education sciences

MDPI

Article

Guiding Students towards an Understanding of Climate Change through a Teaching–Learning Sequence

Stefano Toffaletti [1], Marco Di Mauro [1,*], Tommaso Rosi [1], Massimiliano Malgieri [2] and Pasquale Onorato [1]

[1] Physical Science Communication Laboratory, Department of Physics, University of Trento, 38123 Povo, TN, Italy
[2] Department of Physics, University of Pavia, 27100 Pavia, PV, Italy
* Correspondence: marco.dimauro@unitn.it

Abstract: In this paper, we put forward a proposal for the design and the evaluation of teaching–learning sequences (TLSs) on the greenhouse effect (GHE), relying on the educational reconstruction model (MER). The first design, which starts from a critical analysis of textbook treatments of the GHE, is followed by a cyclic, recursive process, which consists of theoretical reflection, conceptual analysis, design, and test of a sequence. At each iteration, the analysis of the students' learning progression provided relevant information for addressing the persistent hurdles and misunderstandings that affect it. Our findings show how design choices can support the learning of the GHE, leading to the formulation of design principles that help foster understanding. The iterative approach strongly improved the design and evaluation and allowed for a significant refinement of the TLSs. The implementation and evaluation process, which went on from 2017 to 2021, involved undergraduate students attending a course on "experimental physics laboratory" at the University of Trento in those years. The results indicate that, in the end, students can reach an effective understanding of the physical grounds of the GHE.

Keywords: civic scientific literacy; greenhouse effect (GHE); global warming

check for updates

Citation: 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. https://doi.org/10.3390/educsci12110759

Academic Editor: Silvija Markic

Received: 28 September 2022
Accepted: 26 October 2022
Published: 28 October 2022

1. Introduction

It is difficult to underestimate the impact of science and technology on modern society, especially from the twentieth century on. Despite this, the average citizen seems to be painfully unaware of the scientific developments that play such an important role in his life. Already in 1963 (but the following remark is even more valid today), the great physicist and teacher Richard P. Feynman [1] complained that his age was still a fundamentally unscientific one, notwithstanding the huge scientific and technological progress. This unpleasant fact is made worrisome by the observation that many people seem to be completely oblivious of the impact of their presence and of their behaviour on the environment, while the issue of human-induced climate change is becoming more and more pressing. A consistent part of the population is even doubting the existence of the issue (in part because of the existence of a small minority of sceptic scientists, whose weight is however somewhat magnified by media) [2], despite its effects on the climate are becoming plainly visible, with the global increase in temperature and the increasing frequency of extreme events. A related, also concerning issue, is the basic lack of understanding of the working of the scientific method, which has the consequence that many people do not trust science and scientists, as made recently blatant by the ongoing COVID-19 pandemic. In the case of Italy, for example, a recent report evidenced how the unscientific attitude of the population is not a marginal phenomenon [3].

Considering this situation, it is clearly imperative to increase the scientific literacy of citizens, emphasizing socially relevant topics such as climate change. In the case of Italy, the recent introduction (in 2019) of a transversal curriculum in civic education in

high schools offers a good chance of including such topics in the cultural experience of future citizens. This curriculum is in fact conceived in such a way that all subjects must contribute, including scientific ones, thus bringing in the idea of Scientific Civic Education (SCE). The themes of global warming and climate change, which are already by themselves quite interdisciplinary, involving topics from physics to Earth sciences, but also sociology and economy, are in our view particularly suitable for such a curriculum.

In this work, we present our results on a teaching–learning sequence (TLS) that has been developed over the last decade in various Italian universities. The focus is on the physical aspects of the greenhouse effect (GHE) that underlie the current climate change and are simple enough to be proposed to advanced high school students. Both the original and the redesigned versions of the TLS are described, and the results of the redesigned versions, obtained from 2017, are shown and discussed.

The paper is organized as follows. In Section 2, we describe the methodological frameworks that underlie the TLS. In Section 3, we detail the content of the TLS, also describing how its implementation evolved over time as a response to the results obtained in previous incarnations. The results that have been obtained are summarized in Section 4, while Section 5 is devoted to our conclusions.

2. Frameworks (Materials and Methods)

For the design of the TLS, we combine two frameworks, one of which is theoretical, while the other is methodological. The theoretical framework is the so-called model of educational reconstruction (MER) [4] that allows us to identify key concepts, and learning resources and guides throughout design and evaluation of the learning sequences. Let us describe the framework in more detail.

2.1. Model of Education Reconstruction

The MER framework builds on a fundamental idea, namely that there is a close connection between the following three basic aspects. The first aspect is the analysis of the scientific content of the topic to be taught, together with the identification of its key concepts. The second aspect is the consideration of both the students' and the teachers' perspectives, to understand the students' learning processes. The third aspect consists of the design and subsequent evaluation of the teaching–learning activities and environments. A partial selection of instances of new topics that have been tackled with this model is [5–9] and especially [10], which treats climate change.

The MER is not merely a model for initial educational design, but since it focuses on improving real classroom practices, it is based on an iterative structure [4] in which theoretical and classroom research are in a constant dialogical relationship. Therefore, it can be best described as a cyclical, recursive process consisting of theoretical reflection; conceptual analysis, design, and test of a sequence (initially at a small, then progressively larger, scale); classroom research on the real-life interaction of teaching and learning processes and on educational outcomes; and then restart of the cycle with new research results as inputs for a re-design and re-implementation.

2.2. Aims and Research Questions

The aim of our work is to describe the TLS on global warming and to analyse the results we obtained so far to answer the following questions:

- RQ1: Are textbook treatments of the GHE and the accompanying illustrations consistent with the scientific model of the GHE and effective in sustaining student's learning, or are there specific widespread issues with textbooks the risk to elicit misconceptions and alternative models?
- RQ2: How, in the over 15 years that elapsed from the zero version of the TLS on the GHE, did different factors such as analysis of educational outcomes, observation of classroom interactions, progress of related educational research, technical progress,

and widespread availability of the new technologies have an impact in the re-design and evolution of the sequence?

- RQ3: To what extent does the iterative approach improve the design, evaluation, and refinement of TLSs?

3. Educational Reconstruction of Greenhouse Effect

The sequence has been designed and re-designed starting from the analysis of a pre-existing sequence that was proposed and tested in schools by several Italian research groups over the last decade [11–13].

3.1. Key Concepts of Greenhouse Effect

A sound understanding of the greenhouse effect rests on several key physical concepts, which are interconnected in a rather complex and subtle way. In fact, an analysis of school textbooks on various subjects (i.e., physics, chemistry, and earth sciences) performed some years ago [13] shows that they do not always do justice to the complexity of the theme, resulting sometimes in partial, unsatisfactory, and even potentially misleading explanations, often accompanied by equally misleading pictorial representations.

