels of sophistication present in the literature. These elementary ideas often include topics that may have already been touched by students in their curricula

but possibly not at the required level of detail: for example, it is likely that all students participating in our module have been introduced to radiative energy exchanges, but it is also likely that they were not led to reflect in depth on the characteristics of the state of radiative equilibrium and its dependence on the emissivity of the physical objects involved. After this step, we proceeded through a long process made of several subsequent revisions to identify and test significant experiments that could be fruitful in introducing and consolidating the elementary ideas.

## *2.2. The Guiding Principles for the Design of the Experimental Activities*

As highlighted by Kranz et al. [38], in today's world shaped by the centrality of technology and the natural sciences, knowledge and skills related to experimentation have become crucial. This importance is further emphasized by the increasing public debates on scientific topics. However, despite the emphasis given to learning through experiments in science curricula worldwide, students continue to demonstrate difficulties in this area. These difficulties manifest in all stages of scientific inquiry, from the formulation of research questions to the analysis of data and the formulation of conclusions [39]. When designing a practical and laboratory-based educational path, it is appropriate to take into account the major difficulties encountered by students and to hypothesize techniques that will optimize the activity from the point of view of didactic effectiveness.

The experimental activities that we will present in the following chapters, in addition to being aimed at illustrating the elementary physical phenomena necessary for understanding the greenhouse effect, will be geared toward achieving some general learning goals concerning the Physics laboratory, as reported in ref. [15]. In particular, in our sequence, aimed at an introductory physics course, students going through the proposed experiments work mainly on knowledge construction and modeling, while also engaging, at some point, in data analysis and visualization.

In recent decades, the importance of models has been recognized in physics education, and it represents the focus of the Modelling Instruction theoretical framework, which is based on qualitative and quantitative model construction and testing ([40,41]). Modeling is also an important part of the Investigative Science Learning Environment (ISLE) framework [42]. An effective framework for describing experimental and lab activities is the Modelling Framework for Experimental Physics [43], where the cyclic interaction between models and measurement apparatus and the modeling of the measurement system is made explicit. Given the objectives of our educational intervention, our activities are aimed at helping students develop physical models that allow them to make predictions about phenomena and compare these predictions with experimental data. While instrument knowledge of the operation of the experimental apparatus is important, we will not bring attention to modeling the experimental measurement apparatus. From a more pedagogical perspective on how to organize lab activities to foster student learning, research in recent years clearly indicates that traditional confirmation-type labs with tightly structured experimental procedures, in which the result to be obtained is known in advance, are not effective [44]. The proposed activities can be classified as structured inquiry activities; however, the students have a certain autonomy in investigating the phenomena since the results of the experiment are not predetermined. When implementing the proposed activities, we favored the use of devices such as smartphone sensors [45] whenever possible, based on indications from previous research that this could improve interest, portability, and motivation. Simulation environments such as PhET [46,47] were also used. Some demonstration experiments were also proposed, limited to cases where it was deemed essential to illustrate certain phenomena, but there was not enough equipment to allow students to conduct the experiment in small groups independently.

### 3. Climate Models and Key Physics Concepts

The presented activity centers on creating two separate and uncomplicated models of Earth's climate. Each model fundamentally integrates the principle of radiative equilibrium. These models are designed to provide a clear and accessible understanding of how radiative equilibrium influences Earth's climate system, offering students a practical and theoretical framework to explore these essential concepts in climate science.

The initial model, which is simpler and only considers the Earth and the Sun as the main factors [48], predicts an equilibrium temperature of  $-18\text{ }^{\circ}\text{C}$ , which is significantly below the actual temperature. Despite the relatively low relative error of 10%, this temperature estimate is not compatible with the known existence of life on our planet. However, this model fails to accurately account for Earth's atmosphere, prompting the development of a second model. The second model, which incorporates Earth's atmosphere, provides a much better estimation of temperature. While there are numerous additional refinements that can be made to create more comprehensive and accurate models, such as accounting for local variations, altitude dependence, convective heat transfer, and positive and negative feedback, our focus in this section is on the simple Earth–atmosphere model, which allows students to gain an adequate, if general, understanding of the subject. Therefore, we will only present these two simple models in detail and focus our teaching intervention on facilitating the acquisition of the key concepts students need to learn to fully understand them.

#### 3.1. A Brief History of the Climate Models

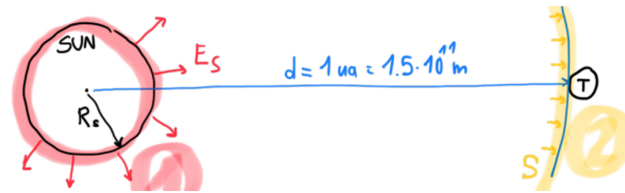
First, let us briefly sketch the history of climate modeling, focusing on the concepts and models which are most important to us (see, e.g., [49,50], and references therein). The first to describe the principle of radiative equilibrium and to recognize the warming effect of the atmosphere due to IR absorption (and to introduce the misleading analogy with actual greenhouses) was, in the 1820s, the French scientist Jean Baptiste Joseph Fourier—whose fame is justly bound to the study of heat flows [51]. Starting from 1859, the Irishman John Tyndall began to quantitatively study the absorption of IR radiation by different gases, identifying the most effective ones, such as carbon dioxide, water vapor, and methane [52], and crucially demonstrating that gases which can absorb IRs are also emitters. These results prompted scientists to investigate the effect of the increase in the concentration of greenhouse gases (GHGs) in the atmosphere. In particular, the Swedish chemist and Nobel prize winner Svante Arrhenius, in a paper published in 1896 focusing right on (natural, as opposed to human-induced) climate change, estimated how much the equilibrium temperature of Earth would change as a consequence of the variation of the concentration of carbon dioxide [53]. An important development took place in 1967, with the model developed by the 2021 Nobel prize winner Shukurō Manabe, which was the first to explore the relationship between radiation and the vertical transport of air masses due to convection while also incorporating the latent heat of water vapor [54].

Manabe's model confirmed the crucial role that carbon dioxide has in warming the planet. It has been the basis of the more refined modern climatological models, which are those currently used for the creation of future forecast scenarios.

#### 3.2. The 0-Dimensional Radiative Energy Budget Model

The initial model focuses exclusively on the energy balance of the two bodies, the Sun and Earth, considered as two ideal black bodies. In this case, the radiation emitted by the Sun reaches Earth, which is assumed to be at a fixed distance equal to the average annual Sun–Earth distance. For the conservation of energy, the power emitted by the Sun's surface must be equal to that which passes through a spherical surface of radius equal to the average Sun–Earth distance. This condition makes it possible to calculate the solar

constant, i.e., the average power of the Sun's emitted energy per unit area that reaches Earth (Figure 1).



**Figure 1.** The distribution of energy from the Sun to the Earth. This scheme can be used to calculate the solar constant.

Using this calculated value and knowing Earth's albedo, we can calculate Earth's average temperature for which radiative equilibrium is achieved, i.e., the temperature that ensures that the solar radiation absorbed by Earth (which is largely visible due to the Sun's high surface temperature) is equal to that emitted by Earth (which instead emits in the far IR, due to the much lower surface temperature). Therefore, assuming that Earth behaves like an ideal black body, we estimate the surface temperature of Earth by using the Stefan–Boltzmann law.

#### The Key Physics Concepts

The fundamental physical principles that underpin the model mentioned above and that students must grasp to comprehend it are as follows. For each stage of the TLS, we provide a summary of the relevant conceptual areas:

1. **Electromagnetic (EM) spectrum:** Knowing the range of the electromagnetic radiation spectrum beyond visible light and being able to sort different types of radiation by frequency and wavelength.
2. **Radiation–Matter interaction:** Examining how electromagnetic radiation interacts with matter, including phenomena like reflection, refraction, absorption, scattering, and selective absorption.
3. **Thermal radiation:** studying the emission of electromagnetic radiation from hot objects, such as the radiation from a filament bulb.
4. **Energy balance:** understanding the balance between the radiation incident on a body and the radiation emitted, and then applying the concept to the Earth system.
5. **Earth's energy balance and GHE:** exploring the role of greenhouse gases in trapping heat and influencing Earth's temperature.

Additionally, we specify the types of experiments to be conducted, whether they involve meticulous measurements and data analysis (quantitative), qualitative observations, or theoretical computations and modeling.

1. **Visualization of continuous and discrete spectra** using a low-cost diffraction grating and smartphone camera to guide students to an understanding of the different spectral bands and reflections regarding different radiation emission mechanisms.
2. **Radiation–Matter interaction experiments** (employing collimated beams and color filters): Both qualitative and quantitative experiments (Snell's law) investigate Radiation–Matter interaction phenomena like reflection, refraction, absorption, scattering, and selective absorption.
3. **The Stefan–Boltzmann law in thermal radiation:** a quantitative experiment measuring the temperature of a bulb to study thermal radiation.

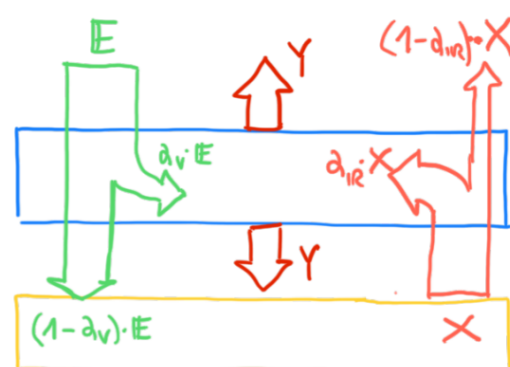
4. **Observation of the emission spectrum of a filament lamp** using the diffraction grating and activity on the “Blackbody Spectrum” [46]. This activity is useful both for visualizing Wien’s law and for investigating blackbody radiation as a whole.
5. **Experiment with black and white discs:** a quantitative experiment used to explain radiative equilibria, stationary states, introduce the concept of albedo, and discuss the mechanism of heat propagation.
6. **Measurement of the power emitted by a light bulb** through a quantitative experiment introducing the concept of radiative equilibrium.
7. **Leaking bucket with one hole:** a known demonstration to introduce the concept of radiative equilibrium and stationary states.
8. **Qualitative demonstration of Leslie cube with thermocouple and IR thermal camera:** needed to explain the concept of emissivity characterizing the Stefan–Boltzmann law for gray bodies.

After conducting these experiments, students engage in a theoretical activity aimed at constructing the first model for climate evaluation to assess the average surface temperature.

### 3.3. The 0-Dimensional Radiative Energy Budget Model Including Atmosphere

The simple model without an atmosphere, presented above, proves inadequate to correctly estimate Earth’s temperature. In fact, it predicts an estimate of Earth’s average temperature that is much lower than the measured one (255 K, compared with 288 K, which is the current average value [55]). Hence, students are supported to reflect on the importance of the role of the atmosphere, which had been neglected in the previous model but which, in fact, plays an essential role because of the presence of the GHGs.

