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LEADING SECONDARY SCHOOL STUDENTS TO FACE THE DISCIPLINARY, EPISTEMOLOGICAL AND SOCIETAL CHALLENGES OF CLIMATE CHANGE: DESIGN AND ANALYSIS OF MULTI-DIMENSIONAL TEACHING/LEARNING EXPERIENCES

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Abstract

The scientific community has been debating climate change (CC) for over two decades. In the light of certain arguments put forward by the aforesaid community, the EU has recommended a set of innovative reforms to science teaching, such as incorporating environmental issues into the scientific curriculum, thereby helping to make schools a place of civic education. However, despite these European recommendations, relatively little emphasis is still given to climate change within science curricula.

The main goal of the research project described in this thesis is to study *if*, *how* and *why* the scientific contents related to CC could be reconstructed so as to integrate the many dimensions involved in the issue. Specifically, the project set out to create and test innovative materials and activities for secondary school students, designed to foster: i) effective and meaningful understanding of the concepts involved in CC (*disciplinary dimension*); ii) a growing *personal involvement* in environmental issues supported also by the maturation of rational arguments for moving consciously through the political, economical, social and ethical dimensions (*societal dimension*); iii) epistemological reflections aimed at problematizing the traditional and outdated image of science which is still widespread among citizens (*epistemological dimension*).

In the design and analysis of the materials, we start from the conjecture that behind many conceptual difficulties and psychological barriers lie particular epistemological obstacles related to a naïve and stereotypical view of science.

In order to reach the main goal, the work has been organized according to four research questions (RQs):

> *RQ_1: What operational criteria can be identified for reconstructing physics so as to integrate the many dimensions considered in the main goal?*
> *RQ_2: (a) Which models of greenhouse effect and GW are effective for implementing the criteria identified? (b) What experimental activities can be designed in order to promote an inquiry-based approach to the study of environmental issues, and to help students understand the models and their multi-dimensionality?*
> *RQ_3: How do secondary school students react to the proposed materials? Are the materials effective in achieving the main goal of the research?*
> *RQ_4: Which analytic methods can be used to investigate the multiple dimensions of a teaching/learning classroom experience?*

In Chapter 1, the analysis of a selection of research papers and international reports is presented. The selected papers and reports concern: the conceptual difficulties that students usually encounter in dealing with physics concepts related to CC; the sociological and behavioural reactions of citizens facing CC; the crucial points regarding the scientific debate on CC; the status of the research on modelling in science education. The match among the main results in so many different research fields led us to point out some design principles which guided the process of instructional design of a multidimensional proposal on climate change intended for upper secondary school students (grade 11^{th}, 12^{th} and 13^{th}). The design principles, the teaching materials and the developed conceptual path are described in chapter 2.

The multidimensional conceptual path was implemented in four different teaching experiences and many data were collected in order to keep tuned the many dimensions involved in the study. The contexts of implementation, the role of each one and the data sources properly designed are described in chapter 3.
The materials and the data tools were initially validated in a pilot-study which aimed to test and revise both the teaching materials and the data sources (chapter 4). On the basis of the results of this pilot-study, the materials have been reviewed in order to emphasize the epistemological dimension. Specifically, the results led us to make the epistemological *fil rouge* on the models and modelling stronger and more evident; to revise (in form and content) the lesson on complexity; and to insert specific tools of investigations aimed at indepth investigation of the epistemological dimension.
The data collection and data analysis focused initially on the single dimensions (conceptual, behavioural, epistemological) and later on the correlations among them. This strategy implied the development of new and original analytic tools able to bootstrap from the data results related to each dimension, but also analytic techniques that could render the results of each dimension comparable to each other (chapters 5-6-7).

As a global result, the analyses highlighted a positive overall trend both on the three dimensions considered individually and with respect to the identification of positive influences and impacts among the different dimensions. Nevertheless, some critical elements emerged from the analyses.

As far as the disciplinary dimension is concerned (chapter 5), the conceptual path revealed to be effective in providing a chance *i)* to resolve the problem of confusing climate change with different environmental phenomena, like the ozone layer depletion and general pollution, and *ii)* to relate the greenhouse effect to the properties of absorbance, reflectance and transmittance. The analysis, however, revealed the permanence in the students of conceptual difficulties which are well-documented in the research literature, such as *i)* the difficulty in managing the concept of emission and *ii)* the confusion between heat and radiation. These two problems are those in which there is the greatest discrepancy between common sense and scientific thinking and, as our other studies on thermodynamics show, they must be addressed indepth from the moment that the basic physics concepts of thermodynamics and electromagnetism are introduced. However, the type of analysis we were able to carry out did not allow us to thoroughly investigate the nature of these unresolved problems.

As far as the societal dimension is concerned, the data analyses showed positive behavioural responses in all the teaching experiments. The analysis of the mutual interaction between knowledge and behavioural response (chapter 6) strengthens this result. Moreover, the evolution of a certain type of knowledge and, mainly, the introduction of the epistemological perspective of complexity appeared potentially able to provide students with the cultural tools necessary to rationally navigate through the jungle of ideological/media wars about environmental issues.

The epistemological dimension constituted the particularly original feature of this research work (chapter 7). As we said above, this study originated from the conjecture that climate change represents not only a societal and disciplinary but also an epistemological challenge. Scientific

debates imply sophisticated epistemological argumentations which refer, more or less implicitly, to a refined way of looking at modelling in climate science.
In the light of the results of our analysis, we can assert that, under certain conditions, specific epistemological know-how can positively impact not only productive disciplinary engagement, but also a more personal and authentic involvement in climate change. The decision to keep together the societal and conceptual dimensions, thanks to the epistemological dimension, proved to be a successful choice. It offered the students the opportunity to understand the increasing importance of the role of models and modelling in coping with scientific issues that have direct impact on the social aspects of people's lives (e.g. climate change, earthquakes, nuclear physics, modern physics applied to medical studies).

Besides the epistemological dimension, the other element of originality of the research work is the construction of new analytic methodologies constructed to exploit the data and correlations between the different dimensions. These new methods can make, in our opinion, a positive contribution to the current debate on methodology in science education research.

Commonly used abbreviations

CC – Climate Change

DBR – Design-based research

EU – European Union

GHE – Greenhouse effect

GHG – Greenhouse gases

GW – Global Warming

IBA – Inquiry Based Approach

IPCC – Intergovernmental Panel on Climate Change

MER – Model of Educational Reconstruction

NOS – Nature of Science

PER – Physics Education Research

RQ – Research Question

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CHAPTER 1

Research Framework

1.1. Introduction: research statement, aims and research questions

The Climate Change issue is a problem which exists from more than two decades. Many recommendations have been produced by the EU about the need to innovate the basic science education both to incorporate environmental issues and to take care that the school can become a place of education for citizenship (e.g. Millar & Osborne, 1998; Osborne & Dillon, 2008). Nevertheless, the problem of formulating educational significant proposals on a cultural and cognitive level is still far from being resolved. An unavoidable source of complexity stems from the many dimensions involved in environmental issues: scientific, psychological-behavioural, political, economic and ethical.

The main goal of the project is to study *if*, *how* and *why* the scientific contents related to CC can be reconstructed so as to integrate, in a *significant* way, the many dimensions involved in the issue (scientific, epistemological, sociological-behavioural, political, economic and ethical). Specifically, this work aims at designing and analyzing innovative materials and activities for secondary school students, prepared in order to foster:

a) effective and meaningful understanding of the concepts involved in CC, through also an Inquiry-Based Approach (*disciplinary dimension*);
b) epistemological reflections aimed at problematizing the traditional and outdated image of science, still widespread among citizens, according to which: i) controversies and scientific debates are not legitimate; ii) the new epistemological paradigm of contemporary physics and the perspective of the physics of complexity are not considered (*epistemological dimension*);
c) a growing *personal involvement* in environmental issues supported also by the maturation of rational arguments for moving consciously through the *political, economical, social* and *ethical* dimensions (*societal dimension*).