Some of the most important criticalities have been found in an improper emphasis on the fact that the most relevant phenomena that are involved in the greenhouse effect are radiative heat transfer and the thermal equilibrium of the atmosphere of the Earth. Sometimes, quick explanations tended to mix up the concepts of heat and of radiation.

Other important criticalities are surely found in the difficulty to understand that the occurrence or not of the phenomena of transparency and of absorption depends on the wavelength of the radiation that impinges on the air molecules, i.e., such phenomena are selective. This is relevant since the Earth and the atmosphere emit radiation in different regions of the electromagnetic spectrum. In fact, taking this aspect into account is crucial to construct a mental model of thermal exchange between the various parts of the system.

To sum up, the key concepts underlying the GHE (which were also evidenced by previous research) are those reported in Table 1.

Table 1. Physical key concepts of greenhouse effect [14].

Conceptual Areas		Sub-Areas	
1.	Heat and temperature	a. b. c.	Heat and temperature Heat propagation Microscopic interpretation
2.	Electromagnetic spectrum, the black body	a. b. c.	Energy of the bands of the spectrum Stefan-Boltzmann law Wien's law
3.	Matter-radiation interaction	a. b. c. d. e. f. g. h.	Reflection Refraction Absorption Scattering (elastic and anelastic) Selective transparency Effects of the concentration Selective transparency and IR radiation Microscopic model
4.	Objects exposed to radiation, stationary state, and energy balance	a. b. c.	Radiative equilibrium Stationary states Black and grey bodies: emissivity and absorbance

Table 1. *Cont.*

Conceptual Areas		Sub-Areas	
5.	Energy balance of earth and the GHE	a. b. c. d.	Properties of greenhouse gases Albedo Feedback Construction of models for the global average temperature
6.	Global Warming Analysis	a. b.	Effects of feedback variations Climate, pollution, and extreme meteorological events

Moreover, some textbooks even missed the point that it is not the greenhouse effect itself that is of concern (it is in fact a natural phenomenon, thanks to which the temperature on Earth is high enough for life to evolve) but rather the increase in the equilibrium temperature of the atmosphere due to the increase in greenhouse gases because of human activity. The explanations in some textbooks also seemed to propagate the common misconception that the atmosphere would not release heat in outer space at all, which would result in a continuous increase in the temperature, without ever reaching thermal equilibrium.

3.1.1. Physical Analysis of the Phenomenon

The first aspect to consider in the development of a TLS on the GHE is the fact that the physical system to be considered is complex and, therefore, to be fully understood, it requires acquaintance with other subjects besides physics, in particular with climatology.

Indeed, here, we find the first studies on the anthropic GHE (AGHE), by Manabe and Strickler [15], who developed the first simplified model on the Earth–atmosphere–Sun system (Radiative Convective Equilibrium model—RCE), which considers the role played by greenhouse gases in the selectivity of interaction phenomena of radiation with the atmosphere.

More recent studies on the energy budget [16] lead to the development of a simplified three-parameter model [17], which was used as the basis of the treatment of climatology in this TLS.

3.1.2. Textbook Analysis

Another important aspect that must be investigated is the role played by textbooks in the students' learning process. We analysed ten Italian school textbooks (three technology and science books for the middle school, three geography books for the high school, and four Earth science books for the high school). Concerning the methodology, we developed the procedure shown in Figure 1, starting from the literature and then adding the peculiar features of our research.

The procedure involves two kinds of analysis of the text: that of contents and that of misconceptions.

Concerning the contents, we perform a conceptual analysis, using the control list method proposed by Ibañez and Ramos [18], with reference to the key concepts about GHE shown in Table 1.; we consider three aspects:

1. Language, examining the definitions, and how they are introduced [19];
2. Pictures, using a semiotic-based theoretical framework [20,21];
3. Explanation, checking their logical completeness, according to the proposal of Viennot and Decamp [20].

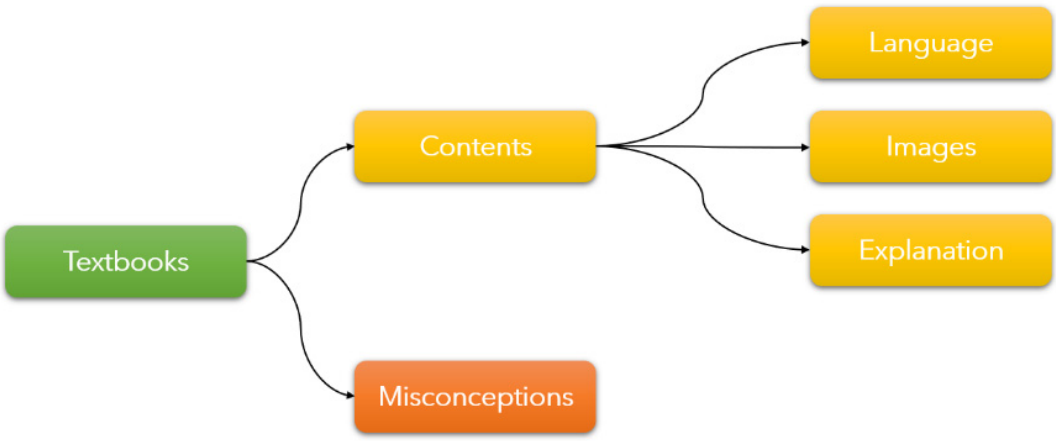


Figure 1. Textbook analysis procedure.

For what concerns misconceptions, we considered the methodology proposed by Choi [22], tracing, for every misconception we found in the literature, the corresponding scientific concept.