We, therefore, started from a simplified adaptation of the Manabe model (Figure 2, adjusted from [20]) to construct the framework presented in reference [29,56]. This model quantifies the interaction between the atmosphere and radiation from both the Sun and Earth’s surface using two parameters,  $\alpha_V$  and  $\alpha_{IR}$ . In this context, the atmosphere is treated as an ideal black body with a certain temperature, which emits radiation (mainly in the far-IR) isotropically, both toward Earth and toward space. This model is one of the so-called zero-dimensional models, as no local variations are considered for both Earth and the atmosphere. Therefore, although this model remains greatly simplified, it does indeed highlight the essential role of the atmosphere in Earth’s radiative budget and allows students to make an adequate estimate of Earth’s mean surface temperature.



**Figure 2.** The two-layer (Earth–atmosphere) model incorporates both the atmosphere and its interaction with radiation. The radiation–atmosphere interaction includes: a portion of radiation from the Sun (considered visible), a portion of IR radiation emitted by the Earth’s surface and absorbed by the atmosphere, radiation emitted in all directions by the atmosphere [29].

## Key Physics Concepts

To grasp the function of the atmosphere within this new model, it is necessary to understand some relevant phenomena that characterize the interaction between radiation and matter in general and between radiation and the atmosphere in particular: selective absorption and selective transparency. In particular, it is necessary to highlight phenomena involving the interaction of infrared (IR) radiation with certain substances, a phenomenon that may be unfamiliar to some students.

Furthermore, for this second model, specific types of experiments are outlined:

1. **Demonstration using an IR camera** to distinguish between visible and IR radiation.
2. **Quantitative experiments and simulations concerning Beer's law:**
  - (a) Conduct an experiment to measure the transmittance as a function of thickness by using many sheets of paper.
  - (b) Perform an experiment to determine the transmittance as a function of the concentration of the absorber with a tray filled with dye.
  - (c) Analyse the transmittance for the various spectral components of radiation incident through a liquid of different colours using light sources at certain wavelengths.
  - (d) Use a PhET simulation [46] to explore Beer's law by determining the transmittance as the substance and solute concentration change.
3. **Exploring selective transparency** with an infrared digital camera for glass, plastic, and silicon wafers.
4. **Using PhET simulations [46]** to study the photon-molecule interaction, particularly for certain gases relevant to the behavior of the atmosphere (GHG) at varying photon energy, thus exploring the microscopic aspects of selective transparency.
5. **Implementing a "leaking bucket with two holes" experiment** to discuss changes in the radiative equilibrium state.

After conducting these experiments, students participate in a theoretical activity aimed at constructing a second model for climate evaluation that includes the atmosphere. The goal of this activity is to assess the average surface temperature based on the knowledge gained from the experiments and simulations.

## 4. The Experiments

Based on general didactic design principles and taking into account physical concepts considered essential for understanding the greenhouse effect, the experimental activities that characterize the learning pathway were designed. For each conceptual area, we also present an overview of the challenges and misconceptions that are most commonly detected among the students, a brief discussion of the background theory, the outcomes of the measurements and the subsequent data analysis, and we discuss the enhancements in the students' understanding of the relevant phenomenon, in relation to the learning goals.

### 4.1. Electromagnetic Spectrum and Infrared Radiation

The first experiments proposed to the students are aimed at helping them visualize distinct segments of the EM spectrum and compare various sources of EM radiation. This approach aims to enable the students to differentiate between the concepts of heat and radiation and to grasp the concept that all objects emit thermal radiation. Through these experiments, students will acquire a better insight into the fundamental principles of thermal radiation and its relation to different objects and heat sources.

#### 4.1.1. Student Difficulties

A significant portion of the challenges students face when grappling with complex phenomena like the GHE arises from their insufficient knowledge of the EM spectrum, particularly in regard to radiation that is not visible, such as IR radiation. The lack of understanding regarding this type of radiation can hinder their comprehension of the GHE and its underlying mechanisms.

In this respect, we indeed found that, before the TLS, less than half of the students (44%) were able to order the different electromagnetic spectrum according to increasing frequency and mentioning all the different kinds of radiation, while one-third of them (37%), while putting the sequence in the correct order, omitted some kinds of radiation (10% omitted visible light, which on the other hand was the only radiation cited by 12% of the students). Among the rest of the students, we found that 10% inverted the order of the spectral bands, 6% did not follow a particular order, and 3% included non-electromagnetic radiation like rays and cosmic rays in the list. Summing up, the answers we collected denote an extensive challenge of linking each wavelength to its corresponding position in the electromagnetic spectrum, while more than 19% of the students had difficulty in identifying the portions of the spectrum themselves.

Regarding the students' understanding of IR radiation, it is evident that they often fail to recognize that IR radiation is a mechanism for the emission of energy. Additionally, a significant proportion of students (39%) do not believe that energy transfer from a hot body through a vacuum is feasible. These misconceptions indicate a need for further clarification and education on the concept of IR radiation and its role in energy transfer processes.

#### 4.1.2. Background Theory

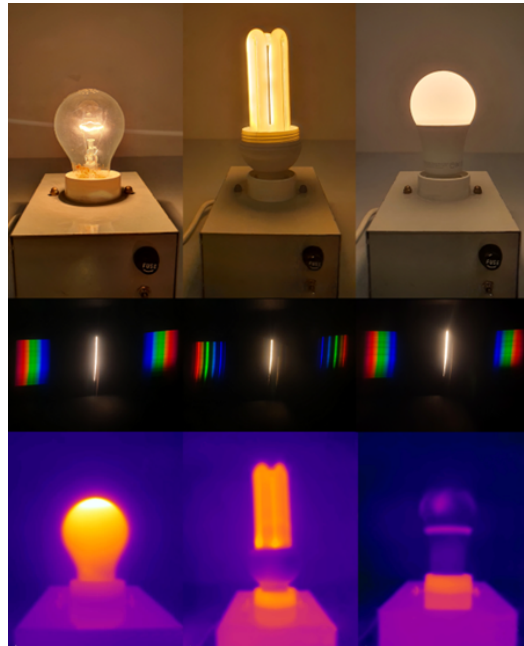
Radiation spectra emitted by different sources can be very different, and in fact, each spectrum is a characteristic signature of the emitting source. Roughly speaking, spectra can be classified into two broad categories, continuous (band) and line spectra, with the latter mainly pertaining to dilute atomic gases, while the former are associated with molecules and condensed matter systems. It is, of course, necessary to specify the frequencies of the spectral bands or lines. For example, an LED, a light bulb with a "cold" filament, and a light bulb with a "hot" filament all generate continuous spectra, which are, however, very different from each other.

#### 4.1.3. Experimental Setup

In all the experimental activities involved in the sequence, the students used a homemade spectroscope for the visible spectrum and a thermal camera for the IR part, Figure 3.

The homemade spectroscope, which is described in refs. [57,58], is made of inexpensive materials, i.e., black cardboard and an easily retrievable diffraction grating, and uses a smartphone camera to take pictures. This allows the wavelengths and intensities of light to be measured with high precision.

In analogy with the homemade spectroscope, an IR thermal camera can be attached to a smartphone, allowing the device's screen to display thermal images. With these simple instruments, students were able to observe and confront the different sources [59,60].



**Figure 3.** Pictures of several radiation sources, taken by the students using a homemade spectroscope and IR thermal camera, are shown.

#### 4.1.4. Students' Understanding and Learning Goals

Regarding the EM spectrum, we found that, after the TLS, the fraction of students capable of ordering spectral bands by increasing frequency, encompassing all types of radiation, increased from 44% to 85%. The activity was, therefore, effective in improving students' knowledge of the EM spectrum and in correctly placing the various wavelengths within it.

In terms of their understanding of IR radiation, we observed that, after the activity, most students consider the role of radiation in transferring energy from a hot body to a vacuum, and only 7% of students fail to acknowledge radiation emission as a method of energy transfer (compared to 39% in the pretest).

In this experiment, students were not required to perform quantitative data analysis. Instead, the focus was on developing manual skills in constructing a simple instrument, technical skills in using laboratory equipment, and technical knowledge in utilizing an IR thermal camera.

#### 4.2. The Stefan–Boltzmann Law

Following the discussion on how bodies emit EM radiation and that thermal radiation is not always visible, attention was directed toward the concepts and laws governing the temperature-dependent emission of radiation from a body, specifically the Stefan–Boltzmann law, with a more quantitative analysis.

##### 4.2.1. Student Difficulties

Previous studies on climate change, as highlighted by L. Jarrett [22], revealed that students frequently do not fully grasp the concept of black-body radiation and, more often, overlook that all objects emit thermal radiation, which varies with their temperature [18]. This observation was confirmed during interviews with students conducted before the teaching intervention, as described earlier.

#### 4.2.2. Background Theory

Let us recall that, by definition, “a black body is an idealized system which is capable of completely absorbing the incoming radiation, of any wavelength” [61]. The emission of radiation by a black body at temperature  $T$  is described by the Planck distribution, according to which the power emitted per unit surface per unit wavelength at the wavelength, which is denoted by  $W(\lambda, T)$ , is given by the following:

$$W(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{kT\lambda}} - 1}$$

where  $h$  is Planck constant ( $h = 6.6 \times 10^{-34}$  J s),  $k$  is Boltzmann constant ( $k = 1.38 \times 10^{-23}$  J K<sup>-1</sup>), and  $c$  is the speed of light in vacuum ( $c = 3 \times 10^8$  m s<sup>-1</sup>).

From Planck’s distribution, it is possible to derive two important consequences. The first is the Stefan–Boltzmann law: the total power irradiated per unit area by a black body at temperature  $T$  is proportional to the fourth power of the temperature:

$$W = \sigma T^4$$

where  $\sigma$  is the Stefan–Boltzmann constant ( $\sigma = 5.67 \times 10^{-8}$  W m<sup>-2</sup> K<sup>-4</sup>). The second is the Wien displacement law: the wavelength corresponding to the maximal radiated power (i.e., the maximum value of  $W(\lambda, T)$  at fixed  $T$ ) is inversely proportional to the temperature:

$$\lambda_{max} T = 2.88 \times 10^{-3} \text{ m K}$$

This law, in particular, is the reason why objects, as the temperature grows, first emit mostly in long wavelength bands, in particular in the IR, and only at higher temperatures do they start emitting visible light (i.e., they become incandescent).