In order to reach the main goal, the work has been organized according to the following research questions (RQs):

RQ_1: What operational criteria can be pointed out for reconstructing physics so as to integrate the many dimensions considered in the main goal?
RQ_2: (a)What models of greenhouse effect and GW are effective for implementing the criteria pointed out? (b)What experimental activities can be designed so as to promote an Inquiry Based Approach to the study of environmental issues and to make students to understand the models and their multi-dimensionality?
RQ_3: How do secondary school students react to the produced materials? Are the materials effective for achieving the main goal of the research?
RQ_4: What analytic methods can be used to investigate the multiple dimensions of a teaching/learning classroom experience?

The research work has been organized in different stages.

Initially, the analysis of a selection of research papers and international reports was carried out in order to point out some design principles. The selected papers and reports concern: the conceptual difficulties that students usually euncouter in dealing with physics concepts related to climate change; the sociological and behavioural reactions of citizens facing climate change; the crucial points regarding the scientific debate on climate change; the status of the research on modelling in science education. The analysis of the literature is presented in chapter 1.

The literature analysis guided the process of instructional design which resulted in the production of design principles, teaching materials and a conceptual path (chapter 2).

The following stage concerned the design of teaching experiments aimed to test and revise the materials (chapter 3). The materials and the data tools were initially validated in a pilot-study (chapter 4).

Finally, the data collected during different implementations have been analysed. The analysis was carried out dimension per dimension, namely conceptual, societal and epistemological (chapters 5-6-7). Nevertheless, a specific analysis aimed at investigating the reciprocal relations between the dimensions has been finally realized (section 7.2).

1.2. Theorethical Framework

At present, the educational proposals and activities designed about Climate Change (CC) issue mirror the research fields where they come from, science education research and research in sociological and behavioural sciences.

The proposals/activities developed within science education research focus mainly on the design of conceptual pathways and teaching resources more and more effective for improving science understanding (e.g. Besson et al., 2010; Lester et al., 2006; Svihla & Linn, 2011; Niebert & Gropengiesser, 2013). The pathways and the teaching resources are constructed on relevant results obtained by studies which show that: i) some basic physics concepts involved in understanding environmental issues are only mentioned or treated superficially (both from textbooks and from teachers); ii) the traditional organization of scientific content in theories (i.e.: thermodynamics and optics) creates barriers in understanding the concepts (i.e: transparency) involved in environmental issues, such as the greenhouse effect, which are typically intra-disciplinary topics (Besson et al., 2010; Papadouris et al., 2008).

The proposals developed within sociological and behavioural sciences concern mainly the design of exemplary activities aimed to affect *behavioural norms* about the conscious use of energy (e.g. Nye & Hargreaves, 2009). These proposals are based on sociological and behavioural surveys aimed at investigating why citizens are so resistant to getting involved with climate change issue (Norgaard, 2009). Examples of results are: i) the constant personal conflict (peoples interviewed often said: “I have a guilty conscience”) between not wanting to give up their well-being and want to sustain an image of thoughtful/careful citizens (Norgaard, 2009); ii) the sense of confusion and distrust of the population facing scientific controversies presented by the media (Standard Eurobarometer, 2009b; 2009c; Lorenzoni et al., 2007).

The identified emotional and cognitive barriers as well as the sense of bewilderment and distrust of the population in the face of scientific controversies presented by the media represent, in our hypothesis, a clear signal of stereotyped beliefs about science – namely, that science still has the role and the power to provide a unique, unquestionable, and certain explanation of events and processes. Such a naïve idea about modelling clashes strongly with the intrinsic complexity of climate science (Pasini, 2003; IPCC, 2007; Tasquier et al., 2014a; 2015a).

Climate change represents a demanding epistemological challenge for students and, more in general, for citizens (Pasini, 2003). Scientific debates on CC imply indeed sophisticated epistemological argumentations which refer to the crucial issue of the predictive power of climate models and to the crucial passage from classical deterministic models to non-linear complex ones. A large body of research demonstrates that, usually, students are not pressed to develop a refined epistemological knowledge and they reach poor understanding of the nature of science (Papadouris & Constantinou, 2011; Pluta et al., 2011) and of what models are (Treagust et al., 2002).

Whilst the conceptual and the beahavioural reactions of students to CC have been widely investigated in, respectively, science education research and behavioural sciences, the role of the epistemological knowledge in facing the conceptual and behavioural barriers is under-investigated.

Our study is strongly focused on this issue and strongly oriented to explore the conjecture that many conceptual difficulties and emotional barriers have their roots in naïve and stereotypical beliefs about the process of modelling in science. The other face of the conjecture is that a teaching path, designed on a strong epistemological *fil rouge*, can help students consciously address both the conceptual and the societal challenges of CC.

1.2.1. Climate Change and Science Education

The complexity related to environmental issues and to the rapid CC occurred in the last decades are one focus of attention of the EU cultural politics. Emblematically, CC is at the heart of a fundamental Societal Challenge of Horizon 2020, where it is claimed: "*There is incomplete knowledge on the ability of society and the economy to adapt to climate change. Effective, equitable and socially acceptable measures towards a climate resilient environment and society require the integrated analysis of current and future impacts, vulnerabilities, population exposure, risks, costs and opportunities associated with climate change and variability, taking into account extreme events and related climate-induced hazards and their recurrence.*" (Horizon 2020, *Ibidem,* 5.1.2).

Despite CC being one of the five major problems facing humanity in this century (Horizon, 2020; Osborne & Dillon, 2008), many reports highlight that there is still relatively little emphasis on it within science curricula (Osborne & Dillon, 2008). The need to renew science curricula is indeed highlighted by many reports and surveys, including for instance the Relevance of Science Education (ROSE) study. In fact, the present structure of science curricula, coupled with teaching and assessing issues, seems to work against the goal of fostering a life-long interest in the sciences (Osborne & Dillon, 2008). Introducing environmental issues like CC into the curriculum might hence have two important implications. It would offer students the opportunity to learn more about socio-scientific topics and contribute to a more sustainable future (Dillon & Scott, 2002) as well as helping to engage and support them in learning more about science (Dillon, 2012; Sjoberg, 2002; Svihla & Linn, 2011). Although environmental issues have proved to be engaging for students, addressing CC at school is challenging from many points of view. It implies addressing conceptual difficulties, overcoming behavioural barriers and developing refined epistemological skills.

Within the field of physics education research, important studies have investigated the conceptual difficulties that students encounter in understanding the greenhouse effect mechanism and its relationship with global warming. More specifically, research has revealed the following issues (Besson et al., 2010; Tasquier, 2013): (i) infrared emission of bodies is usually not taken into account as an energy-loss mechanism, (ii) emittance, when considered, is often confused with reflectance, (iii) students tend to give absolute meaning to properties like transparency, absorptivity and emissivity, rather than seeing them as interactive properties, (iv) radiation is often confused with heat, and (v) students tend to apply a temporal or linear causal reasoning (Rozier & Viennot, 1991; Constantinou & Papadouris, 2012) for explaining processes instead of causal schemes based on balancing and equilibration (diSessa, 2014). These tendencies lead students to interpret the greenhouse effect with the naïf metaphor of "trapping" (Besson et al., 2010) which is not only misleading but also ineffective for grasping concepts such as feedback. The known difficulties are not surprising since the crucial physics concepts involved in understanding the greenhouse effect (e.g. absorption, transparency, black body) are often treated superficially, both in textbooks and by teachers (Besson et al., 2010). Furthermore, the traditional organization of scientific content in theories (i.e. thermodynamics, optics) could in itself be responsible for creating barriers in understanding the greenhouse effect, considering that this is clearly an intra-disciplinary issue

(Besson et al., 2010; Tasquier, Pongiglione, & Levrini, 2014). Having acknowledged the difficulties discussed above, several scholars produced teaching proposals, materials and applets for use in class to improve students' understanding (e.g. Besson et al., 2010; Punter, Ochando-Pardo, & Garcia, 2011; Svihla & Linn, 2011).
The challenge of producing citizens who feel personally involved in such a social issue is, however, much more complex than simply enabling students to understand the greenhouse mechanism, since psychological and social aspects are involved. This is the topic presented in the next section.