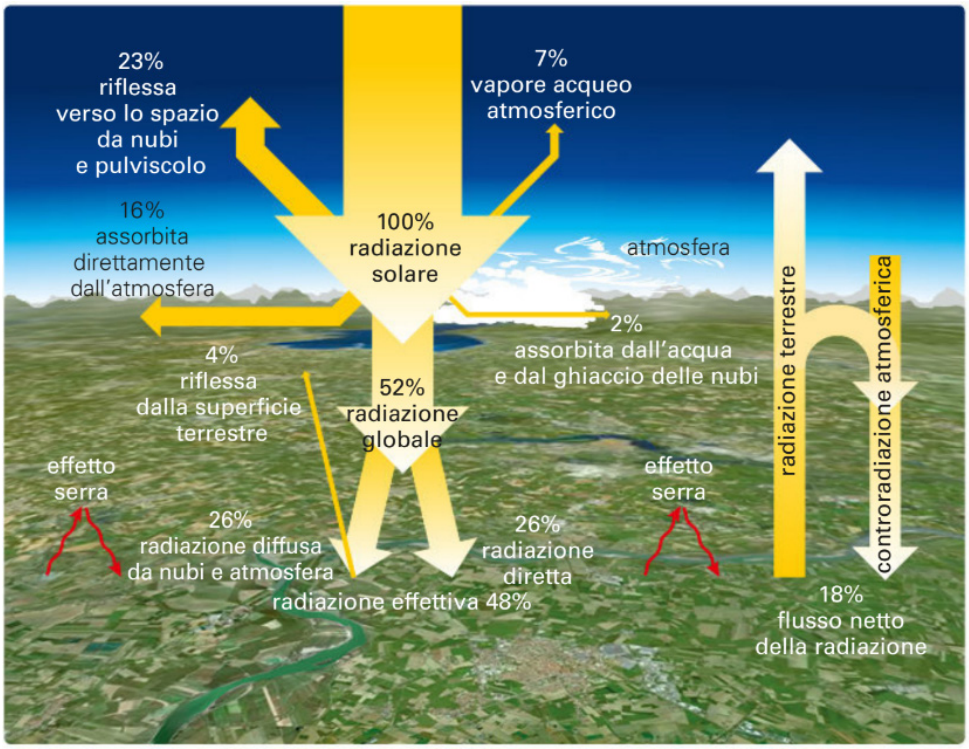
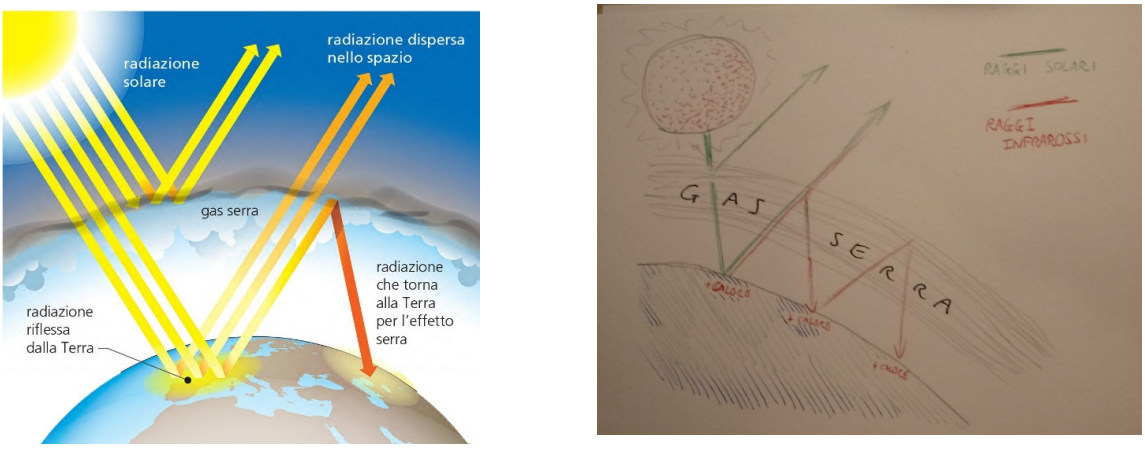


Figure 2. Thermal balance of the Earth–atmosphere system (reproduced with permission from Ref. [23] 2016 Mondadori Editore). The Italian captions can be translated as follows. Radiazione solare = solar radiation; radiazione globale = global radiation; radiazione effettiva = effective radiation; riflessa verso lo spazio da nubi e pulviscolo = reflected towards outer space by clouds and dust; assorbita direttamente dall'atmosfera = absorbed directly by the atmosphere: riflessa dalla superficie terrestre = reflected by Earth's surface; effetto serra = greenhouse effect; radiazione diffusa da nubi e atmosfera = radiation scattered by clouds and atmosphere; vapore acqueo atmosferico = atmospheric water vapor; assorbita dall'acqua e dal ghiaccio delle nubi = absorbed by water and ice in clouds; radiazione diretta = direct radiation; radiazione terrestre = Earth's radiation; controradiazione atmosferica = atmosphere's counter-radiation; flusso netto di radiazione = net flux of radiation.

As an example, let us consider Figure 2, which is taken from a high school science textbook. In it, the thermal balance of the Earth–atmosphere system is depicted. By analysing it with the procedure described above, we can draw some interesting considerations:

- The picture includes both real world elements and schematic and symbolic entities;
- Some elements present polysemy of the symbols: yellow arrows represent incoming, outgoing, absorbed, and reflected radiation; nevertheless, arrows of different sizes represent different entities;
- Some elements (the red arrows under the caption "effetto serra") reinforce the misconceptions of trapping and of multiple reflection [24];
- The arrows on the left represent, through their thickness, the different parts of the incoming radiation that are absorbed, reflected, or transmitted by the various parts of the system, in such a way as to enlighten the various phenomena that involve this radiation. However, other elements (we refer to the arrows on the right, which all have the same thickness) could be interpreted as hinting that outgoing radiation undergoes total reflection, or total transmission, and this could strengthen the misconceptions on the radiative balance of the Earth–atmosphere–sun system. Moreover, the different thicknesses of the incoming arrows, with respect to the outgoing ones, create the impression that the Earth absorbs much more radiation than it emits, thus nourishing misconceptions about the energy balance and the radiative equilibrium: from this point of view, the captions use non-standard terminology, which contributes to clarify what we just highlighted.

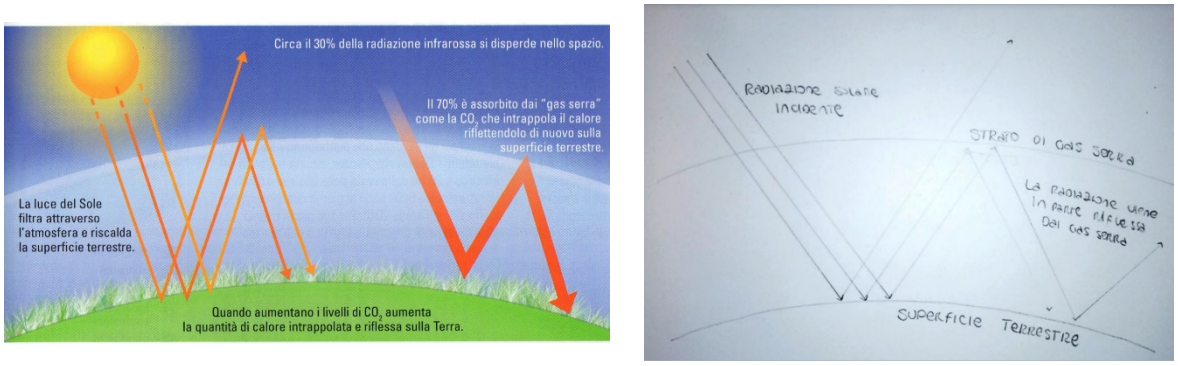
An interesting aspect that emerged from this analysis, which had already been observed in this context [25,26], is that even advanced students (high school and undergraduate) keep the imprinting of possible misconceptions that they took from elementary or middle school textbooks. Indeed, in our analysis we noticed clear analogies between the drawings produced by the students attending the university course where the TLS was proposed and the pictures we found in the analysed textbooks. For example, Figure 3 gives the misconception that greenhouse gases form a well-defined and limited layer in the atmosphere.