While the above-stated laws give a good qualitative account of the emissivity properties of real bodies, it is important to emphasize that the latter are not ideal black bodies (sometimes one speaks of grey bodies), and they may be closer to or farther from the ideal case in different regions of the spectrum. In general, a non-ideal body absorbs and emits less radiation than an ideal black body at the same temperature. For what concerns us, this is considered by introducing an emissivity coefficient  $\epsilon$  (whose value is less than 1) in the Stefan–Boltzmann law:

$$W = \epsilon \sigma T^4$$

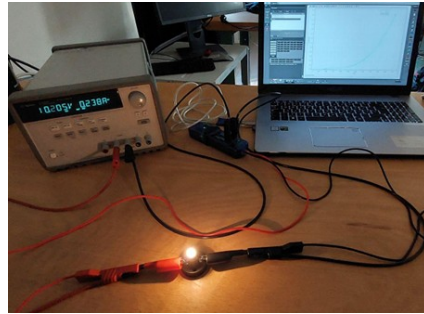
In general, thus, if the Stefan–Boltzmann law for the black body is employed to infer the temperature of a body (as is done by IR thermometers and IR cameras), the result will be lower than the actual one.

#### 4.2.3. Experimental Setup

The experimental apparatus is reported in Figure 4.

1. Measurements are performed employing a lamp constructed to work at a voltage of 12 V, absorbing a power of 3 W. Included in the setup are a power supplier with adjustable output voltage and a voltage and current sensor manufactured by PASCO [62].
2. By simply putting a diffraction grating in front of the smartphone camera, it is possible to capture the main features of the visible spectrum of the light bulb.
3. Since the glass of the bulb is not transparent to IR radiation, to explicitly see what happens before a body becomes incandescent with the IR camera, we substituted the bulb with a graphite pencil lead (this is the same setup used above to demonstrate how thermal radiation is often invisible).

4. Emissivity and the emissivity coefficient are discussed using the Leslie cube (Figure 5), which is an aluminum cube heated up by a light bulb put inside it, whose four lateral faces are finished differently to have different emissivities [62].



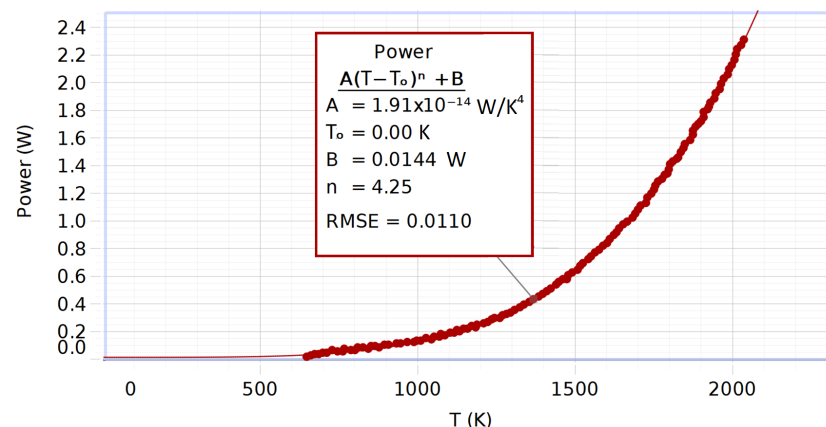
**Figure 4.** The setup for the experiment includes an incandescent light bulb, a PASCO voltage-current sensor [62], and a DC power supply.



**Figure 5.** Leslie cube makes it possible to measure the emissivity of different surfaces placed at the same temperature. In fact, the different faces of the cube have significantly different emissivity characteristics.

#### 4.2.4. Results of the Measurements and Data Analysis

You can determine the temperature of a tungsten filament based on electric current measurements [63–66]. By knowing the experimental ratio of resistances ( $\frac{R}{R_{ref}}$ ) for each current value, students can estimate the filament's temperature with about 10% accuracy. The filament acts as a resistor heated by the Joule effect [67,68], allowing students to analyze how absorbed power (calculated from voltage and current measurements) relates to the estimated resistance. Data collected by students, shown in Figure 6, align well with the Stefan–Boltzmann law. They fitted the data using a power law function ( $J(T) = T^n$ ), with an estimated exponent ( $n = 4.2 \pm 0.1$ ).



**Figure 6.** The relationship between electric power from the Joule effect and the extrapolated temperature from resistivity demonstrates a strong alignment with the Stefan–Boltzmann law.

#### 4.2.5. Students' Understanding and Learning Goals

After this step of the sequence, we observed that the percentage of students who refer implicitly or explicitly to radiative phenomena related to temperature increased from 35% to 72%.

In this activity, the student skills involved are the ability to take measurements with the experimental apparatus and analyze the data to determine the mathematical relationship between quantities. This same activity also allows students to observe that the resistance of the bulb in series with the variable DC power supply is not constant but increases as the potential difference and temperature increase. In the part involving the use of the infrared camera (graphite lead, Leslie cube), students worked on the design phase of the experimental apparatus to optimize measurements and further develop technical laboratory skills.

#### 4.3. Radiation–Matter Interaction

The role of the atmosphere within simplified climate models is to absorb radiation at some wavelengths and transmit it at others. To present this mechanism, we propose some experiments showing the behavior of different materials when interacting with electromagnetic radiation belonging to different parts of the spectrum.

##### 4.3.1. Student Difficulties

Before conducting the experiments, students were asked to make predictions about the behavior of a beam of light traveling through a container filled with liquid. While students demonstrated a good understanding of reflection and refraction phenomena, they tended to overlook the concepts of light absorption and scattering. Specifically, 82% of the students mentioned refraction, and 52% mentioned reflection, with some accurately referencing quantitative laws such as the Snell law. However, only a small percentage of students, 5% and 4% respectively, mentioned absorption and scattering, and no student listed all four phenomena.

Another question asked the students to explain what transparency means for a material. Only 13% of the students indicated that transparency is a property dependent on wavelength, demonstrating an understanding that transparency can be selective. Approximately 58% of the students perceived transparency as an absolute phenomenon, assuming that if a material is transparent, it remains so for any kind of electromagnetic radiation. Moreover, 20% of the students specifically associated transparency with “seeing through a body”, which indicated that they were considering only visible radiation.

##### 4.3.2. Background Theory

When a beam of monochromatic electromagnetic radiation with an initial intensity  $I_0$  passes through a material over a distance  $x$ , its intensity diminishes exponentially. This phenomenon is described by Beer–Lambert law, expressed as follows:

$$I(x) = I_0 e^{-\alpha_\lambda c x} = I_0 e^{-\frac{x}{l(\lambda)}}$$

Here,  $I(x)$  represents the intensity of the light beam after traveling a distance  $x$  within the material. The term  $\alpha_\lambda$  is a wavelength-dependent absorption coefficient, which also depends on the material and the concentration  $c$  of the absorbing substance. The parameter  $l$  is known as the mean free path, while  $T(x, \lambda) = \frac{I(x)}{I_0}$  is called transmittance of the material. The dependence of the absorptivity on the wavelength of the incident radiation, which is, in fact, quite strong, is usually called “selective transmission”. It is the consequence of the fact that the way radiation interacts with an object is dependent on the frequency and nature of the microscopic component of the object.

A similar pattern is observed when light passes through multiple layers of a material with equal thickness. In this scenario, the light's intensity is reduced by an amount that depends on the thickness of the material traversed. Assuming that the effects of multiple reflections within the layers can be ignored [69], the transmission for a specific wavelength of light as a function of the number of layers  $n$  follows a law similar to the one above:

$$T_n = T_0 e^{-\alpha n} = T_1^n$$

where we assume  $T_0 = 1$  and  $T_1 = e^{-\alpha}$  represents the transmission of a single layer.

This law holds for all kinds of electromagnetic radiation and hence for IR and visible light in particular. Of course, the sources and the absorbers are different in the two cases (a light bulb and paper sheets for the latter, a heated foil and plastic sheets for the former).

#### 4.3.3. Qualitative Experiments

The first activity we propose to the students demonstrates the main phenomena of geometric optics: a brush of white light passes through a container filled with water (Figure 7, left), enabling students to witness various essential phenomena of light-matter interaction, including scattering, refraction, reflection, and absorption.

The second activity employs an infrared camera, which demonstrates the distinct behavior of certain bodies when interacting with visible light or infrared radiation. For example, the transparency properties of a silicon wafer and a glass plate are shown (Figure 7, right).



**Figure 7.** On the left: reflection, refraction, and transmission of a light beam were observed using a rectangular plastic container filled with water. On the right: an infrared image of a student holding a silicon wafer in their hands.

#### 4.3.4. Quantitative Experiments

This activity comprises three planned experiments:

1. The first experiment uses a visible light source and a light sensor to measure how the intensity of transmitted light depends on the thickness of the material passed through. We used a table lamp as the source, a smartphone as the sensor, and several overlapping sheets of paper as the material. To control the ambient light sensor of the smartphone, we used the Physics Toolbox app [70] (Figure 8, left).
2. The second activity reproduces the previous one but with an IR radiation source. In this case, the black face of a Leslie cube constitutes our source, a smartphone equipped with an IR camera, our intensity sensor, and some plastic sheets replace the sheets of paper. IR images are obtained by adding one plastic sheet at a time in front of the face of the cube and capturing images using the IR thermal camera.

- The third experiment aims to measure how the intensity of transmitted light depends on the nature of the material passed through, the color of the incident radiation, and the concentration of an absorber in solution. The source consists of an LED torch, and three colored filters are used to produce monochromatic light. A smartphone is used as a sensor. A plastic cube containing water is gradually infused with food coloring, drop by drop, as shown in Figure 8 (right). Initially, the light intensity is measured using the smartphone's ambient light sensor without any filters. Subsequently, three colored filters are placed in front of the light source, one at a time. The dye concentration is then incrementally increased by adding one drop at a time, with measurements taken at each step. This entire procedure is repeated ten times.



**Figure 8.** On the left: the desk lamp and the smartphone are positioned less than 10 cm apart, with sheets of paper added one by one above the sensor. On the right: the setup for studying Beer's law of transmittance versus concentration includes a torch with a color filter, a plastic container filled with water, and a smartphone's ambient light sensor to measure light intensity. Drops of color dye are gradually added to the water.

#### 4.3.5. Students' Understanding and Learning Goals

Following these lab activities and repeating the test, the percentages of students mentioning the various phenomena increased as follows:

- Students mentioning reflection: from 52% to 97%;
- Students mentioning refraction: from 82% to 89%;
- Students mentioning absorption: from 5% to 90%;
- Students mentioning scattering: from 4% to 68%;
- Students mentioning all four phenomena: from 0% to 61%.

Regarding the concept of transparency, there was a notable shift in student responses. The number of students who remarked on selectivity raised significantly (from 13% to 85%), indicating a better understanding that transparency is a wavelength-dependent property. Conversely, the number of students who perceived transparency as an absolute phenomenon diminished (from 58% to 15%), indicating a reduced belief that transparency applies uniformly to all kinds of electromagnetic radiation. No students associated transparency with the idea of "seeing through a body" (they constituted the 20% before).