1.2.2. Climate Change and psychological and social aspects

The challenge of producing citizens who feel personally involved in such a social issue is, however, much more complex than simply enabling students to understand the greenhouse mechanism.
From several years the phenomenon of CC is also studied by psychologists and cognitive scientists, who wonder why this global issue is still so little known and understood, and why it raises up opposite reactions among people, as well as a low interest and an excessive underestimation of the problem, or a high level of worry which can be transformed in an uncontrolled fear or an effect of apathy.
Climate change seems to be psychologically distant (Lorenzoni et al., 2007; Moser & Dilling, 2004), and humans have a natural inclination to discount the future (Liverani, 2010). The greatest damage of it will fall on the next generations, will be more evident in a long term future, and still seems to be "far away". Moreover, the consequences it involves are not "cognitively available" (Sunstein, 2006), since there is still some confusion about causes, consequences and proper actions, and very often spreading knowledge in this regard is not the first concern of governments, as Sunstein has well stated referring to the United Stated previous (Bush) policy. Along with the cognitive availability, there is the perception of the actual risks (Sunstein, 2006) raised by climate change, another crucial point that has an influence on the decision making: the more urgent the risk appears, the more likely is a society to react[1].
The decision-making process concerning sustainability policies is strongly influenced by the characters of climate change above mentioned. As it has been suggested by Jacques and collegues, our mind is likely to "misunderstand climate dynamics" (Jaques et al., 2008).
The problems met by humans in the decision making are the direct consequence of what CC itself is. First of all, there are problems with the long/short-termism: all the positive effects of environmentally good behaviours are gradual, and, if successful, their benefits will just partly be experienced by the current generation. It is difficult to be deeply concerned for something, unless one acknowledges it as "urgent", close, with immediate effects on one's own life. Humans are very likely to lose motivation when dealing with a too distant future. They normally need a reward for actions they consider sacrifices – if not a reward, at least a feedback. Negative feedbacks could be, for instance, sanctions. In this case it has been suggested that there is a specific need of a "positive feedback" (Liverani, 2010), in order to prevent the human tendency of changing plans in midstream, preferring to pursue an easier, more reachable, or just more immediately rewarding objective.

[1] Some research highlight that it has also been noticed that the mere perception of the risk do not imply necessarily a behaviour change (Norgaard, 2009).

Climate change poses a serious challenge to human beings and to their mental abilities (Bostrom et al., 1994), since it requires an immediate sacrifice that promises in exchange a distant and rather vague benefit. In fact, it is undoubtedly true that measures that seek to prevent it, like the cut of CO_2 emissions, cause, in the short term, an economic damage, and therefore, they can be considered to be (at least from an economic perspective) as “sacrifices” (Bord et al., 1998), conflicting directly with an innate instinct of human beings: self-interest. Furthermore, the benefits produced by sustainability policies in the long term are very often not economically quantifiable, since they will primarily concern the natural environment. Who would really place the interest of the community before his own interest? Someone would, but it is the great majority that has to be considered.

In general, humans are extremely ill-equipped to deal both with problems characteristic of the long-term future (Gardiner, 2008) and with multiple-cause problems (Bazerman, 2006).

Several statistical surveys were carried out in recent years between Europe and the United States (respectively from the Eurobarometer and the American group of the Yale Project on Climate Change Communication), as well as numerous smaller studies localized in specific areas often based on qualitative surveys. The picture that emerges from these studies is that it is a problem still poorly understood. For its intrinsic characteristics it gives rise to frequent errors of perception, which in turn facilitate the psychological reaction of "removal" or "denial" of the problem, followed by a behavioural paralysis.

In particular there are three typologies of perception that appear to be the basis of psychological and behavioral responses to the issue, mentioned above. Such perception become barriers that hinder individuals both in the understanding of the issue than in the practical/behavioural response, that are:

(a) the fact that climate change should be considered a problem is not individual but collective
(b) the fact that climate change are often perceived as a problem too big or too small
(c) the fact that climate change should be considered a problem too far, that in any case does not concern the present generation.

(a) Barrier: “not individual but collective”

As far as the first barrier is concerned, the issue is essentially that the individual can not be placed in the problem of climate change. Specifically, the problem of climate change is perceived as something that is worrying at a global level but not an individual one (Leiserowitz et al., 2010; Special Eurobarometer, 2008; 2009), indeed these studies highlight that even though a large percentage of Europeans and Americans say that they are worried about climate change, very few of them believe that it will have some effect on their community, or that it will bounce off them closely. Another reason is that the role of the individual is often perceived as insignificant compared to the political or economic agents. Indeed, since it is considered a global problem, the only action on “large-scale” (e.g. industries, national or supranational entities) is considered effective. Since the action of the individual is not covered of the right importance, it is encouraged the social phenomenon called “free-riding” that is, the choise of not to do anything for the environment or to continue with harmful behaviour, in the belief that individual actions could not have impact on the overall situation. At last, the lack of understanding of some basic climate dynamics means that the individual does not awar its role as the "causal agent" within the climate problems: individuals do not grasp the exixtence of their interaction with nature, and consequently do not percived the effect of their actions on the environment.

(b) Barrier: “too big or too small”
The second problem leads directly to the issue of the risk perception, which is either not perceived, especially in their own personal dimension and local, nor perceived as something too huge, against which it can not be possible to do anything.
The lack of understanding of climate dynamics and consequences that global warming may cause the ecosystem, often leads to diminish the importance of the risks. The scientific data concerning the rise of temperature of a few degrees in a long time (which is often the only result that is attributed to climate change) is not considered a "threat" (Leiserowitz, 2006). On the other hand, sociological surveys in regions affected more significantly by climate change (Strauss, 2008; Lorenzoni et al., 2007; Norgaard, 2006) have highlighted the fact that in the face of a risk perceived as vivid and concrete but also "too big" , the individual reacts with the same lack of action of those who tend to diminish. The risk is removed in both cases. The uncertainty on some specific aspects of the scientific debate on global warming is often used in public debates to argue opposing arguments: the public manifestation of scientific controversy produces disorientation and loneliness. Individuals often fail to understand what aspects of climate change are actually in discussion, and tend to extend the uncertainty to any problem, also to justify the fact that they “do not take the matter”.

(c) Barrier: “too far”
Another important factor that constitutes an additional barrier to the conscious recognition of climate change, is the fact that their most harmful consequences are temporally distant (Oppenheimer & Todorow, 2006). Specifically, it is unclear to individuals what of these consequences can already take place in the near future, and what instead in the long-term. The difficult interpretation of the data in terms of time induces an attitude of indifference to the problem, because much more a risk is perceived far, much more easy it is to ignore it. Furthermore, the fact that the most dangerous consequences of climate change will impact on future generations raises a further question: the present generation feels called to "pay" for the sake of the next generation, which it is not always willing to do, especially in the case in which the price is high (both in terms of costs and in terms of changing habits), and the benefits remain mostly vague.

The issue of how to addres the barriers from an educational reconstruction of the scientific content, is new in science education and represent one of the more original feature of the materials that we designed (see chapter 2).

1.2.3. Climate Change and the scientific debate

The issue of CC involves not only the scientific community but also external actors, such as politicians and citizens, precisely because of the extent of the problem. Indeed, its consequences affect not only environmental, but also social and economic choices and the actuation of precise policies by each State (IPCC, 2007).
The issue of CC, in terms of GW, has been debated since the end of the nineteenth century, when some scientists formulated the first hypotheses and performed the first studies on the Earth's average temperature and its possible variations related to natural causes and/or anthropogenic

(Arrhenius, 1896). In the twentieth century some international conferences, research programs and protocols signed by the representatives of some States articulated the recognition of the ongoing climate change. In 1988 the Intergovernmental Panel on Climate Change (IPCC), which brings together scientists from the governments of member countries, produced every five years a declaration of public knowledge on CC. The IPCC report is used both as a scientific source on the issue and as the basis for political negotiations.