(**a**) (**b**)

Figure 3. Misconception of the greenhouse gas layer: (**a**) in a technology textbook for the middle school (reproduced with permission from Ref. [27]. 2014. Zanichelli Editore S.p.A.) and (**b**) in a drawing produced by a university student in the TLS pre-test. The Italian captions can be translated as follows. (**a**). radiazione solare = solar radiation; radiazione dispersa nello spazio = radiation scattered towards outer space; gas serra = greenhouse gases; radiazione riflessa dalla terra = radiation reflected by the Earth; radiazione che torna alla Terra per l'effetto serra = radiation coming back to Earth due to the greenhouse effect. (**b**). Raggi solari = solar radiation; raggi infrarossi = infrared radiation; gas serra = greenhouse gases; calore = heat.

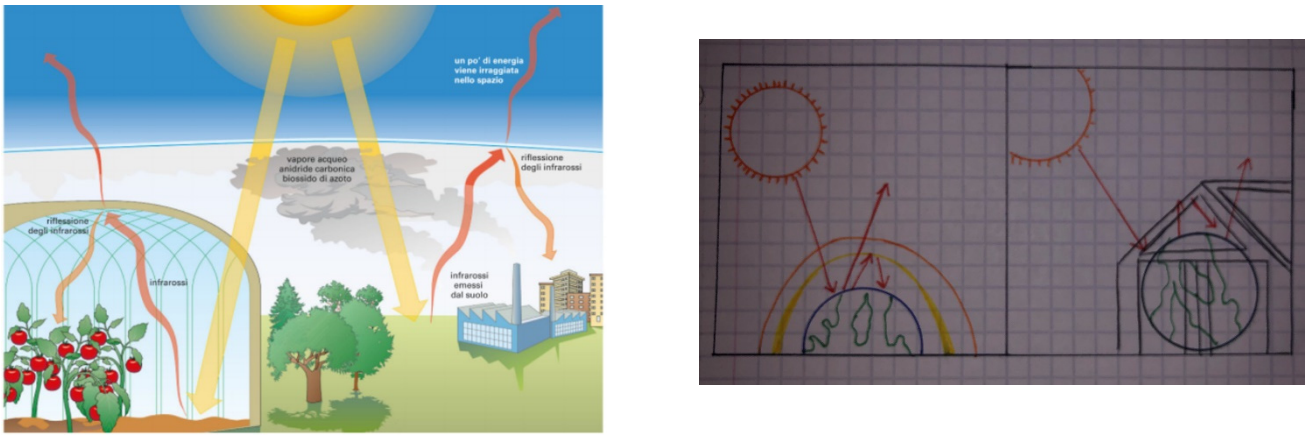
Another frequent misconception is that reported in Figure 4, about the multiple reflection of "rays coming from the sun" and the lack of distinction between the wavelengths of the incoming and of the outgoing radiation.



(**a**) (**b**)

Figure 4. Misconception of the multiple reflections: (**a**) in a technology textbook for the middle school (reproduced with permission from Ref. [28]. 2014, Mondadori Education S.p.A.) and (**b**) in the answer by a university student to the TLS pre-test.

Finally, in Figure 5, we report an example of the inadequate analogy [29,30] of using an actual greenhouse for picturing the natural GHE.



(**a**) (**b**)

Figure 5. Inappropriate analogy [29,30] of the comparison with an actual greenhouse (**a**) in a technology textbook for the middle school (reproduced with permission from Ref. [31]. 2014, Mondadori Education S.p.A.) and (**b**) in the answer by a university student to the TLS pre-test.

3.2. Student Perspectives on Greenhouse Effect

3.2.1. Significance of the Subject Matter for Students

One of the most important aspects to consider in the analysis of the subject matter from the point of view of the student is the significance of the topic within the curriculum of students and for their education in general [4]. First of all, as mentioned in the Introduction, the topic of GHE combines disciplinary aspects with those related to environmental awareness and active citizenship, whose importance cannot be underestimated. It is essential that students are provided with the cultural and scientific instruments necessary to be constantly confident of the soundness and consistency of the scientific analysis of global warming and to be able to effectively counter negationist argumentations. This issue has reflexes on the educational design, in the sense that in emphasizes the problem of elementarization [4] with the search for the most fundamental elements of the phenomenon of greenhouse effect,

which, on the one hand, cannot be overlooked by any scientific model and, on the other, should be clearly completely and completely understandable by students. This was also one of the reasons that led us to follow a strategy of progressive construction, introducing first a basic model of the phenomenon containing only the essential features [15], and then more refined and complete ones [17].

A second aspect to consider is 'longitudinal' [32] knowledge integration. The GHE is a topic that connects two areas of the physics curriculum that are often treated (and viewed by students) as disconnected: the theory of light and thermodynamics. The concept that more than any others serve as a bridge between these areas of physics is, of course, energy. Thus, a sequence on GHE can become an important context for emphasizing the unity and coherence of physics and taking steps forwards in the progressive construction of the far-reaching and unifying concept of energy.

3.2.2. Student Difficulties on Greenhouse Effect according to Research Literature

In the last twenty years, several studies focused on the understanding of the greenhouse effect and of global warming by students at different levels [24,33–36]. The results show that this is a topic that is still not well-known and, moreover, that students at all levels and ages have misconceptions. This issue was also investigated in the first implementation of the sequence, which we shall dub the "zero" version, highlighting several of these misconceptions. Most notably, student lack a proper understanding of heat transfer by IR radiative emission and of the wavelength dependence of optical properties and cannot distinguish between transients and stationary processes. Moreover, they have problems with considering the interdependence of all involved phenomena. More information can be gained from concept inventories involving large numbers of students. For example, from Keller [37], we learn that many students think that the GHS is due to an increase in incoming solar radiation and to a decrease in outgoing energy flux, related also to the idea that radiation is in some way trapped by the atmosphere. Additionally, they tend to mix up global warming with ozone depletion and that the sun emits mostly UV. More general studies [38,39] show that students have difficulties in the identification of greenhouse gases and in understanding physical concepts such as blackbody radiation, energy balances, and the interaction between radiation and the atmosphere.

3.3. Design and Development of the Teaching–Learning Sequence

Let us now switch to the description of the TLS. We start by describing the zero version, and then, we discuss the variations and improvement that were implemented in the subsequent realizations.

The introduction of such a complex theme requires a progressive conceptual construction, built from several steps, crucially involving experimental activity at each step. Starting from the recognition that radiative transfer phenomena and radiative thermal equilibrium are the main culprits as far as the energy balance of Earth is concerned (unlike what happens in an actual greenhouse), the main thread of the TLS consists of a redefinition of the ways in which thermal and optical phenomena are usually treated in class, giving space to important but often neglected aspects such as matter-radiation interaction and thermal emission, and emphasizing their connection, and giving a central role to energy concepts.