It is worth dwelling on the improvements shown by the students after this activity to emphasize how effective the use of the IR thermal camera is. The surprised reactions of the students when they were able to literally "see objects with different eyes", while not quantifiable, were evident (Figure 7).

During these lab activities, the student skills involved are the ability to take measurements with the various experimental apparatus and analyze the data appropriately to determine the mathematical relationship between quantities. They also have to learn to minimize experimental uncertainties and identify the assumptions made in the mathematical model.

#### 4.4. Radiative Equilibrium

The final phase of the investigation involves examining the concepts of energy balance and radiative equilibrium. The fundamental concept is that, for a body exposed to EM radiation, the final steady-state in which the temperature remains constant does not correspond to a state of thermal equilibrium between the body and the source but to a condition of dynamic equilibrium where the amount of energy entering a system is balanced by the amount of energy leaving it.

##### 4.4.1. Student Difficulties

Previous research has revealed that a significant portion of students attribute the temperature reached by an object exposed to radiation solely to its heat capacity, while only about a third of the students consider the color of the object as a fundamental factor.

When we requested students to forecast the outcome for two identical objects, differing solely in color (one white and one black), when exposed to sunlight, over 80% accurately predicted that both objects would reach a constant equilibrium temperature, with the black object having a higher temperature. However, some students also mentioned ideas such as the existence of a limiting temperature or the possibility of reaching the fusion temperature (especially if the objects were metallic) in their explanations. Regarding the difference between the two objects, students correctly identified that it lies in their distinct abilities to reflect and absorb radiation.

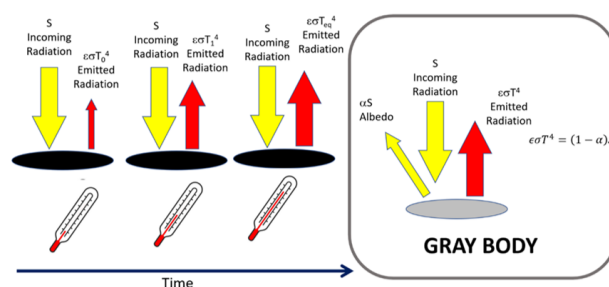
Despite this understanding in specific contexts, the idea of radiative balance is not consistently evident in students' answers. In particular, the drawings produced by the students before starting the course, stimulated by the request to represent the Greenhouse effect based on their prior knowledge, were analyzed.

##### 4.4.2. Background Theory

In Figure 9, the approach to radiative equilibrium by an object exposed to radiation of constant intensity is represented. If the object is modeled as a gray body, the stationary temperature can be computed using the Stefan–Boltzmann law, taking into account the albedo  $a$  (i.e., the fraction of radiation that is reflected back by the body) and the emissivity  $\epsilon$ :

$$S(1 - a) = \epsilon\sigma T^4 \quad \rightarrow \quad T = \sqrt[4]{\frac{S(1 - a)}{\epsilon\sigma}}$$

where  $S$  is the power per surface unit that reaches the body.

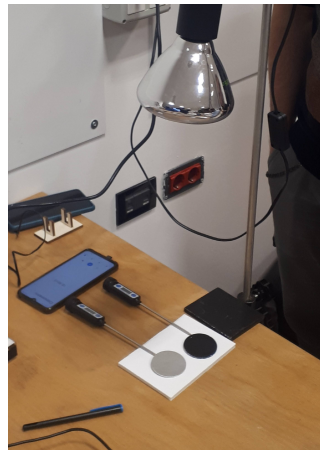


**Figure 9.** On the left: radiative balance. Yellow arrows denote the intensity of the radiation coming from the lamp (which is kept constant), and red arrows denote the intensity of the radiation emitted from the plate (which depends on the temperature).  $T_i$  indicates the temperatures of the plate, with  $T_1 > T_2 > T_3$ , in particular  $T_3$  is the stationary temperature reached by the plate. On the right: radiative balance that includes the albedo and the emissivity to explain the different behavior of the black and white plates.

#### 4.4.3. Experimental Setup

We use an incandescent lamp and two aluminum discs colored white and black, respectively. The aluminum discs are in contact with two digital thermometers (or two temperature sensors) and are placed symmetrically under the lamp as shown in Figure 10. The students take the temperatures measured by the two thermometers as a function of time with the lamp switched on until the temperature appears approximately constant. Then, the lamp is switched off, and the students measure the cooling curve of the aluminum discs in the environment.

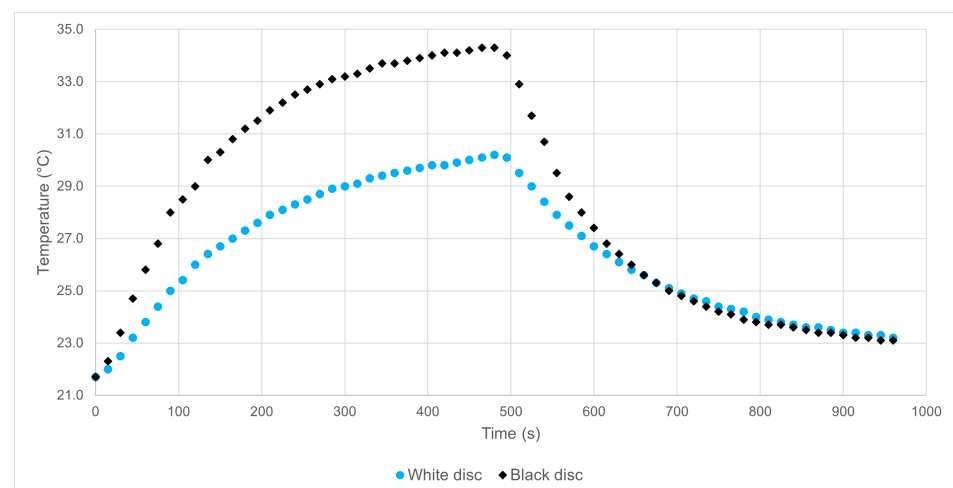
The same experiment can be performed outdoors, measuring the temperature of the discs exposed to the Sun as a function of time: in this way, students can measure the solar constant.



**Figure 10.** The experimental setup includes thermometers in contact with both the blackened and whitened discs resting on an insulating material.

#### 4.4.4. Experimental Results and Data Analysis

Typical experiment results obtained by the students are shown in Figure 11. The estimate of the bulb power is usually in reasonably good agreement with the nominal power (so is the estimate of the solar constant).



**Figure 11.** Students' recorded data using a stopwatch and a thermometer, and processed using spreadsheet software (Microsoft Excel).

#### 4.4.5. Students' Understanding and Learning Goals

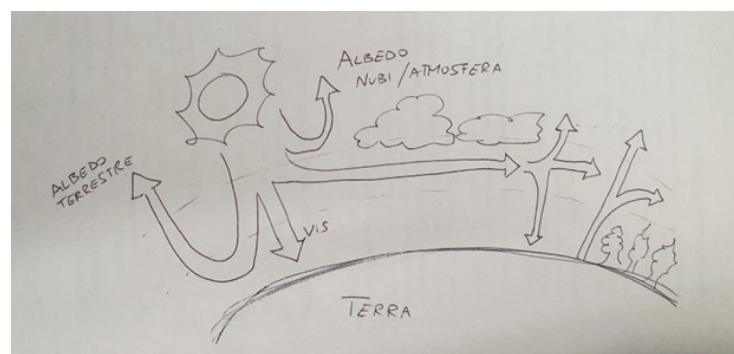
The concept of radiative balance was not used by students before following the TLS activities either to explain the greenhouse effect or to justify reaching a limiting temperature

for a body exposed to radiation. However, by the end of the TLS, most students had appropriated this concept and used it both to justify the behavior of bodies exposed to radiation (around 70% of students) and as a mechanism for Earth's greenhouse effect to work (around 90% of students). Furthermore, unlike before the teaching intervention, the majority of students (around 80%) appropriated the Earth–atmosphere model proposed in Figure 2 and used it to represent the mechanisms underlying the greenhouse effect.

Also, in these lab activities, the student skills involved are the ability to take measurements with the various experimental apparatus and analyze the data appropriately to evaluate their own hypotheses.

## 5. Results of the Tests

After studying the physical basis of the greenhouse effect in depth, models describing the Earth–atmosphere system and the representations in which energy flows in a steady state, as characterized by climatological measurements, are usually depicted (see Figure 12).



**Figure 12.** Sketch of the energy fluxes constructed collectively as a result of the discussion during the experimentation of the activity.

Observe that this model may be considered as a “two-component model” since it involves Earth and the atmosphere, each of which reflects and emits (and in the case of the atmosphere, also transmits and absorbs) radiation, as in the models discussed in Section 3.

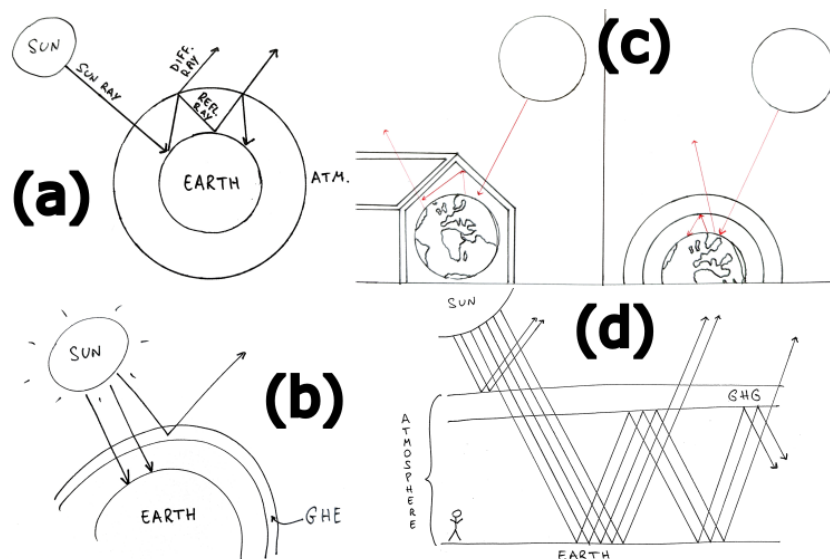
### *Students' Drawings and Conceptual Understanding*

At the beginning and end of the TLS, students were asked to illustrate and explain Earth's greenhouse effect. Figure 13 shows some examples of drawings made at the beginning of the TLS. In these representations, the pre-didactic concepts commonly found in the literature are manifested. These concepts form the basis for the most common explanations of the GHE, as reported in the literature [71]:

- Trapping;
- Multiple reflections;
- The presence of a defined layer of greenhouse gases (or occasionally dust) acting as a physical barrier;
- Analogy with an agricultural greenhouse.