The last report (IPCC, 2007) declared that warming of the climate system is unequivocal, as it is nowadays evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. Furthermore, it asserts that the increase in global average temperatures observed since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gases (GHG) concentrations.

The evidence, the causes and consequences of the phenomenon have been and are still being challenged in different environments and for different reasons and purposes.

The temperature was a first significant parameter in the recognition and analysis of the phenomenon, but strong evidence comes from the world of ice - the extent and volume are clearly in decline - and the bio-marine - variety of tropical fish, sensitive temperature changes, have been spotted in unusual latitudes in search of new food. Even these consequences were challenging: meteorologists argued that the ice in the last three years has increased in scope and volume. Indeed, in 2007 there was an evident decrease of the surface, resulting in an apparent increase in the thickness of the ice. In assessing also the progress of the Arctic Ocean, some scholars arbitrarily chose to compare the period of minimum surface with another arbitrary period. Official figures say that in the last thirty/forty years the trend curve of these parameters is clearly decreasing.

The phenomena associated with increasing temperature can be considered manifestations of natural events: the debated problem concerned the nature of the causes – wheter they wre related to natural dynamics internal to the system or of anthropogenic origin. We know “with certainty” that the increase in greenhouse gases in the atmosphere, altering the absorbance of the atmosphere, a corresponding increase in temperature that is not only one of the possible interactions in the complex system of the climate, but above the engine which then triggers other feedback tending to mitigate or amplify the effect.

The difficulty in attaching causes and effects in a very complex system, due to the need to take into account all the variables involved and the implications of their nonlinear, is tackled through the process of modeling the phenomenon. Over the past ten years the quality of climate models has been improved, but the elaborated patterns have still strong limitations - in particular the components of the hydrological cycle (water, moisture in the air, changes in cloud, precipitation) are still difficult to be parameterized.

The actual models let to run of two hundred or three hundred years, taking into account the variation over the solar cycle, the effects of volcanoes predictable on a historical basis, considering feedback in ocean level and beyond, taking the increase in concentration of CO_2. It is observed that all the different models agree on the effects of global warming, although they show fluctuations due to differences in their parameterization. Such models highlight that the temperature record is comparable with the measured only if the increase of CO_2 is taken into acoount: climate models are thus a tool to detect the human footprint in the ongoing CC.

It is important to stress the crucial nature of communicating to a wide audience the nature of the scientific debate on a very topical issue, which shows the complexity of the climate problem and the

construction of many voices of its modeling. Indeed, The elaboration of models which can provide forecasts with an increasing level of reliability is an important part of the scientific debate on climate change.
Furthermore, the issue of modelling represents *per se* a big challenge of science and science education.

1.2.4. Climate Change as an epistemological challenge

Although modelling is considered a fundamental part of *any* authentic scientific inquiry (Giere, 2004; Godfrey-Smith, 2006; Nersessian, 2002), much work is still needed in order to turn models and modelling into an essential feature of school science teaching. Authoritative EU and US reports (e.g. Millar & Osborne, 1998; National Research Council 1996, 2000; Rocard, Csermely, Jorde, Lenzen, Walwerg-Heriksson, & Hemmo, 2007; Sjoberg, 2002) ascribe two crucial roles to modelling in teaching: i) since models are at the heart of scientific inquiry, they are fundamental for developing epistemological knowledge about the nature of science (NOS); ii) the development of epistemological competencies on modelling are needed in a complex risk society. Numerous research studies in science education advocate and support the relevance of model-based science education (Schwarz, 2002). Two main strands oriented our work: (1) theoretical and/or empirical studies where types, features and functions of models are discussed with regard to their educational relevance, and/or where models and modelling are investigated as teaching/learning tools for developing students' or teachers' specific knowledge, competencies and skills; (2) empirical studies that investigate students' difficulties in dealing with models and modelling and/or studies that apply specific investigation tools and strategies for fostering and evaluating the development of students' epistemological knowledge about models.
Within the first strand, many studies describe the benefits of engaging students in a model-based science education: (i) it provides students with opportunities to become acquainted and feel more comfortable with scientific practices (e.g. Hestenes, 1992; Penner, Lehrer, & Schauble, 1998); (ii) it fosters students' conceptual development (e.g. Nersessian, 1999; White, 1993), (iii) it enhances the understanding of abstract concepts through the exploration of concrete, visual structures (Barab, Hay, Barnett, & Keating, 2000) and (iv) it fosters the meta-cognitive abilities necessary to improve learning, such as the ability to express and externalize thinking (Gilbert J.K., 1995; White, 1993). Other research studies stress the potential of modelling in developing epistemic skills (e.g. Carey & Smith, 1993; Pluta, Chinn, & Duncan, 2011; Shwarz & White, 2005) and fostering productive epistemologies of science (Gilbert S.W., 1991; Schwarz & White, 2005). Further studies highlight the benefits of modelling for developing fundamental life skills, such as awareness of the semantic relation between theory and phenomena (Gilbert J.K., 2004; Greca & Moreira, 2000), metaphorical competencies which underlie every language (Hofstadter, 2013; Lakoff & Johnson, 1980) and analogical causal reasoning (diSessa, 2014; Harrison & Treagust, 2000). Additionally, many model-centred tools and educational software (such as Boxer, Cocoa, Genscope, Explorer, MARS, Model-it, StarLOGO, STELLA, and ThinkerTools) have been constructed and implemented in order to promote subject matter expertise, inquiry skills, and systems thinking (Schwarz & White, 2005). An interesting study that oriented our analysis concerns the philosophical underpinnings of how models and modelling are addressed in physics education (Koponen, 2007). In this study, Koponen concluded that "*The model-based view (MBV) of science education strives for authenticity in*

science teaching, and many of its advocates seek support from philosophical perspectives related to realistic versions of the Semantic View of Theories (SVT)[2]". Koponen argues that such philosophical underpinnings are too strong to produce an authentic picture of physics practice where a more pragmatic attitude toward models is adopted. In particular, he retains that an authentic image of physics requires only minimum realism and he suggests that physics education should focus on concepts like *reliability*, *accuracy* and *usefulness of model* instead of trying to demonstrate models' reality and truth.

The second research strand includes empirical studies aimed at investigating students' and/or teachers' epistemological positions on models. Some of these studies show the lack of explicit and aware epistemological stances (Levrini & Fantini, 2013; Levriniet al., 2014a; Van Driel & Verloop, 1999) or the robustness and resistance of views consistent with a naïve realist epistemology. As highlighted by Grosslight et al., "[students] are more likely to think of models as physical copies of reality that embody different spatio-temporal perspectives than as constructed representations that may embody different theoretical perspectives" (Grosslight et al., 1991). The roots of such miscomprehension have been related to the limited emphasis and span given in teaching to the roles, purposes and functions of models in science (Treagust et al, 2002). Without enough span or a refined epistemological guide, students are left with hyper-simplified and stereotyped views of models where the expression *constructed representation* is perceived as synonymous of *not real* and *too subjective* to be scientific. In the paper of Levrini et al (2014a), an articulated reaction of a class of students to the *representation* function of models and theories is described. As regards the *representation* issue, students were torn between the perception of being faced with something very puzzling and the concern that it could undermine the roots of one's own image of physics, based on categories like certainty, objectiveness and truth. The empirical studies led to the production of a rich variety of investigative tools, from Likert-type scale questionnaires to clinical interviews, involving also open-ended questionnaires. These investigative tools differ in their proximity/distance to specific contexts in the questions, as well as in the quantitative or qualitative analysis they imply. In some cases, students or teachers are asked to recognize models or modelling processes in specific physics problems concerning, for example, thermal phenomena or electric circuits (e.g. Etkina et al. 2005; Fazio et al., 2012; Fazio et al., 2013). In other cases, students or teachers are asked to answer general epistemological questions on model types, functions, definitions or application (e.g. Van Driel & Verloop, 1999).