3.3.1. Zero Version

The TLS, in its first incarnation, started by introducing or recalling some preliminary topics, which were waves on the one hand, and thermal phenomena on the other hand. While for the wave part, it was sufficient to recall and build on topics that had often already been treated in class, with emphasis on transparency, the second topic had to be developed at variance with the usual approach. Upon identifying five crucial cognitive steps, the zero version involved five experimental activities:

1. The first step involves investigating the concepts of energy balance and radiative equilibrium for objects which are exposed to radiation. This is carried out by measuring

the time evolution of temperature of metal cylinders of different colours, exposed either to solar radiation or to a table lamp.

2. It is important for the students to distinguish between the two concepts of heat and radiation [11], while understanding that hot objects emit thermal radiation. Therefore, the activity involved measurements of the IR radiation emitted by bodies at different temperatures with a radiometer.
3. IR radiation must be distinguished from visible radiation, as must the behaviours of a material interacting with different kind of radiation. In fact, it turns out that typically high school students do not know how the matter–radiation interaction depends on the frequency of the radiation. For this, a qualitative experiment involving the vision of IR radiation emitted by a remote control by means of a digital camera was conceived; moreover, it was shown how materials that are transparent to visible light can be opaque to the IR and vice versa.
4. The abovementioned pieces must then be put together to understand that the GHE is radiative in nature. This involves a qualitative analysis of the spectrum of radiation.
5. The GHE and the subsequent global warming can finally be understood by means of a model of energy fluxes. For this, the model of an actual greenhouse can be studied.
6. The results obtained with high school students [40] show a strong decrease in the number of students explaining the GHE with thermal isolation only, while the number of students using the fact that absorption and emission are different for visible light and the IR increased. However, the latter increase was only of about 50%. Thus, in the subsequent redesign of the sequence, some of the cognitive steps were detailed with more care.

3.3.2. Version One

Version 1 was proposed in the academic years 2017–2018 and 2018–2019 and was characterized by a greater emphasis on the experimental aspects. The sequence was divided in conceptual areas and sub-areas, each of which was the focus of some activity and experiment based. Some of the proposed experiments were quantitative, involving detailed data analysis. Additionally, the TLS is supplemented by several simulations, e.g., PhET [41]. Simulations were used to discuss the microscopic aspect of light–matter interaction, which is of course outside the scope of feasible experiments. Compared with the previous version, version 1 involved simpler and cheaper instrumentation, with the aim of meeting the constraints of a typical high school laboratory. This included a massive use of the sensors provided by common smartphones, in a BYOD (Bring Your Own Device) perspective, and an IR camera, in place of the radiometer. Finally, every step was based on the Predict-Observe-Explain (POE) strategy [42]: students were requested to make predictions or to explain their ideas on a given phenomenon; then, experiments were performed and interpreted, comparing the predictions with the observations and with data, when available.

Having realized that several conceptual nodes of the greenhouse effect revolve around the basic issue of absorption and reemission of radiation, the first part of the TLS revolved around a central experiment, which concerned Beer's law [43]. Additionally, a common thread through the whole TLS was constituted by energy conservation: new conceptual steps were motivated by apparent violations of this principle, as evidenced by experiments.

The first experiment was performed by using a tray filled with water and soap, as a playground in which all the main optical phenomena, namely reflection, refraction, absorption, and diffusion were observed. Then, Beer's law was investigated in a similar setting, in which a beaker was used, and in which soap was gradually poured into water. The quantity of light that passed through was measured using a smartphone. By considering light of different colours, the idea that absorption is wavelength-dependent was introduced. The investigation of Beer's law was finally completed by the PhET simulation "Beer's law".

The second experiment started from the observation that Beer's law involves an apparent violation of the principle of energy conservation. This conundrum is resolved by

switching to the microscopic point of view on light–matter interaction, with the appropriate PhET simulation, "Molecules and Light". This led to two experiments on elastic and anelastic diffusion, using milk dissolved in water and fluorescence, respectively. The aim of these experiments was to explain the energy loss as due to scattered light and to an increase in the temperature of the medium. The latter hypothesis was validated by a further experiment, where the temperature of a dark object put under a lamp was measured. This experiment was quite crucial, since it allowed us to include several important physical ingredients of the GHE: albedo, radiative transfer, and equilibrium temperature in the presence of radiative transfer. To complete the first part of the TLS, black-body radiation was investigated. In particular, the Stefan–Boltzmann law was tackled with an experiment involving a Leslie cube, while the Wien displacement law was studied by the PhET simulation "Blackbody radiation".

The second part of the TLS consisted in the construction of a model for the Earth's climate. A first, provisional model paralleled the experiment with a dark body under a lamp, with the Earth playing the role of the body and the Sun playing the role of the lamp. The nit is showing how this model is not correct, since the prevision it makes for the equilibrium temperature is not compatible with the measured average temperature of the Earth. This was the starting point for building a more elaborate model, also involving the atmosphere and the GHE, which allows for a much better quantitative prediction for the temperature. The TLS was completed with the PhET simulation on the GHE.

3.3.3. Upgraded Version (Version 1b)

The results obtained after implementing version 1, as reported in the next section, revealed that students still had difficulties with selective transparency, which could be traced back to the fact that they are not familiar with the electromagnetic spectrum. Moreover, some problems persisted with the concepts of heat and radiation, which continued to be confused by many students. These issues were tackled by redesigning the sequence, adding specific activities involving these concepts. This new upgraded version has been proposed since the academic year 2020–2021. The results, discussed in the next section, showed remarkable improvements.

4. Results

In this section, the results of an assessment questionnaire, given to the students at the end of the sequence, will be briefly illustrated.

As explained in the previous section, between the two-year periods 2017–2018 and 2020–2021, changes were made to the sequence to achieve a better comprehension of the physical basis of the greenhouse effect. In this section, the gain in the conceptual areas involved in that re-designing will be shown.

Table 2 shows the cohorts of students enrolled in the trials, divided according to the academic year during which they attended the class.

Table 2. Cohort composition and version of sequence attended.

Academic Year	Version of Sequence	Number of Attendees
2017–2018	Version one	22
2018–2019	Version one	25
2020–2021	Upgraded version	18
2021–2022	Upgraded version	15

4.1. The Questionnaire and the Evaluation Grid

The questionnaire, developed by the Trento group [14], consists of 11 questions pointed towards the assessment of the greenhouse effect keynotes' understanding, as shown in Table 3. It was submitted to about 80 undergraduate students (divided as shown in Table 2), attending the "experimental physics laboratory" class at the University of Trento, for 4 years (during the following academic years: 2017–2018, 2018–2019, 2020–2021 and 2021–2022).

Table 3. Questions of the final questionnaire given to the undergraduate students.