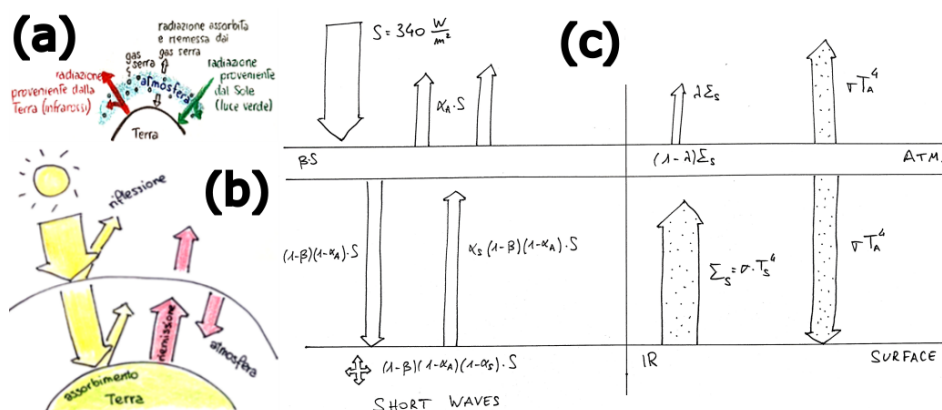
From the explanations of the GHE that accompanied the drawings, we could infer that more than half of the students (56%) think that the GHE is due to repeated reflections between Earth's surface and the atmosphere of the solar radiation, which is therefore trapped. Moreover, 26% of the students only refer to reflection without explicitly referring to trapping. Only a small fraction of students (about 10%) identify a correspondence between the energy of radiation and its color (typically representing solar radiation in yellow and terrestrial radiation in red) or its wavelength (representing waves with different wavelengths for solar radiation and terrestrial radiation). We also noticed that 11% of the

students do not link the GHE with any physical phenomena but use ideas such as the carbon cycle and the depletion of the ozone layer.



**Figure 13.** A selection of the students’ drawings before the TLS: (a) Reflection and refraction; (b) The student wrote: “GHGs retain some of the heat from the sun’s rays that are reflected back from Earth causing global warming”; (c) Inadequate analogy of using an actual greenhouse for picturing the natural GHE; (d) The student wrote: “GHGs prevent solar radiation from leaving the Earth. This results in more energy being absorbed, increasing the Earth’s temperature”.

The analysis of the students’ drawings at the end of the TLS (reported in Figure 14) allows one to understand how much the students understood the models of the GHE and how effective the activity was, also considering the complexity of the model and the presence of formal elements. The students described the GHE in an original way, reproducing the phenomenological model of the energy fluxes and of the balance, i.e., the two-component model (see Figure 2). Students demonstrate confidence in providing qualitative explanations, and a substantial number of them also incorporate quantitative models and formulas, with the Stefan–Boltzmann law being predominantly utilized. Furthermore, approximately 25% of the students refer to some of the conducted experiments.



**Figure 14.** A selection of the students’ drawings after the TLS: (a) Qualitative drawing including absorption and emission by the atmosphere, there is distinction between light and infrared; (b) Qualitative drawing that includes reflection in addition to absorption and emission by the atmosphere, there is distinction between light and infrared; (c) Quantitative scheme including formulas and references to models shown during the TLS, there is distinction between light and infrared.

A positive result of the TLS is that the ideas that emerged during the pretest relating to capture and the analogy with an agricultural greenhouse disappeared from the students' representations at the end of the course.

## 6. Discussion

This study centers on climate education (CE), defined as a comprehensive educational framework aimed at enhancing students' understanding of the climate issue and fostering societal efforts toward both mitigation and adaptation. CE endeavors to equip students with the scientific knowledge, skills, values, and reflective attitudes necessary to comprehend and effectively address the multifaceted climate crisis. This encompasses not only scientific awareness, including risk perception and mechanistic understanding, but also crucial psychological and behavioral factors such as anxiety, engagement, and pro-environmental action.

Drawing upon the existing literature, key objectives of CE include empowering learners to take informed action on climate change at individual and collective levels, both locally and globally [9]. Furthermore, CE aims to cultivate critical thinking skills, enabling students to approach information, including misinformation, with discernment and conscious evaluation [10]. It also emphasizes the development of students' capacity to form conscious, critically reflected, and well-reasoned opinions and judgments.

The design of an educative curriculum for climate change education in this study incorporates five relevant steps: engaging students with specific scientific phenomena and instructional representations; anticipating and addressing students' preconceptions; fostering questioning and data analysis; promoting evidence-based explanations and scientific communication; and ultimately developing their subject matter knowledge about climate change. While these steps initially prioritize scientific understanding, the pedagogical approach explicitly integrates reflections on psychological and social dimensions. This is achieved through activities such as utilizing the Cranky Uncle game [72] to counter misinformation, prompting students to analyze climate change denial mechanisms [73], encouraging reflection on psychological barriers to action [27], examining energy production and consumption through ecological footprint calculation, investigating future climate scenarios, for instance, using the En-ROADS simulator [74], and engaging with the ClimarisQ [75] game to understand climate system complexity and the urgency of collective action.

Consequently, the analysis of the intervention's effectiveness is structured along two distinct pathways: one focusing on the comprehension of disciplinary (scientific) aspects and the other examining the impact on psychological and social dimensions.

### 6.1. Disciplinary Aspects

From a discipline-specific education perspective, the findings of this study provide a detailed account of the experimental teaching sequence's effectiveness in enhancing students' understanding of the fundamental physical processes governing the GHE and the underlying scientific principles of climate change. The science education community widely acknowledges the inherent difficulty students face with certain scientific concepts due to the counter-intuitive nature of the associated scientific reasoning [76–78]. Prior research highlights that processes involving the interaction of matter and radiation particularly fall into this challenging category [79,80]. Consequently, effective teaching and learning of scientific explanations for climate necessitate a focus on developing reasoning skills related to these core scientific concepts and principles.

The quantitative analysis of pre- and post-test data discussed above revealed significant improvements across several conceptual domains. Notably, a marked increase

was observed in students' comprehension of the electromagnetic spectrum, indicating the experimental activities effectively addressed prior gaps in their understanding of the nature and classification of various forms of electromagnetic radiation. Furthermore, the study documented a significant positive shift in students' conceptualization of infrared radiation. This outcome strongly suggests that direct engagement with tools such as an IR thermal camera played a crucial role in enabling students to grasp the radiative nature of heat and its involvement in energy exchange processes. These findings are consistent with conceptual difficulties reported in the existing literature concerning the understanding of the GHE and related radiative phenomena [21–24].

Moreover, the learning pathway proved effective in fostering a more robust understanding of the overall mechanism underpinning the GHE. Consistent with Besson's findings [18], the results suggest that upon completion of the sequence, students were more likely to consider the infrared emission of bodies within the energy budget, recognize that transparency to electromagnetic radiation is contingent on both the material and the radiation's frequency, avoid the misconception of "trapping solar radiation" in their explanations of the greenhouse effect, and acknowledge the active role of the Earth in exchanging infrared radiation. The results also demonstrate an improvement compared to Moggio's findings [19], which highlighted students' difficulties in discussing selective transparency due to a lack of understanding of electromagnetic spectrum properties and their struggles with the concept of heat, often failing to differentiate between heat and radiation. Furthermore, the study shows progress compared to Besson regarding the prevalence of analogies with agricultural greenhouses in students' explanations [18].

#### 6.1.1. Inquiry-Based Learning, Critical Thinking, and Metacognition

Our TLS is distinguished by its adoption of active teaching methodologies, aligning with the principles of active learning and Inquiry-Based Learning (IBL). The engagement in hands-on experimental activities and the utilization of tools such as the self-constructed spectrometer and PhET simulations were instrumental in enabling students to construct mental models of physical phenomena, formulate testable hypotheses, and experimentally verify them. This approach fostered a more meaningful and enduring learning experience, simultaneously stimulating critical thinking skills and enhancing scientific literacy [81].

Furthermore, the experimental activity provided a valuable and explicit opportunity for students to develop awareness regarding their own learning processes. The inherent necessity to interpret experimental data, rigorously compare it with theoretical predictions derived from scientific principles and engage in critical discussions of the resulting outcomes actively encouraged reflection on the cognitive strategies they employed. This process facilitated the identification of existing misconceptions and promoted the self-regulation of their learning. This metacognitive dimension holds particular salience within the context of sustainability education, where the cultivation of critical thinking and autonomous learning skills is paramount for effectively addressing the inherently complex challenges posed by climate change and for promoting active and informed engagement toward a sustainable future [38].

Metacognition, defined as the capacity to reflect upon the reliability and potential fallibility of one's own knowledge and deeply held beliefs, plays a crucial role in navigating intricate global issues. In such domains, deeply ingrained and often polarized beliefs can significantly impede the establishment of common ground, thereby hindering the effective resolution of global problems. Indeed, metacognition emerges as a crucial instrument for effectively confronting these overarching global challenges. Enhancing awareness of the inherent limitations of one's own knowledge base has the potential to mitigate

polarization, foster more constructive and evidence-based debates, and ultimately promote more informed and rational decision-making processes [82].

A central aspect connecting metacognition to the learning process is the explicit consideration of experimental uncertainty, a concept of paramount relevance within the domain of climate science. A heightened awareness of this critical aspect is actively fostered by the experimental activities strategically integrated within the proposed learning sequence and further stimulated through explicit reflection on the fundamental aspects of scientific knowledge construction. Through this deliberate reflection on the inherent uncertainty within scientific inquiry, students developed a robust awareness of the terms underpinning trust in science, grounded in its methodological approach: *“an aspect fundamental to the scientific process: it is not based on faith or dogma, but on continuous self-correction. The reason why we can trust science lies in the fact that nothing is ever accepted as absolute, but every theory is subjected to rigorous verification. Science evolves precisely because it is willing to question itself, abandoning theories that do not stand the test of facts”*. Students further emphasized the importance of understanding the underlying mechanisms of scientific research: *“it is necessary that every student, as a future citizen and active member of society, is aware of how research and the scientific process work, especially considering a widespread thought today according to which science is democratic, based on opinions and ‘hearsay’, without feeling the need to report data, studies, and reliable sources. It is therefore important that the student, in addition to what science teaches, knows how science works, so that they can become a conscious and responsible citizen”*. From this perspective, both the inquiry-based learning activities and the explicit reflection on the nature of science proved to be fundamentally important.