The research work developed in this thesis aims to enrich the research on models and modelling by showing and discussing: i) the benefits of a model-based approach to climate change teaching, ii) opportunities that climate change physics can offer to increase the span of roles, purposes and functions of models in science; iii) types of difficulties that students can meet in dealing with models and modelling (chapter 7).

1.3. Methodological Framework

The whole research work is methodologically framed within two research strands: the *Model of Educational Reconstruction* (Kattmann et al., 1996; Duit, 2006; Niebert & Gropengiesser, 2013) and the *design-based research methods* (The Design-Based Research Collective, 2002).

The Model of Educational Reconstruction (MER) was developed in the mid-1990s on the basis of a continental European view of science education (Duit, 2006).

The MER is framed within epistemologically constructivism (diSessa & Sherin, 1998). In such a view, learning is seen as the construction of the proper knowledge from previous existing one. Moreover, scientific knowledge is considered as a human construction (diSessa, 1993), i.e. there is not an immutable truth in the content structure of a particular area, but a consensus of a particular community of scientists; each presentation of this consensus, even the one we find in the textbooks, is a reconstruction of the idiosyncratic implicit or explicit purpose of the authors. The sense of such perspective is that the structure of the scientific content for education can and should be built according different criteria and on the basis of the purposes that scholars and teachers want to achieve with the teaching of that particular subject content.

In our approach, the MER has been applied in the elaboration of an original design approach and in the production of materials on climate change (chapter 2). This design approach is characterized by some original design principles that the physics education research group of the University of Bologna called *multi-perspectiveness, multi-dimensionality* and *longitudinality* (Levrini & Fantini, 2013; Levrini et al., 2014a; 2014b). *Multi-perspectiveness* means that the same concepts are analysed from different perspectives (e.g. the macroscopic and microscopic perspective in thermal phenomena). *Multi-dimensionality* means that scientific contents are analysed and compared at different levels, conceptual, experimental, applicative but also for their philosophical-epistemological peculiarities or, in the case of climate changes, for their sociological, political and economical implications. *Longitudinality* means that students are guided throughout the whole physics curriculum to recognise long-term stories that go across different scientific domains and topics and that characterise science as a whole. Examples of stories are: modelling and its specifications in different topics and domains; forms of creativity and intuition in the history of science; the relationship between constraints (the objective core of scientific thinking as it is shared by the scientific community) and freedom (the room for personal interpretations, intuition and invention) in science. Operationally, multidimensionality was implemented through the differentiation of activities, such as: i) activities for analysing and understanding authentic scientific discourse as it appears in original papers from peer reviewed scientific journals, epistemological essays, international reports like the International Panel of Climate Change (IPCC) report; ii) textual analysis, writing and classroom discussions for transparent argument formation and for recognising the consistency of the an argument and its different layers; iii) inquiry-based activities. Longitudinality is implemented by tutorials or by specific lessons. Particularly, specific tutorials and classroom discussions on modelling are systematically planned and realized (Tasquier, Levrini & Dillon, 2015a). So far, the designed materials have been proved to foster conceptual development (chapter 5), behavioural attitudes (chapter 6) and epistemological competences (chapter 7).

The Design-based research (DBR) is an emerging paradigm for the study of learning in context through the systematic design and study of instructional strategies and tools. At the basis of the methodology of DBR there is not the idea of putting together the "best practices" and provide instructions on how to operationally realize good activities of teaching/learning. Rather, its aim is to develop theories to go beyond the phenomenological study of specific situations. This does not mean removing concreteness or set aside the goal of improving practice, but it means to orient theoretically the work so as to foster and to mark an improvement of the phenomenology of education.

The PhD dissertation work lies in the perspective of the DBR in the sense that the following ideas have been borrowed from the DBR: i) the theoretical orientation: *"Design studies are conducted to develop theories, not merely to empirically tune "what works"*; ii) the iterative design. As the first point is concerned, Cobb's and collegues words are particularly explicative: "in order to pursue the intimate relationship between developing theory and improving instruction, the Design Studies indicates that, in collecting and analyzing data, *what works* must be underpinned by a concern for *how, when and why it works*, and by a detailed specification of *what, exactly, 'it' is*" (Cobb et al., 2003). As the second point is concerned, the iterative design implies a back and forth process of designing, testing and revising of the design in a mutual interaction among the discipline and the learners.

According to the DBR, the data analysis is essentially qualitative (Anfara et al., 2002; Denzin & Lincoln, 2005a; 2005b) and it is mainly framed within the theoretical orientation of the Grounded Theory (Bryant & Charmaz, 2008; Charmaz, 2005; 2006; Cohen et al., 2007; Glaser & Strauss, 1967).

The Grounded Theory is nowadays one of the most widespread methods among the qualitative analysis within the science education. Recently, also the use of a mixed methods is widespread (e.g. Battaglia et al., 2013; Fazio et al., 2012; Johnson & Christensen, 2004), mixed in the sense that there is a main reference theory but other methods - qualitative or not - have been borrowed and use together. Particularly, in this research work as well as, the data analysis also refer to discourse analysis, case studies and semi-quantitative analysis. The various methods are explained in the specific chapter of the analysis in which they have been used (chapters 4-5-6-7).

Consistently with the Grounded Theory methods, all the strategies of validation, needed for guarantee the criteria of credibility, transferability, dependability and confirmability (Anfara et al., 2002) have been applied (e.g. triangulation, thick description, peer-to-peer debriefing, audit trail, member checking, etc.).

CHAPTER 2

Conceptual Path on Climate Change

As presented in the previous chapter, one aim of the research is to design teaching materials on the basis of a specific educational reconstruction (Duit, 2006; Kattmann et al., 1996) of content knowledge on climate science. Due to the complexity of the issue, the specific goal of this part is to study *if*, *how* and *why* the scientific contents related to CC can be reconstructed so as to integrate, in a *significant* way, the many dimensions involved in the issue: scientific, epistemological, sociological-behavioural, political, economic and ethical (see chapter 1). The RQs that guided the process were:

> *RQ_1: What operational criteria can be identified for reconstructing physics so as to integrate the many dimensions considered in the main goal?*
> *RQ_2: (a) Which models of greenhouse effect and GW are effective for implementing the criteria identified? (b) What experimental activities can be designed in order to promote an inquiry-based approach to the study of environmental issues, and to help students understand the models and their multi-dimensionality?*

The process of educational reconstruction that we carried out is the result of a team-work that involved, besides myself:

- Prof. Rolando Rizzi, professor in Atmospheric Physics at the Department of Physics and Astronomy of the University of Bologna;
- Prof. Paola Fantini, expert secondary school teacher who has been collaborating for years with the research group in Physics Education of the University of Bologna and who was, at that period, attending the PhD programme in Anthropology and Epistemology of Complexity at the University of Bergamo;
- Dr. Francesca Pongiglione, researcher in Moral Philosophy at the University Vita-Salute San Raffaele, Milano;
- Prof. Olivia Levrini, professor in Physics Education at the Department of Physics and Astronomy of the University of Bologna.

The work was organized in the following stages. Firstly, the identified emotional/cognitive/cultural barriers (see chapter 1) were analysed from the perspective of the model of Educational Reconstruction (Kattmann et al., 1996) and some operational criteria were pointed out in order to address them explicitly in the process of disciplinary reconstruction (Pecori et al., 2014). For the first barrier (*not individual but collective*) the criterion was to discuss explicitly the role of the individuals in the modelling of GW. For the second barrier (*too big or too small*), the criterion pointed out was to include, in the discussion of CC, examples of causal connections, typical of complex systems, between man-nature-technology, and examples of feedback to show that small causes can have large effects and *vice versa*. Hence, for the last barrier (*too far*) the criterion was to place the previous examples of feedbacks on a time scale, typical of an evolutionary approach to complex systems, to reflect on possible future scenarios (i.e. the melting ice).