#	Question	Type
Q1	What do you think about the use of the smartphone in class as a measurement instrument [1]	open-ended
Q2	Write the bands of the electromagnetic spectrum in ascending order of frequency (energy).	open-ended
Q3	What does it mean that a body is transparent?	open-ended
Q4	Which phenomena can be observed in the passage of a ray of light through a container filled with water?	open-ended
Q5	An object, having a certain temperature T, is placed in a vacuum (for example in space). How does its temperature evolve over time?	open-ended
Q6	Select the bands of the electromagnetic spectrum for which the Earth's atmosphere is opaque (i.e., absorbs).	multi-select multiple choice question
Q7	What is the effect of greenhouse gases in the atmosphere?	multiple choice question
Q8	On average, the total amount of energy that leaves the Earth system and goes into space:	multiple choice question
Q9	Which of the following is a characteristic property of greenhouse gases?	multiple choice question
Q10	Choose the diagram that best represents the energy (radiation) balance in the Earth system.	image question
Q11	Regarding the greenhouse effect, the average surface temperature of the Earth mainly depends on:	multiple choice question

[1] This question is not about the physical basis of the GHE and was not covered in this article.

Each question aims to investigate the understanding of a specific concept. Table 4 shows the relative evaluation grids.

Table 4. Evaluation grid of the final questionnaire.

#	Knowledge Assessment
Q2	The electromagnetic spectrum is in the correct order and the visible part is mentioned
Q3	The selectivity of the transparency is considered
Q4	Must mention the four phenomena: reflection, refraction, absorption, and scattering. [1]
Q5	Radiation heat transfer in vacuum.
Q6	Infrared absorption of the Earth's atmosphere
Q7	Increase in the absorption of the atmosphere towards low frequency radiation.
Q8	Radiative equilibrium.
Q9	Selective transparency of the greenhouse gases.
Q10	Energy balance, included the radiation role of the atmosphere.
Q11	Removal of the misconception concerning the greenhouse effect (i.e., trapping, ray multiple-reflection, greenhouse analogy, greenhouse gas layer)

[1] The answers that reported at least the absorption, as it is the main phenomenon for understanding the model, were also considered correct (as reported with the Q4* caption in Figures 6–8).

4.2. Results Analysis

The results analysis is divided into three parts. The first one concerns the overall results of the four years during which the experimentation has been carried out. The second one concerns the results in which performance gains are assessed with respect to comparable questions submitted to students during the sequence but before the related

topic was addressed. The last one concerns the results in which the effectiveness of the changes made to the sequence in version 1b is evaluated.

4.2.1. Overall Results

Figure 6 shows the results for all the questions (from Q2 to Q11) submitted to the 80 students during the four years in which the experimentation was carried out.

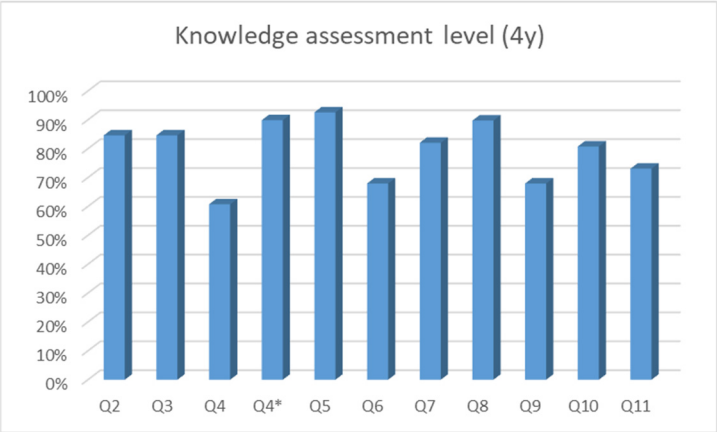


Figure 6. Knowledge assessment level during the 4 years.

From Figure 6, it emerges that nearly all questions obtained at least 80% of answers that are considered correct. The remaining ones, Q4, Q6, and Q9, obtained less than 70%. Therefore, these questions must be analysed more in detail, since they involve concepts that are key to the student's physical understanding of the greenhouse effect but are still critical.

Concerning question Q4, we observe that the phenomenon of diffusion was not mentioned by 32% of the students. This was the main source of errors. However, among the four phenomena indicated on the possible answers, the most important for understanding the greenhouse effect is absorption. To keep track of this, we included the column Q4*, where we considered as correct all answers which mentioned absorption. This made the percentage of correct answers rise to 90%.

As for question Q6, it will be analysed more thoroughly in Section 4.2.3, being related to one of the aspects that were involved in the redesign of the TLS.

Finally, a detailed analysis of question Q9 (shown in Table 5) shows that the students still have some misconceptions and preconceptions, such as the trapping and the multiple reflection of the radiation in the atmosphere.

Table 5. Answers to multiple choices question Q9.

#	Question	%
Q9-R1	They can destroy certain molecules present in the atmosphere.	3%
Q9-R2	They bend and amplify the light coming from the Sun that enters the atmosphere.	1%
Q9-R3	They can trap certain molecules in the atmosphere. [1]	5%
Q9-R4	They can reflect some of the radiation from the Earth's surface. [2]	23%
Q9-R5	They are transparent to some forms of radiation, but not to all.	68%

[1] "Trapping" misconception. [2] "Multiple reflections" misconception.

4.2.2. Pre–Post Comparison

During the TLS, before introducing new topics, some questions were proposed to the students to evaluate their knowledge of the key concepts to be presented. The comparison between these results of these tests and those of the final test, shown in the preceding Section, is drawn in Figure 7.