Developing metacognitive self-awareness directly helps in drawing evidence-based and, therefore, justified conclusions. In this way, metacognition also influences how one acts. For example, an individual’s confidence level significantly guides information organization strategies: individuals tend to seek information that aligns with their previous choices as their confidence in those decisions increases. This cognitive bias can potentially undermine confidence in accurate knowledge and/or reinforce confidence in inaccurate knowledge. Recent studies show how this issue is very relevant in the context of understanding climate change: citizens often lack confidence in accurate knowledge about climate change and, conversely, show a certain inclination to trust inaccurate knowledge [82].

#### 6.1.2. Difficulties for Students in Experimental Activities

Inquiry-Based Learning is a fundamental pedagogical strategy for engaging students in scientific learning [81] as it allows for the development of an in-depth understanding of scientific concepts, inquiry methods, and the nature of scientific knowledge [83]. IBL is defined through three key dimensions [84]: the conceptual domain, including declarative knowledge of facts, theories, and scientific principles; the epistemic domain, which concerns the understanding of how scientific knowledge is generated; and the procedural domain, which refers to the knowledge of practices and methods used in scientific inquiry [85]. Spanning these three domains, the experimental process is a problem-solving process that follows the hypothetico-deductive method and is structured in several phases [86], each of which involves some difficulties for students: formulation of research questions (e.g., difficulty in formulating causal research questions); generation of hypotheses (e.g., difficulty in distinguishing between hypotheses and predictions); planning and conducting the experiment (e.g., difficulty in conducting experiments independently or coordinating theory and evidence); data analysis and formulation of conclusions (e.g., difficulty in generalizing, or in identifying errors).

In this TLS, an attempt was made to address the main difficulties perceived by students in the experimental activity through a structured inquiry approach by guiding the

proposed activities in the different phases while trying to maintain the level of student engagement and participation as high as possible. In particular, each activity is introduced by guiding students to reflect on the hypotheses, objectives, and methods of carrying out the experiment; at the conclusion of each activity, students are supported to extrapolate and generalize the results deducible from the observations, aiding in the process of abstraction and connection with the theory.

### 6.2. Individual Internalization of Sustainability

From a broader sustainability education perspective, Lozano [87] highlights the necessity of congruence between informational, emotional, and behavioral attitudes for individual internalization of sustainability. While education is crucial for fostering a sustainable mindset [88], it does not always directly impact attitudes [89]. This underscores the need for integrated educational models like CARE-KNOW-DO [90], combining knowledge, empathy, and action to prepare students for a sustainable future, as knowledge underpins acceptance of political measures and evidence-based decisions.

The psychology of learning about climate change plays a central role, and it explores psychological factors influencing engagement in climate activism and how learning and motivation can promote pro-environmental behaviors. This interdisciplinary field integrates psychology, environmental education, and social sciences to develop effective approaches for climate awareness and action, examining how emotions, beliefs, and cognitive processes shape our understanding and response to climate change.

#### 6.2.1. Psychology in Climate Change Education

The psychology behind climate education recognizes that knowledge is fundamental for the acceptance of policy measures, democratic participation, and evidence-based decision-making. However, knowledge alone is insufficient, as confidence in one's answers is often inversely proportional to their correctness, highlighting the risks of overconfidence [9]. The combination of partial knowledge and misplaced confidence can distort the perception of reality and compromise decision-making. To mitigate this problem, physics education in schools must address the causes and consequences of climate change in order to build a more solid foundation for the decision-making process. Engagement with climate change is conceptualized through two interconnected perspectives: personal engagement and civic engagement. Personal engagement implies "a personal state of connection with the issue of climate change" that "encompasses cognitive, affective, and behavioral aspects" [91], which from a psychological perspective "involves what people think, feel and do about climate change: it is typically associated with knowledge, awareness and perceptions of climate change, with related attitudes, emotions and values, and with behaviors that cause or help to mitigate it" [92]. Civic engagement, on the other hand, refers to the active participation of citizens in the collective resolution of problems, policy-making, deliberation, and dialogue [91,93]. In this light, the literature in climate psychology identifies several psychological factors that dispose people to engage in collective climate action [27], among which we find affective engagement, which includes risk perception, emotional responses, self-efficacy (an individual's confidence in their ability to effect changes through personal actions) and collective efficacy (the perception of society's ability to tackle climate change). Furthermore, research suggests that metacognition, or the ability to understand the reliability and limitations of one's own knowledge, plays a crucial role in how individuals form beliefs, process information, and make decisions in politically controversial contexts. In particular, the ability to recognize one's own errors can reduce the polarization of opinions [82]. Intellectual humility is seen as a cognitive virtue that promotes the pursuit of truth, compromise, and the reduction of polarization.

Metacognitive ability, or the capacity for introspection on one's own performance, is crucial for intellectual humility. People with greater intellectual humility are more capable of distinguishing correct interpretations from incorrect ones and of calibrating their confidence based on the accuracy of their interpretations [82]. Moreover, the role of metacognition is fundamental in the search for information to evaluate ambiguous news. Subjective confidence in a news item is a determining factor in the decision to seek further information: the lower the confidence, the greater the desire to investigate further. News characteristics such as inaccuracy and the tendency to polarize opinions can lead to incorrect evaluations, highlighting individuals' vulnerability to ambiguity [94].

### 6.2.2. Activities Devoted to Overcome Psychological Obstacles

To address psychological barriers, an explicit and reflective approach was implemented to stimulate students' metacognition regarding the psychological factors that impede climate action. Thus, concurrently with the construction of scientific knowledge, which aligns with informational attitudes, we explicitly and reflectively presented students with psychological factors, as identified by Castiglione et al. [27], including affective engagement (i.e., anxiety, sense of threat, worry, and concern about the environment and ecological extinction), worldviews (i.e., egalitarian [95], nature-loving [96], and anti-consumerist beliefs [97]), collective efficacy (i.e., the perception that the actions of one's group can have an impact), and social norms (i.e., the perceived approval of one's engagement in activism from people in one's social circle [98]). Throughout the learning sequence, beyond the overview of these psychological aspects, specific activities were also integrated to strengthen certain factors. These included enhancing affective engagement by illustrating the dramatic impacts of climate change (e.g., the melting of Alpine glaciers in the students' local area), reinforcing collective efficacy by presenting examples of successful movements, and promoting self-efficacy through reflective exercises.

### 6.2.3. Some Results from Our Students

Delving deeper into the psychological aspect of climate education, an analysis of the responses to the interviews conducted with a small group of our students reveals some interesting trends. Their opinions show a certain awareness of the limits of science and its evolving nature while still maintaining trust in the scientific method and scientists. Expectedly, it emerges that understanding scientific theories is associated with greater trust in science. Regarding climate change, the majority of students recognize the necessity of reducing consumption, although they express skepticism about the collective willingness to implement such change. Almost all perceive the broad scientific agreement on the existence and anthropogenic origin of climate change.

Comparing these initial observations with those that emerged by interviewing students in lower grades, a greater trust in science is noted among university students. Younger students, while believing in the scientific method, tend to view scientists as more influenced by external factors. Furthermore, they show less awareness of human responsibility in climate change and the scientific consensus on the issue. However, the relationship between understanding and trust appears similar across different educational levels.

In conclusion, the activities proposed in the TLS promote students' awareness, but knowledge of the mechanisms alone does not suffice to stimulate a robust change in attitudes or behaviors. Indeed, our students demonstrate a high level of awareness, as one student articulated: *"how human behaviors (political decisions, economic choices, individual changes) influence the climate and are difficult to predict. Climate models, in fact, can provide future forecasts. . . ; however, what the future scenario will be depends largely on human decisions.*

*Therefore, understanding the uncertainty related to human behavior is fundamental to making less uncertain predictions about the future of the climate”.*

### 6.3. Denialism and Misinformation

The convergence of partial knowledge and misplaced confidence can significantly distort perceptions of reality and precipitate poor decision-making. To effectively mitigate this critical issue, physics education must directly address the fundamental causes and far-reaching consequences of climate change, thereby establishing a more informed and robust foundation for subsequent decision-making [9]. Accomplishing this necessitates actively grappling with the pervasive issue of misinformation and directly counteracting both traditional and contemporary forms of climate change denial, as well as the erosion of trust in established scientific understanding. In the TLS presented within this work, the experimental activities meticulously designed to elucidate the fundamental physico-chemical mechanisms underlying the GHE and the phenomenon of global warming were strategically complemented by carefully crafted activities specifically aimed at fostering a deeper understanding of misinformation mechanisms and promoting critical reflection on the multifaceted nature of denialism. This reflection encompassed both its well-established historical characteristics (often termed “old denialism”) and its more recent and evolving manifestations (referred to as “new denialism”), partly spurred by significant advancements and shifts within the field of communication.

Throughout the proposed learning pathway, students actively engage with the Cranky Uncle game, which strategically employs cartoons and critical thinking exercises as effective tools to directly counter misinformation. Furthermore, they are intentionally prompted to critically confront the underlying mechanisms that drive both traditional and contemporary manifestations of climate change denial. In particular, students critically reflected upon two key assertions that frequently characterize the new denial: namely, the claim that solutions to climate change are either ineffective or detrimental to economic stability and the assertion that climate science and the broader climate movement are inherently unreliable due to purportedly uncertain predictions. In direct contrast to these denialist positions, students at the conclusion of the learning pathway articulated a robust trust in the scientific process, explicitly grounding this trust in the inherent self-correcting nature of science: *“science makes no claim to infallibility; in fact, its value lies not in being absolute and immutable, but in its capacity for self-correction”*, and *“scientific knowledge is provisional; we must not convey the idea that science is weak, but rather that science is stronger than other forms of knowledge precisely because it is capable of questioning itself!”*

Regarding the uncertainty often highlighted by deniers, one student insightfully stated: *“we know with certainty that the increase in CO<sub>2</sub> concentration in the atmosphere is causing the increase in the Earth’s average temperature. Therefore, uncertainty in climate models is not an excuse for inaction: we know the risk exists, and we must address it. Uncertainty is inherent in complex phenomena and systems and in scientific research itself; it is a component that scientists constantly deal with. If we followed the belief: ‘action cannot be taken until knowledge is complete’, there would be no scientific research and, consequently, no progress”*.

Addressing the economic concerns raised by denialist viewpoints and political stances, one student astutely wrote: *“We have satellite images, past and present temperature records, as well as direct evidence every day. There is no correlation between the fight against global warming and the competitiveness of the world economy. On the contrary, the effects of climate change could have very negative impacts on the global economy. Some are already being seen; just think of the damage caused by extreme events. Focusing on renewable energy could also lead to economic growth in various sectors such as wind power, solar energy, and sustainable mobility”*. Another student offered a critical perspective on certain political views: *“Science is not based on popular*

*consensus; it is not democratic. Scientific theories are based on objective data and evidence, not on subjective opinions. . . Some politicians seem unaware of how scientific knowledge is constructed and what the fundamental aspects of scientific research are. Scientific experiments must be reproducible and falsifiable, so that in light of new data, a theory can be modified or replaced. In this sense, 'science does not trust itself.' We must trust science precisely because of its continuous evolution and the fact that it is not imposed by someone but built through collaboration and continuous comparison with empirical data''.*

## 7. Conclusions

In this paper, we have presented an experiment-based teaching–learning sequence aimed at familiarizing undergraduate students with a simplified model of Earth’s climate. The model encompasses the key physical elements and principles of the greenhouse effect, which guide students to gain a thorough understanding of its mechanisms. This knowledge is crucial for any STEM student today, particularly considering that many students often bring pre-instructional misconceptions related to these topics as they begin their undergraduate studies. While the TLS has currently been proposed for physics and mathematics students, it also holds potential applicability for other disciplines.