As second stage, the disciplinary contents were re-considered so as to build a multi-disciplinary path. The materials were designed starting from the comparison of two approaches on CC: the approach adopted by the research group in physics education of the University of Pavia (Besson, 2009; Besson et al., 2010; Onorato et al., 2011) and the approach adopted by Prof. Rizzi for his university course in Atmospheric Physics (Rizzi, 2013). The two approaches were combined, re-adapted for secondary school students and revised in order to
foster at the same time:

- deep understanding of the basic concepts involved in GW and CC (*disciplinary dimension*);

- appropriation of a refined epistemological discourse where: *i)* controversies and scientific debates find legitimacy; and *ii)* modelling in CC is discussed and progressively framed within the epistemological perspective of complexity (*epistemological dimension*);
- critical thinking about the relation Science & Society for enabling students to get acquainted with political and economic debates (*societal dimension*).

The content reconstruction resulted in the design of a lab-course articulated in five lessons The structure of the course is shown in the table below (table 2.1).

Table 2.1. Structure of the lab-course.

	Topic of the lesson	**Speaker**
1st	Introduction to climate change: the scientific research and new terms of the scientific controversy **(general climate science)**	Prof. Rolando Rizzi
2nd	Experiments on examples of interaction between radiation and matter **(physics)**	Giulia Tasquier
3rd	Experiments for the construction of a Greenhouse model **(physics)**	Giulia Tasquier
4th	The epistemological perspective of complexity: Introduction to the basic concepts for looking at complex systems **(mathematics & physics)**	Prof. Paola Fantini
5th	Political and Economic scenarios: overview of climate treaties and proposals to cut emissions **(political, economic and sociological science)**	Dr. Francesca Pongiglione

The structure which keeps together the multi-disciplinary nature of the path intends, in a certain way, to mirror (or to be a metaphor of) the complexity of the issue, by exploiting the feedback interactions among the pieces of the whole system, as it is shown by figure 2.1:

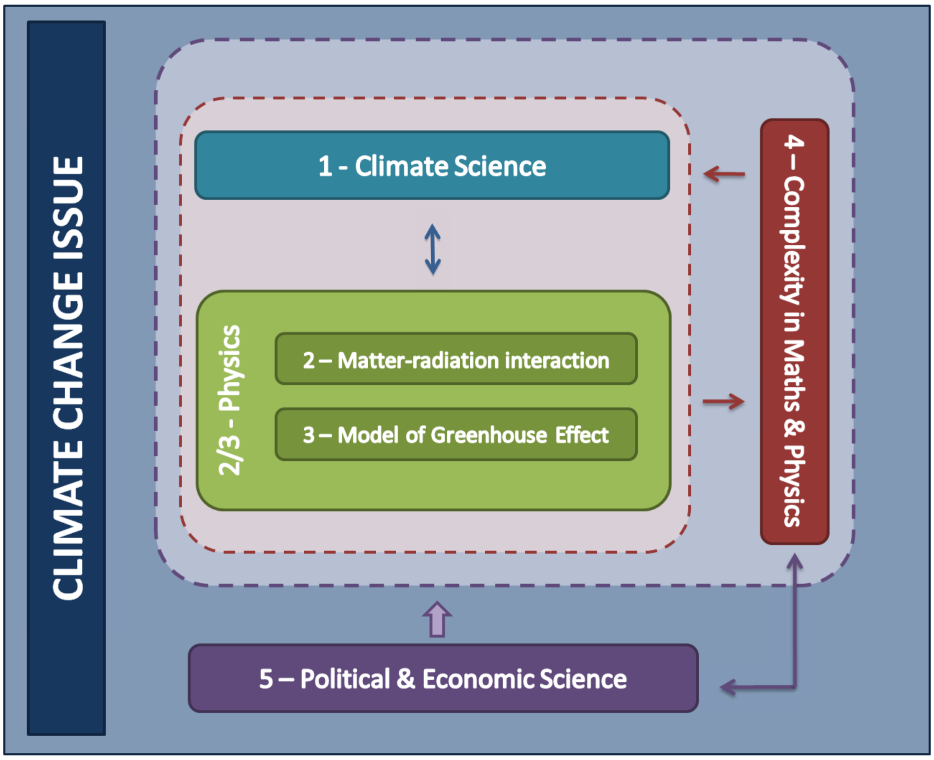


Figure 2.1. Structure of the path

The course was realized 4 times (see chapter 3) and the materials were progressively refined throughout the various implementations.
In the following paragraphs, the final version of the course is presented and discussed lesson by lesson, by describing, at first, the *conceptual skeleton* (2.1), that is the specific scientific contents that were addressed across the whole path and then the *epistemological fil rouge*, that is the specific epistemological message consistent with the topic of each lessons (2.2).
The whole path was designed targeted to secondary school students of the last three years (grade 11^{th}, 12^{th} and 13^{th}). The path, initially, was thought to be the follow up of teaching thermodynamics, on which we designed innovative materials (Tasquier, 2009; Levrini et al., 2014a) that have been proved to foster interesting processes of individual appropriation (Levrini et al., 2010; Levrini et al., 2011a; 2011b; Levrini et al., 2014b; Levin et al., 2013; Fantini et al., 2014).
Throughout the work, however, we tried to design a conceptual path that could be used without strong pre-requisites. It requires students have simply addressed calorimetry, waves, optics and electricity at grade 9th and 10th (from a phenomenological perspective) and to have acquired some basic concepts of thermodynamics (temperature, heat, internal energy).

2.1 The conceptual skeleton

The conceptual skeleton of the path is here presented lesson by lesson. For each lesson, the presentation includes: *i)* a summary of the lesson with the aims, the main messages and the main concepts developed, and *ii)* a detailed description of the disciplinary content knowledge of the lesson and how students were guided in developing their knowledge.

2.1.1 Lesson 1: "Introduction to climate change: the scientific research and the new terms of the scientific controversy"

Summary

The aim of lesson 1 is to stress what is shared by the scientific community (e.g. the increase of temperature of the Earth surface; the reduction of the ice-surface and the ice-thickness) and what is still object of controversial issues. In particular, by referring to the IPCC reports, it is stressed that: i) warming of the climate system is unequivocal, ii) global warming is very likely [90%] due to anthropogenic causes of greenhouse gases increases, and iii) the origin of many controversies is the intrinsic difficulty in producing mathematical and physical models able to take into account a huge number of variables.

In order to achieve the aim, students are introduced to climate science and progressively guided to grasp: i) how climate science is located within science and what are its specificities with respect to meteorology; ii) what are the data and the main evidence that lead scientists to argue that we are in front of significant climate changes; iii) what characterises climate systems and the climate models and why they are said to be "complex".

The crucial point of the lesson from a conceptual point of view is the qualitative introduction of the notion of feedback mechanism, presented as a typical way of reasoning in complex systems and, hence, in climatology.

After a general introduction on science and its modelling nature, the lesson addresses the positioning of climate science with respect to other two disciplines that are often confused: atmospheric physics and meteorology.