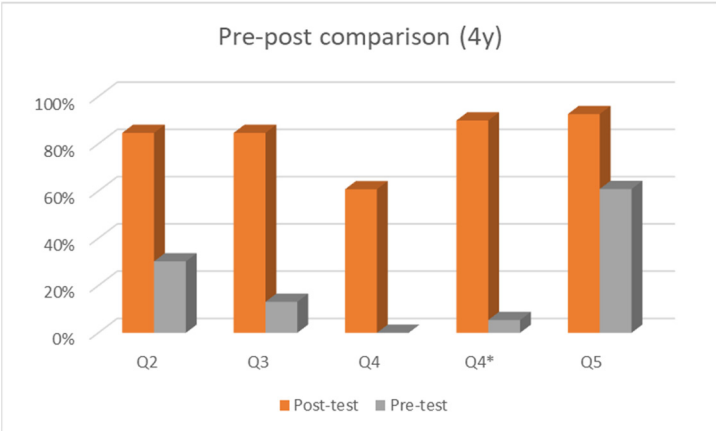


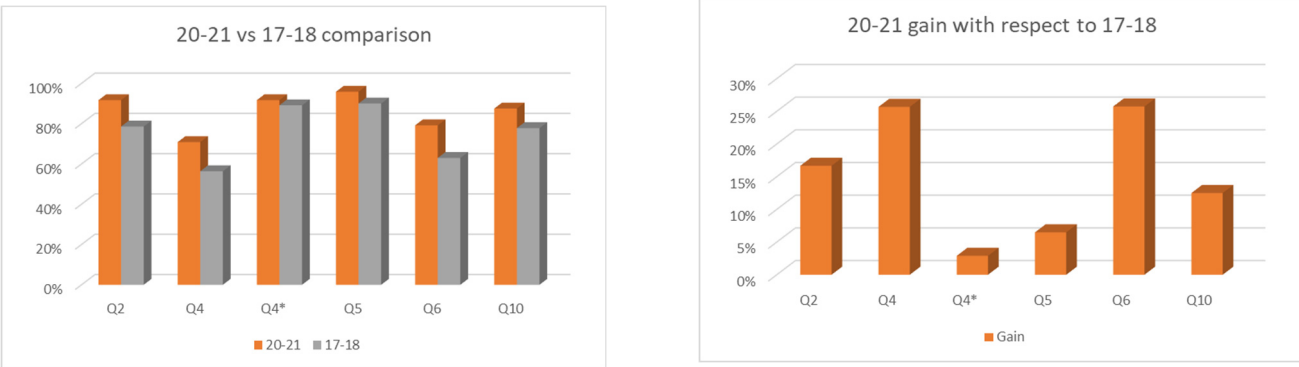
Figure 7. Pre–post knowledge comparison during the 4 years for the questions from Q2 to Q5.

The graph clearly shows that the students' knowledge of these key concepts before the TLS was very poor (apart from question Q5, where the situation is better but not sufficient yet). The gain at the end of the sequence is thus evident.

4.2.3. The New Sequence Version

Version 1 of the TLS was proposed to the students of the course "Experimental Physics Laboratory at High School Level I" in the years 2017–2018, while version 1b was considered in the years 2020–2021. We illustrated the differences between the two versions in Section 3.3.3.

In Figure 8a,b, we show the comparison between the results obtained in the two periods concerning the questions that were involved in the redesign of the TLS, namely Q2, Q4, Q5, Q6, and Q10.



(**a**) (**b**)

Figure 8. Comparison between the 20–21 and 17–18 two-year periods: (**a**) Results for the two-year period. (**b**) Gain percentage increase for each question, 2020–2021 vs. 2017–2018.

The analysis of the results shows that the overviews of electromagnetic waves and of radiative phenomena improved the students' performance on the related topics (questions Q2 and Q5). Moreover, the new simplified model for climate, which introduced specific coefficients for the absorption of electromagnetic radiation by the atmosphere in visible light and in the infrared, helped improve the understanding of the phenomena of absorption and of selective transparency and find a correct graph for the Earth's radiative balance (questions Q4, Q6, and Q10).

5. Conclusions

During this study, we obtained some important answers to our research questions.

First of all, analysing some recent textbooks (from middle school and high school) and comparing our results with those of previous research showed that although we identified some improvements in the treatment of GHE and related illustrations, there still remain widespread problems that are likely to elicit misconceptions and alternative patterns in students. Evidence of the latter is the fact that most of the drawings produced by the students who participated in the university course show clear signs of the misconceptions received from the imprinting of their early school texts.

Moreover, over the course of these 15 years of TLS experimentation and redesign on the GHE, the analysis of learning outcomes and classroom interactions, as well as the availability of new technologies and the results of educational research in this field, have allowed us to continuously keep the instructional path updated and to measure, over time, its effectiveness. It clearly emerges that focusing on the key concepts for understanding the phenomenon and re-designing the sequence in a way that favours their understanding, has allowed us to achieve (as shown in the previous paragraph) an effective improvement in student performance. In particular, the central importance of the key concept of selective transparency for understanding the role of humans in anthropogenic GHE has emerged.

Thus, the fundamental importance of the iterative approach to TLS design and refinement emerges from this study. Indeed, thanks to it, it was possible to identify the key passages about GHE that were most critical to students and their associated misconceptions and, subsequently, to re-design teaching activities (or create new ones, also taking advantage of advances in research and technology) to foster and enhance learning about the physical phenomena underlying GHE and to understand the role of humans in this process.

Author Contributions: Data curation, S.T.; Formal analysis, S.T.; Methodology, M.D.M. and M.M.; Supervision, M.M. and P.O.; Writing—original draft, S.T. and M.D.M.; Writing—review & editing, T.R., M.M. and P.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data used in this study are available under reasonable request from the authors.

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

References

1. Feynman, R.P. *The Meaning of It All: Thoughts of a Citizen-Scientist*; Addison-Wesley: Reading, MA, USA, 1998.
2. Somerville, R.C.J.; Hassol, S.J. Communicating the Science of Climate Change. *Phys. Today* **2011**, *64*, 48. [CrossRef]
3. CENSIS. Available online: Https://www.Censis.It/Rapporto-Annuale/La-Societa-Irrazionale (accessed on 27 September 2022).
4. Duit, R.; Gropengießer, H.; Kattmann, U.; Komorek, M.; Parchmann, I. The Model of Educational Reconstruction–A Framework for Improving Teaching and Learning Science. In *Science Education Research and Practice in Europe: Retrospective and Prospective*; Brill: Leiden, The Netherlands, 2012.
5. Duit, R.; Komorek, M. Studies on Educational Reconstruction of Chaos Theory. *Res. Sci. Educ.* **1997**, *27*, 339–357. [CrossRef]
6. Komorek, M.; Duit, R. The Teaching Experiment as a Powerful Method to Develop and Evaluate Teaching and Learning Sequences in the Domain of Non-Linear Systems. *Int. J. Sci. Educ.* **2004**, *26*, 619–633. [CrossRef]
7. Laherto, A. An Analysis of the Educational Significance of Nanoscience and Nanotechnology in Scientific and Technological Literacy. *Sci. Educ. Int.* **2010**, *21*, 160–175.
8. Laherto, A. Informing the Development of Science Exhibitions Through Educational Research. *Int. J. Sci. Educ. B Commun. Public Engagem.* **2013**, *3*, 121–143. [CrossRef]
9. Reinfried, S.; Aeschbacher, U.; Kienzler, P.M.; Tempelmann, S. The Model of Educational Reconstruction–A Powerful Strategy to Teach for Conceptual Development in Physical Geography: The Case of Water Springs. *Int. Res. Geogr. Environ. Educ.* **2015**, *24*, 237–257. [CrossRef]
10. Niebert, K.; Gropengiesser, H. The Model of Educational Reconstruction: A Framework for the Design of Theory-Based Content Specific Interventions. In *Educational Design Research—Part B: Illustrative Cases*; Plomp, T., Nieveen, N., Eds.; SLO: Enschede, The Netherlands, 2014; pp. 511–531.
11. 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. [CrossRef]