A secondary objective of the sequence is to enhance students’ confidence in conducting laboratory experiments that involve both quantitative and qualitative approaches along with data analysis. The gathered results thus far are encouraging, particularly because a significant number of students commence their undergraduate studies with pre-existing difficulties related to these topics. The results show that the students’ understanding of the fundamental aspects, the mechanisms involved, and the overall functioning of the Greenhouse Effect was greatly enhanced by the educational intervention. Following the TLS, a majority of students appear to have overcome their difficulties and have achieved a good level of understanding.

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## References

1. Versteijlen, M.; Wals, A.E.J. Developing Design Principles for Sustainability-Oriented Blended Learning in Higher Education. *Sustainability* **2023**, *15*, 8150. [CrossRef]
2. Tilbury, D. Education for Sustainable Development: An Expert Review of Processes and Learning. Available online: <https://unesdoc.unesco.org/ark:/48223/pf0000191442> (accessed on 28 February 2025).
3. Sterling, S. *Science, Society, and Sustainability*; Number 27 in Routledge Research in Education; Routledge: New York, NY, USA, 2009; Chapter Sustainable Education.
4. Ramakrishna, S. Incorporating sustainability into the university curriculum. *Dry. Technol.* **2021**, *39*, 985–988. [CrossRef]
5. Gosselin, D.; Parnell, R.; Smith-Sebasto, N.J.; Vincent, S. Integration of sustainability in higher education: Three case studies of curricular implementation. *J. Environ. Stud. Sci.* **2013**, *3*, 316–330. [CrossRef]
6. Mochizuki, Y.; Bryan, A. Climate Change Education in the Context of Education for Sustainable Development: Rationale and Principles. *J. Educ. Sustain. Dev.* **2015**, *9*, 4–26. [CrossRef]
7. IPCC. *Climate Change 2021—The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2023; pp. 3–32. [CrossRef]
8. UNESCO. Climate Change Education. 2024. Available online: <https://www.unesco.org/en/climate-change/education> (accessed on 28 February 2025).
9. Schubatzky, T. Climate Change in Physics Education: Why, What and How? In Proceedings of the 4th World Conference on Physics Education 2024, Kraków, Poland, 26–30 August 2024.
10. Chew Hung, C. *Climate Change Education: Knowing, Doing and Being*; Routledge: London, UK, 2022. [CrossRef]
11. Kasperson, R.E.; Kasperson, J. *Social Contours of Risk: Volume I Publics, Risk Communication and the Social*; Taylor & Francis Group: Abingdon, UK, 2012; p. 376.
12. Steffen, W.; Grinevald, J.; Crutzen, P.; McNeill, J. The Anthropocene: Conceptual and historical perspectives. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2011**, *369*, 842–867. [CrossRef]
13. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [CrossRef]
14. Ghil, M.; Lucarini, V. The physics of climate variability and climate change. *Rev. Mod. Phys.* **2020**, *92*, 035002. [CrossRef]
15. AAPT. *Recommendations for the Undergraduate Physics Laboratory Curriculum*; American Association of Physics Teachers (AAPT): College Park, MD, USA, 2010.
16. Steffen, W.; Persson, A.; Deutsch, L.; Zalasiewicz, J.; Williams, M.; Richardson, K.; Crumley, C.; Crutzen, P.; Folke, C.; Gordon, L.; et al. The Anthropocene: From Global Change to Planetary Stewardship. *Ambio* **2011**, *40*, 739–761. [CrossRef]
17. Ding, D.; Maibach, E.W.; Zhao, X.; Roser-Renouf, C.; Leiserowitz, A. Support for climate policy and societal action are linked to perceptions about scientific agreement. *Nat. Clim. Chang.* **2011**, *1*, 462–466. [CrossRef]
18. Besson, U.; De Ambrosis, A.; Mascheretti, P. Studying the physical basis of global warming: Thermal effects of the interaction between radiation and matter and greenhouse effect. *Eur. J. Phys.* **2010**, *31*, 375–388.
19. Moggio, L. Design and Experimentation of Communication and of a Teaching Sequence on Atmospheric Physics. Ph.D. Thesis, Università degli studi di Trento, Trento, Italy, 2017.
20. Wallace, J.M. *Atmospheric Science: An Introductory Survey*, 2nd ed.; Number Volume 92 in International Geophysics; Academic Press: Cambridge, MA, USA; Elsevier: Burlington, MA, USA, 2006.
21. Gautier, C.; Deutsch, K.; Rebich, S. Misconceptions About the Greenhouse Effect. *J. Geosci. Educ.* **2006**, *54*, 386–395.
22. Jarrett, L. Investigating Secondary School Students' Understanding of Climate Change. Ph.D. Thesis, University of Wollongong, Wollongong, Australia, 2013.
23. Koulaidis, V.; Christidou, V. Models of students' thinking concerning the greenhouse effect and teaching implications. *Sci. Educ.* **1999**, *83*, 559–576.
24. Shepardson, D.P.; Niyogi, D.; Choi, S.; Charusombat, U. Students' conceptions about the greenhouse effect, global warming, and climate change. *Clim. Change* **2010**, *104*, 481–507.
25. Ke, L.; Sadler, T.D.; Zangori, L.; Friedrichsen, P.J. Developing and Using Multiple Models to Promote Scientific Literacy in the Context of Socio-Scientific Issues. *Sci. Educ.* **2021**, *30*, 589–607. [CrossRef]
26. Kumar, V.; Choudhary, S.K.; Singh, R. Environmental socio-scientific issues as contexts in developing scientific literacy in science education: A systematic literature review. *Soc. Sci. Humanit. Open* **2024**, *9*, 100765. [CrossRef]
27. Castiglione, A.; Brick, C.; Holden, S.; Miles-Urdan, E.; Aron, A.R. Discovering the psychological building blocks underlying climate action—A longitudinal study of real-world activism. *R. Soc. Open Sci.* **2021**, *9*, 210006. [CrossRef]
28. Niebert, K.; Gropengiesser, H. The model of educational reconstruction: A framework for the design of theory-based content specific interventions. The example of climate change. In *Educational Design Research—Part B: Illustrative Cases*; SLO—Netherlands Institute for Curriculum Development: Enschede, The Netherlands, 2013; pp. 511–531.
29. Toffaletti, S.; Di Mauro, M.; Rosi, T.; Malgieri, M.; Onorato, P. Guiding Students towards an Understanding of Climate Change through a Teaching–Learning Sequence. *Educ. Sci.* **2022**, *12*, 759.

30. Marzari, A.; Di Mauro, M.; Rosi, T.; Onorato, P.; Malgieri, M. Investigating the Principle of Relativity and the Principle of Equivalence in Classical Mechanics: Design and Evaluation of a Teaching–Learning Sequence Based on Experiments and Simulations. *Educ. Sci.* **2023**, *13*, 712. [[CrossRef](#)]
31. Ambrosis, A.D.; Malgieri, M.; Mascheretti, P.; Onorato, P. Investigating the role of sliding friction in rolling motion: A teaching sequence based on experiments and simulations. *Eur. J. Phys.* **2015**, *36*, 035020. [[CrossRef](#)]
32. Besson, U.; Borghi, L.; De Ambrosis, A.; Mascheretti, P. A Three-Dimensional Approach and Open Source Structure for the Design and Experimentation of Teaching–Learning Sequences: The case of friction. *Int. J. Sci. Educ.* **2010**, *32*, 1289–1313. [[CrossRef](#)]
33. Pesman, H.; Ari, U.; Cirit, D.K.; Ayazgok, B. Effect of Amount of Guidance in Inquiry-Based Physics Laboratory on Conceptual Understanding and Metacognitive Awareness. *Sci. Educ.* **2024**, *34*, 1–21. [[CrossRef](#)]
34. Holstermann, N.; Grube, D.; Bögeholz, S. Hands-on Activities and Their Influence on Students’ Interest. *Res. Sci. Educ.* **2010**, *40*, 743–757. [[CrossRef](#)]
35. Kampourakis, K. On the Meaning of Concepts in Science Education. *Sci. Educ.* **2018**, *27*, 591–592. [[CrossRef](#)]
36. Girwidz, R.; Theyßen, H.; Widenhorn, R. Experiments in Physics Teaching. In *Physics Education*; Springer International Publishing: Berlin/Heidelberg, Germany, 2022; pp. 269–296. [[CrossRef](#)]
37. Redish, E.F.; Burciaga, J.R. Teaching Physics with the Physics Suite. *Am. J. Phys.* **2004**, *72*, 414–414. [[CrossRef](#)]
38. Kranz, J.; Baur, A.; Möller, A. Learners’ challenges in understanding and performing experiments: A systematic review of the literature. *Stud. Sci. Educ.* **2022**, *59*, 321–367. [[CrossRef](#)]
39. Zimmerman, C. The development of scientific thinking skills in elementary and middle school. *Dev. Rev.* **2007**, *27*, 172–223. [[CrossRef](#)]
40. Brewster, E. Modeling theory applied: Modeling Instruction in introductory physics. *Am. J. Phys.* **2008**, *76*, 1155–1160.
41. Hestenes, D. Toward a modeling theory of physics instruction. *Am. J. Phys.* **1987**, *55*, 440–454.
42. Etkina, E.; Warren, A.; Gentile, M. The Role of Models in Physics Instruction. *Phys. Teach.* **2005**, *44*, 34–39.
43. Zwickl, B.M.; Finkelstein, N.; Lewandowski, H.J. The process of transforming an advanced lab course: Goals, curriculum, and assessments. *Am. J. Phys.* **2012**, *81*, 63–70.
44. Wilcox, B.R.; Lewandowski, H.J. Open-ended versus guided laboratory activities: Impact on students’ beliefs about experimental physics. *Phys. Rev. Phys. Educ. Res.* **2016**, *12*, 020132.
45. Monteiro, M.; Martí, A.C. Resource Letter MDS-1: Mobile devices and sensors for physics teaching. *Am. J. Phys.* **2022**, *90*, 328–343. [[CrossRef](#)]
46. PhET. 2025. Available online: <https://phet.colorado.edu/> (accessed on 28 February 2025).
47. Wieman, C.E.; Adams, W.K.; Loeblein, P.; Perkins, K.K. Teaching Physics Using PhET Simulations. *Phys. Teach.* **2010**, *48*, 225–227.
48. Houghton, J. *Global Warming: The Complete Briefing*, 5th ed.; Cambridge University Press: West Nyack, NY, USA, 2015.
49. Edwards, P.N. History of climate modeling. *WIREs Clim. Chang.* **2010**, *2*, 128–139. [[CrossRef](#)]
50. Krauss, L.M. *The Physics of Climate Change*; Head of Zeus: London, UK, 2024.
51. Fourier, J. Mémoire sur les températures du globe terrestre et des espaces planétaires. *Mémoires L’académie R. Sci. L’institut Fr.* **1827**, *7*, 570–604.
52. Tyndall, J. On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction. *Philos. Trans. R. Soc. Lond.* **1861**, *151*, 1–36.
53. Arrhenius, S. XXXI. On the influence of carbonic acid in the air upon the temperature of the ground. *Lond. Edinb. Dublin Philos. Mag. J. Sci.* **1896**, *41*, 237–276.
54. Manabe, S.; Wetherald, R.T. Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity. *J. Atmos. Sci.* **1967**, *24*, 241–259.
55. Stocker, T. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: New York, NY, USA, 2014.
56. Toffaletti, S.; Di Mauro, M.; Malgieri, M.; Rosi, T.; Tufino, E.; Onorato, P.; Oss, S. A teaching–learning sequence about climate change: From theory to practice. *Am. J. Phys.* **2023**, *91*, 676–684.
57. Onorato, P.; Malgieri, M.; Ambrosis, A.D. Measuring the hydrogen Balmer series and Rydberg’s constant with a homemade spectrophotometer. *Eur. J. Phys.* **2015**, *36*, 058001. [[CrossRef](#)]
58. Rosi, T.; Malgieri, M.; Onorato, P.; Oss, S. What are we looking at when we say magenta? Quantitative measurements of RGB and CMYK colours with a homemade spectrophotometer. *Eur. J. Phys.* **2016**, *37*, 065301. [[CrossRef](#)]
59. Haglund, J. *Thermal Cameras in Science Education*; Number v.26 in Innovations in Science Education and Technology Series; Springer International Publishing: Cham, Switzerland, 2022; ISSN 2213-2236. [[CrossRef](#)]
60. Vollmer, M.; Möllmann, K.P. *Infrared Thermal Imaging: Fundamentals, Research and Applications*, 2nd ed.; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2018. [[CrossRef](#)]
61. Cheron. *Transferts Thermiques: Résumé de Cours, problèmes Corrigés*; Ellipses Marketing: Paris, France, 1999.
62. PASCO. 2025. Available online: <https://www.pasco.com/> (accessed on 28 February 2025).