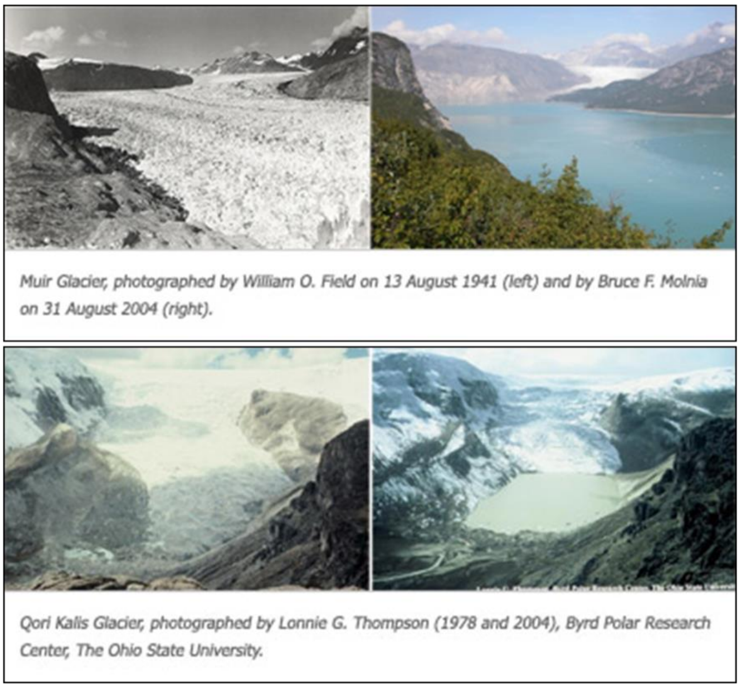
Both meteorology and climatology are introduced as special fields within atmospheric physic, the latter including all the phenomena related to atmosphere: from the eddies of air in our backyards, to storms, tornadoes, cyclones and anticyclones, tropical cyclones, the planetary waves.

Within atmospheric physics, meteorology studies those phenomena that are organized and developed over distances ranging from tens to thousands of kilometres, like storms or cyclones, and tries to predict the dynamic evolution over time scales ranging from a few hours to ten days. Climatology, instead, studies the long-term behaviour of an atmospheric system (about 20-30 years).

The distinction of the space-time scale of the meteorological and climatologic phenomena is argued to be fundamental, since the arguments against the evidence of CC are often based on specific selection of data referring to short periods (less than 20-30 years).

The "climate debate" is then discussed on the basis of evidence-based argumentation and starts with the presentation of examples of climate observations. After mentioning of the well known evidence of the increase of the average temperature, the lecture zooms in on one of the main evidence observed by climatologists, that it the state of glaciers (the surface and the volume) that has been changing in the last years.

The reduction in the extent of glaciers is visible to the human eye by comparing photos of glaciers taken with some thirty years later, as the following pictures show:


Muir Glacier, photographed by William O. Field on 13 August 1941 (left) and by Bruce F. Molnia on 31 August 2004 (right).

Qori Kalis Glacier, photographed by Lonnie G. Thompson (1978 and 2004), Byrd Polar Research Center, The Ohio State University.

Figure 2.2. Pictures of the evolution of two glaciers: Muir Glaciers, Alaska (up); Qori Kalls Glaciers, Perù (down).

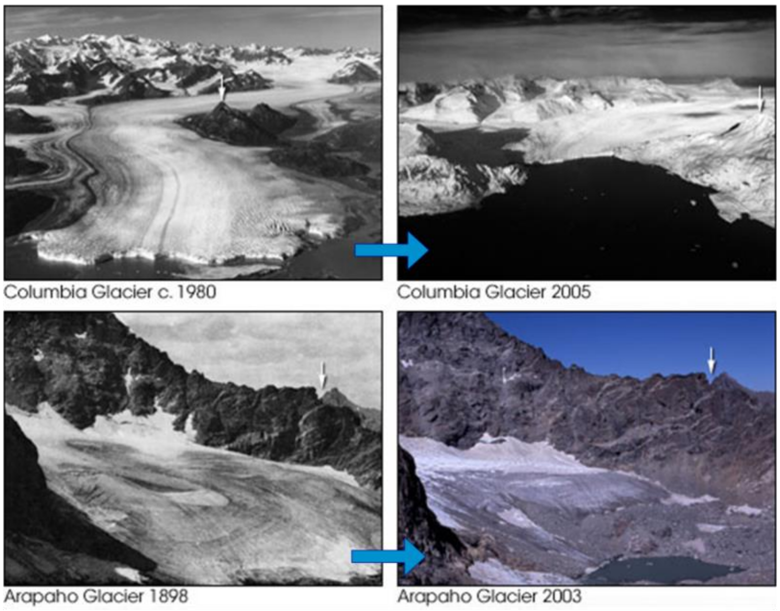


Figure 2.3. The Columbia Glacier flows down from the Chugach Mountains and into Prince William Sound about 40 miles west of Valdez, Alaska. Since the Columbia began retreating around 1980, the terminus has retreated approximately 15 kilometers. The Arapaho Glacier is in the Rocky Mountains in, Colorado.

Another evident case of change is the reduction of the extent of sea ice covering the Arctic Ocean. This example is introduced also because it offers the opportunity to discuss the type of data that scientists have in order to reconstruct the past story of a phenomenon. It is specifically stressed that the Arctic sea ice extent is known in detail by the end of the 70s, but only recently data come from satellite measurements. Previously there were more piecemeal information relying on records of fishing expeditions and surveys performed by American submarines.
The data collected and reported in a graph (Figure 2.4) shows an evident extent decreasing over time.

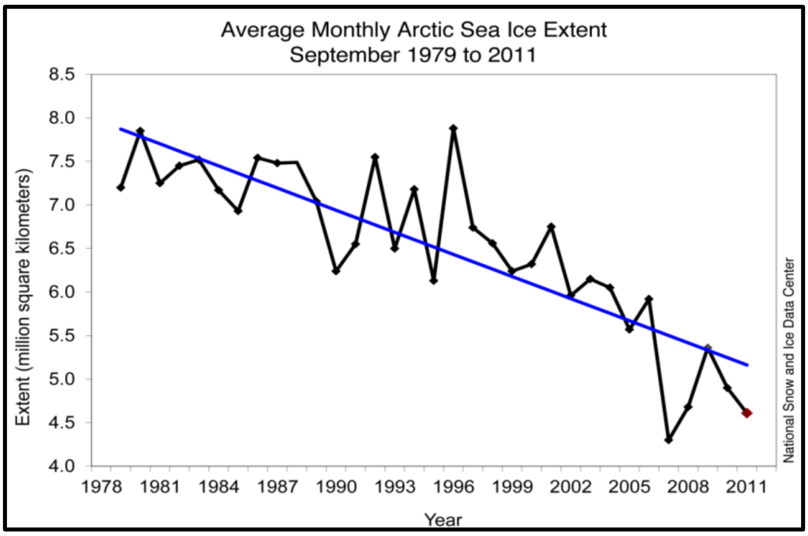


Figure 2.4. Average monthly arctic see ice extent (taken during the month of September from 1979 to 2011)

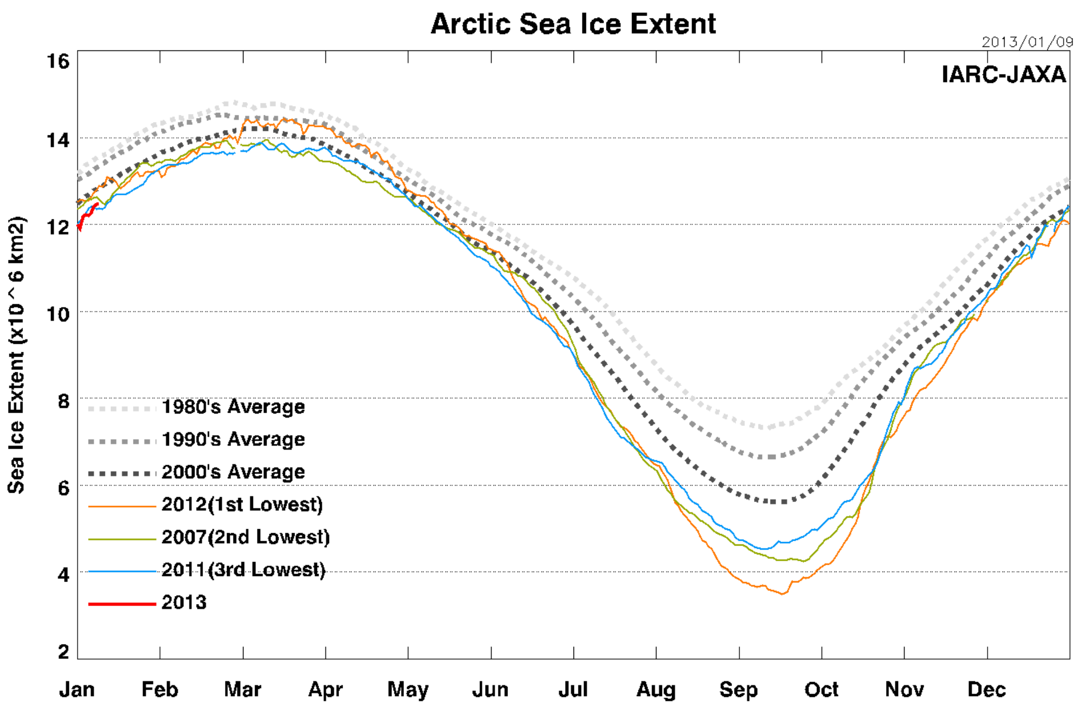


Figure 2.5. Arctic see ice extent (by monitoring month per month)