12. Tasquier, G.; Pongiglione, F.; Levrini, O. Climate Change: An Educational Proposal Integrating the Physical and Social Sciences. *Procedia Soc. Behav. Sci.* **2014**, *116*, 820–825. [CrossRef]
13. Moggio, L. Design and Experimentation of Communication and of a Teaching Sequence on Atmospheric Physics. Ph.D. Thesis, University of Trento, Trento, Italy, 2016.
14. Onorato, P.; Malgieri, M.; Rosi, T.; Salmoiraghi, A.; Oss, S.; De Ambrosis, A. Insegnare Le Basi Fisiche Dell'effetto Serra e Del Riscaldamento Globale-Teaching the Physical Basis of Greenhouse and Global Warming. *G. Fis.* **2021**, *62*, 67–93.
15. Manabe, S.; Strickler, R.F. Thermal Equilibrium of the Atmosphere with a Convective Adjustment. *J. Atmos. Sci.* **1964**, *21*, 361–385. [CrossRef]
16. Trenberth, K.E.; Fasullo, J.T.; Kiehl, J. Earth's Global Energy Budget. *Bull. Am. Meteorol. Soc.* **2009**, *90*, 311–324. [CrossRef]
17. Houghton, J. *Global Warming*; Cambridge University Press: Cambridge, UK, 2009; ISBN 9780521882569.
18. Ibáñez, M.; Ramos, M.C. Physics Textbooks Presentation of the Energy-Conservation Principle in Hydrodynamics. *J. Sci. Educ. Technol.* **2004**, *13*, 267–276. [CrossRef]
19. Taibu, R.; Rudge, D.; Schuster, D. Textbook Presentations of Weight: Conceptual Difficulties and Language Ambiguities. *Phys. Rev. Spec. Top.-Phys. Educ. Res.* **2015**, *11*, 10117. [CrossRef]
20. Viennot, L.; Décamp, N. *Developing Critical Thinking in Physics*; Springer: Cham, Switzerland, 2020.
21. Testa, I.; Leccia, S.; Puddu, E. Astronomy Textbook Images: Do They Really Help Students? *Phys. Educ.* **2014**, *49*, 332–343. [CrossRef]
22. Choi, S.; Niyogi, D.; Shepardson, D.P.; Charusombat, U. Do Earth and Environmental Science Textbooks Promote Middle and High School Students' Conceptual Development about Climate Change? Textbooks' Consideration of Students' Misconceptions. *Bull. Am. Meteorol. Soc.* **2010**, *91*, 889–898. [CrossRef]
23. Crippa, M.; Fiorani, M. *Sistema Terra–Volume EFG.*; Mondadori Education S.p.A.: Milano, Italy, 2016.
24. Shepardson, D.P.; Niyogi, D.; Choi, S.; Charusombat, U. Students' Conceptions about the Greenhouse Effect, Global Warming, and Climate Change. *Clim. Chang.* **2011**, *104*, 481–507. [CrossRef]
25. Besson, U. *Didattica Della Fisica*; Carocci Editore: Roma, Italy, 2015; ISBN 978-88-430-7735-9.
26. McDermott, L.C. Oersted Medal Lecture 2001: Physics Education Research—The Key to Student Learning. *Am. J. Phys.* **2001**, *69*, 1127–1137. [CrossRef]
27. Paci, G.; Paci, R. *Idea, Progetto, Innovazione-Tecnologia*; Zanichelli Editore S.p.A.: Bologna, Italy, 2014.
28. Chini, A.; Conti, A. *Imparo e Applico Con 10 in Tecnologia-Processi Produttivi Ed Energia*; Mondadori Education S.p.A.: Milano, Italy, 2014.
29. Oh, J.Y.; Jeon, E.C. Greenhouse Effects in Global Warming Based on Analogical Reasoning. *Found. Sci.* **2017**, *22*, 827–847. [CrossRef]
30. Chen, X. The Greenhouse Metaphor and the Greenhouse Effect: A Case Study of a Flawed Analogous Model. In *Research Topics in Wind Energy*; Springer Professional: Wiesbaden, Germany, 2014; Volume 2.
31. Crippa, M.; Fiorani, M. *Sistema Terra-Volume AB.*; Mondadori Education S.p.A.: Milano, Italy, 2014.
32. Levrini, O.; Altamore, A.; Balzano, E.; Bertozzi, E.; Gagliardi, M.; Giordano, E.; Guidoni, P.; Rinaudo, G.; Tarsitani, C. Looking at the Physics Curriculum in Terms of Framing Ideas. In Proceedings of the GIREP 2008 International Conference Physics Curriculum Design and Validation, Nicosia, Cyprus, 18–22 August 2008; pp. 18–22.
33. Gautier, C.; Deutsch, K.; Rebich, S. Misconceptions About the Greenhouse Effect. *J. Geosci. Educ.* **2006**, *54*, 386–395. [CrossRef]
34. Rajeev Gowda, M.V.; Fox, J.C.; Magelky, R.D. Students' Understanding of Climate Change: Insights for Scientists and Educators. *Bull. Am. Meteorol. Soc.* **1997**, *78*, 2232–2240. [CrossRef]
35. Koulaidis, V.; Christidou, V. Models of Students' Thinking Concerning the Greenhouse Effect and Teaching Implications. *Sci. Educ.* **1999**, *83*, 559–576. [CrossRef]
36. Shepardson, D.P.; Choia, S.; Niyogi, D.; Charusombat, U. Seventh Grade Students' Mental Models of the Greenhouse Effect. *Environ. Educ. Res.* **2011**, *17*, 1–17. [CrossRef]
37. Keller, J.M. *Part I. Development of a Concept Inventory Addressing Students' Beliefs and Reasoning Difficulties Regarding the Greenhouse Effect, Part II. Distribution of Chlorine Measured by the Mars Odyssey Gamma Ray Spectrometer*; The University of Arizona: Tucson, AZ, USA, 2006.
38. Jarret, L.E. Investigating Secondary School Students' Understanding of Climate Change. Ph.D. Thesis, University of Wollongong, Wollongong, NSW, Australia, 2013.
39. Jarrett, L.; Ferry, B.; Takacs, G. Development and Validation of a Concept Inventory for Introductory-Level Climate Change Science. *Int. J. Innov. Sci. Math. Educ.* **2012**, *20*, 25–41.
40. De Ambrosis, A.; Onorato, P. Energia, Effetto Serra e Riscaldamento Globale. In *Proceedings of the L'insegnamento Della Matematica e Delle Scienze Nella Società Della Conoscenza. Il Piano Lauree Scientifiche (PLS) Dopo 10 Anni di Attività*; Anzellotti, G., Catena, L.M., Catti, M., Cosentino, U., Immè, J., Vittorio, N., Eds.; Mondadori: Segrate, Italy, 2014; pp. 275–281.
41. University of Colorado Boulder PhET: Free Online Physics, Chemistry, Biology, Earth Science and Math Simulations. Available online: https://phet.colorado.edu/ (accessed on 21 October 2022).
42. White, R.; Gunstone, R. *Probing Understanding*; Routledge: Oxfordshire, UK, 2014; ISBN 9781134732340.
43. Beer, A. Bestimmung der absorption des rothen lichts in farbigen Flüssigkeiten. *Ann. Phys.* **1852**, *162*, 78–88. [CrossRef]