63. de Izarra, C.; Gitton, J.M. Calibration and temperature profile of a tungsten filament lamp. *Eur. J. Phys.* **2010**, *31*, 933–942.
64. Onorato, P.; Rosi, T.; Tufino, E.; Caprara, C.; Malgieri, M. Quantitative experiments in a distance lab: Studying blackbody radiation with a smartphone. *Eur. J. Phys.* **2021**, *42*, 045103. [[CrossRef](#)]
65. Pathare, S.; Lahane, R.; Sawant, S.; Patil, C. Power loss from hot tungsten filament. *Phys. Educ.* **2010**, *27*, 15.
66. Prasad, B.S.N.; Mascarenhas, R. A laboratory experiment on the application of Stefan's law to tungsten filament electric lamps. *Am. J. Phys.* **1978**, *46*, 420–423.
67. Deiber, A.; Kempf, O. Lampe à incandescence, corps noir, loi de Stefan et filtre passe-bas thermique. *Bull. Union Phys.* **2000**, *827*, 1595–1624. (In French)
68. Durand, F. Étude d'une lampe a incandescence. *Bull. Union Phys.* **2000**, *94*, 1625–1633.
69. Bouquet, F.; Dauphin, C.; Bernard, F.; Bobroff, J. Low-cost experiments with everyday objects for homework assignments. *Phys. Educ.* **2019**, *54*, 025001.
70. Vieyra Software. Physics Toolbox. 2024. Available online: <https://www.vieyrasoftware.net/physics-toolbox-sensor-suite> (accessed on 28 February 2025).
71. Shepardson, D.P.; Niyogi, D.; Choi, S.; Charusombat, U. Seventh grade students' conceptions of global warming and climate change. *Environ. Educ. Res.* **2009**, *15*, 549–570. [[CrossRef](#)]
72. Cook, J. Cranky Uncle Game. Melbourne Centre for Behaviour Change, University of Melbourne. 2025. Available online: <https://crankyuncle.com/> (accessed on 28 February 2025).
73. Center for Countering Digital Hate. The New Climate Denial 2024. 2024. Available online: <https://counterhate.com/research/new-climate-denial/> (accessed on 28 February 2025).
74. Climate Interactive. En-ROADS. 2025. Available online: <https://www.climateinteractive.org/en-roads> (accessed on 28 February 2025).
75. Davide Faranda, Lucas Taligrot, N.C.A.T.F.R.R.C.P.C. ClimarisQ. 2025. Available online: <https://climarisq.ipsl.fr/en/le-jeu/> (accessed on 28 February 2025).
76. Chi, M.T.H.; Roscoe, R.D.; Slotta, J.D.; Roy, M.; Chase, C.C. Misconceived Causal Explanations for Emergent Processes. *Cogn. Sci.* **2011**, *36*, 1–61. [[CrossRef](#)]
77. Jin, H.; Wei, X. Using Ideas from the History of Science and Linguistics to Develop a Learning Progression for Energy in Socio-ecological Systems. In *Teaching and Learning of Energy in K–12 Education*; Springer International Publishing: Berlin/Heidelberg, Germany, 2014; pp. 157–173. [[CrossRef](#)]
78. Lombrozo, T.; Carey, S. Functional explanation and the function of explanation. *Cognition* **2006**, *99*, 167–204. [[CrossRef](#)] [[PubMed](#)]
79. Jin, H.; Anderson, C.W. A learning progression for energy in socio-ecological systems. *J. Res. Sci. Teach.* **2012**, *49*, 1149–1180. [[CrossRef](#)]
80. Mohan, L.; Chen, J.; Anderson, C.W. Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *J. Res. Sci. Teach.* **2009**, *46*, 675–698. [[CrossRef](#)]
81. Rönnebeck, S.; Bernholt, S.; Ropohl, M. Searching for a common ground—A literature review of empirical research on scientific inquiry activities. *Stud. Sci. Educ.* **2016**, *52*, 161–197. [[CrossRef](#)]
82. Fischer, H.; Fleming, S. Why metacognition matters in politically contested domains. *Trends Cogn. Sci.* **2024**, *28*, 783–785. [[CrossRef](#)]
83. Osborne, J. Teaching Scientific Practices: Meeting the Challenge of Change. *J. Sci. Teach. Educ.* **2014**, *25*, 177–196. [[CrossRef](#)]
84. *PISA 2018 Assessment and Analytical Framework*; OECD: Paris, France, 2019. [[CrossRef](#)]
85. Roberts, R.; Gott, R.; Glaesser, J. Students' approaches to open-ended science investigation: The importance of substantive and procedural understanding. *Res. Pap. Educ.* **2010**, *25*, 377–407. [[CrossRef](#)]
86. Pedaste, M.; Mäeots, M.; Siiman, L.A.; de Jong, T.; van Riesen, S.A.; Kamp, E.T.; Manoli, C.C.; Zacharia, Z.C.; Tsourlidaki, E. Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educ. Res. Rev.* **2015**, *14*, 47–61. [[CrossRef](#)]
87. Lozano, R. Envisioning sustainability three-dimensionally. *J. Clean. Prod.* **2008**, *16*, 1838–1846. [[CrossRef](#)]
88. Kassel, K.; Rimanczy, I.; Mitchell, S.F. The Sustainable Mindset: Connecting Being, Thinking, and Doing in Management Education. *Acad. Manag. Proc.* **2016**, *2016*, 16659. [[CrossRef](#)]
89. Kusumojanto, D.D.; Wibowo, A.; Kustiandi, J.; Narmaditya, B.S. Do entrepreneurship education and environment promote students' entrepreneurial intention? The role of entrepreneurial attitude. *Cogent Educ.* **2021**, *8*, 1–17. [[CrossRef](#)]
90. Anâker, A.; Spante, M.; Elf, M. Nursing students' perception of climate change and sustainability actions—A mismatched discourse: A qualitative, descriptive exploratory study. *Nurse Educ. Today* **2021**, *105*, 105028. [[CrossRef](#)]
91. Lorenzoni, I.; Nicholson-Cole, S.; Whitmarsh, L. Barriers perceived to engaging with climate change among the UK public and their policy implications. *Glob. Environ. Chang.* **2007**, *17*, 445–459. [[CrossRef](#)]
92. Whitmarsh, L.; O'Neill, S.; Lorenzoni, I. Public engagement with climate change: What do we know and where do we go from here? *Int. J. Media Cult. Politics* **2013**, *9*, 7–25. [[CrossRef](#)] [[PubMed](#)]

93. Kumpu, V. What is Public Engagement and How Does it Help to Address Climate Change? A Review of Climate Communication Research. *Environ. Commun.* **2022**, *16*, 304–316. [[CrossRef](#)]
94. Guigon, V.; Villeval, M.C.; Dreher, J.C. Metacognition biases information seeking in assessing ambiguous news. *Commun. Psychol.* **2024**, *2*, 122. [[CrossRef](#)] [[PubMed](#)]
95. Stern, P.C.; Kalof, L.; Dietz, T.; Guagnano, G.A. Values, Beliefs, and Proenvironmental Action: Attitude Formation Toward Emergent Attitude Objects1. *J. Appl. Soc. Psychol.* **1995**, *25*, 1611–1636. [[CrossRef](#)]
96. Bamberg, S.; Rees, J.; Seebauer, S. Collective climate action: Determinants of participation intention in community-based pro-environmental initiatives. *J. Environ. Psychol.* **2015**, *43*, 155–165.
97. Kormos, C.; Gifford, R. The validity of self-report measures of proenvironmental behavior: A meta-analytic review. *J. Environ. Psychol.* **2014**, *40*, 359–371. [[CrossRef](#)]
98. Ockwell, D.; Whitmarsh, L.; O'Neill, S. Reorienting Climate Change Communication for Effective Mitigation: Forcing People to be Green or Fostering Grass-Roots Engagement? *Sci. Commun.* **2009**, *30*, 305–327. [[CrossRef](#)]

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