To enlarge the basis for evidence, it is then stressed that the reduction in the extent of glaciers is not the only effect observed. Also the thickness of the glaciers has been reduced (and it is reducing), as it is shown by the following graph:

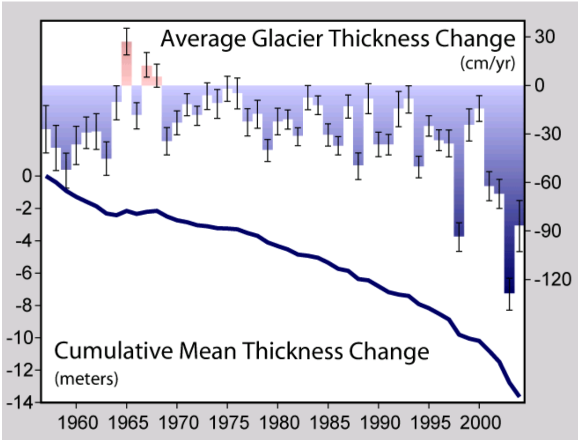


Figure 2.6. Average glacier thickness (from 1960 to 2005)

This figure shows the average rate of thickness change in mountain glaciers around the world. Still, it is highlighted that this kind of information, known as the glaciological mass balance, is found by measuring the annual snow accumulation and subtracting surface ablation driven by melting, sublimation, or wind erosion. These measurements do not account for thinning associated with iceberg calving, flow related thinning, or subglacial erosion. All values are corrected for variations in snow and firn density and are expressed in meters of water equivalent.
Furthermore, it is stressed that what it is recently observed is that, in the last few years, most of the Arctic ice is not part of the permanent ice but it is produced in the previous year. This is a new fact that implies that the volume of Arctic ice is shrinking fast.

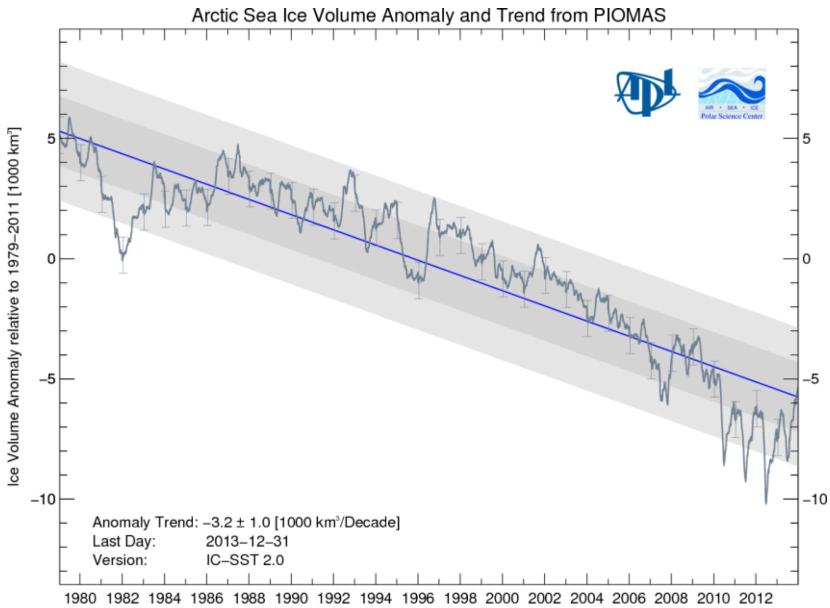


Figure 2.7. The picture above is from the University of Washington's Applied Physics Laboratory, and shows yearly Arctic Ice Pack volume anomalies.

What it is observed through these examples is that there are less and less extensive glaciers, more thin, more fragmented and made up of young ice, seasonal and potentially more vulnerable to temperature increases.
Such examples provide an evident base to argue that: 1) there has been an evident change in the global conditions that influence ice-extents; 2) the rate of change is increasing.
How these changes are related to what we can call “Clima”?
According to the introduction to climatology, a climate system is presented as the result of interactions that take place on a huge variety of spatial and temporal scales between five components: atmosphere, hydrosphere, cryosphere, lithosphere, biosphere.

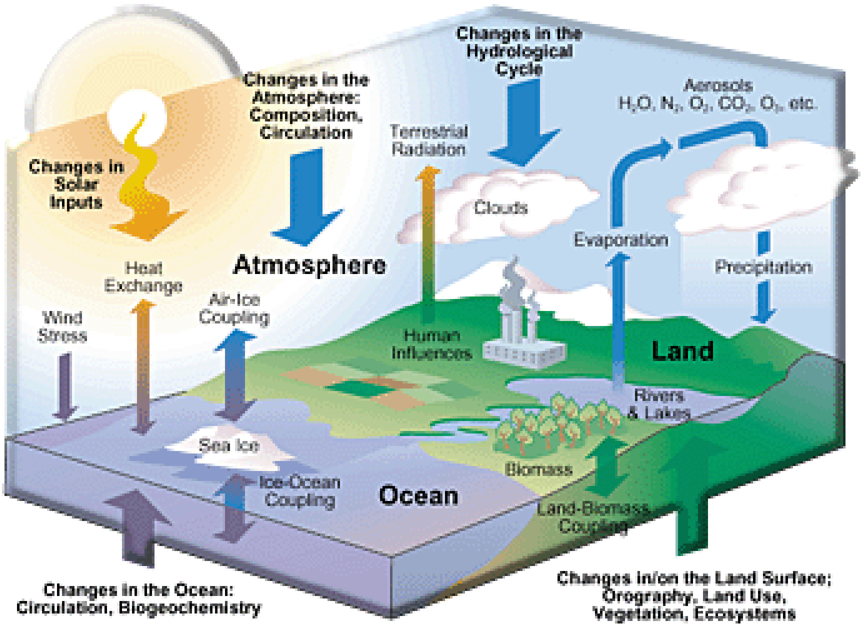


Figure 2.8. The Climate System.

Climate system is then described as a *complex system* in the specific sense that: i) there are many internal processes in action and they are described from many co-related variables/parameters; ii) many of the internal processes are not linear and they influenced each others.
If we consider Earth as a climate system and we try to investigate the causal net related to the observed phenomena of melting ices, we have to take into account that, in a climate system, it often happens that the variation of a parameter affects another which, in turn, has an impact on the first. When this happens we say that the system has some counteractions, called feedbacks. In order to introduce qualitatively the notion of feedback, two examples are presented:

1. the feedback between the change of the surface of the Arctic ice and the temperature of the first 150m of the Arctic Ocean;
2. the feedback between temperature rise and the hydrological cycle (water vapor, cloud cover).

As far as the first feedback is concerned, the surface of the ice varies during each year, in response to meteorological phenomena: it has a maximum at the end of the winter months and a minimum at the end of the warm period (around September). In the region covered by ice much of the solar radiation is reflected back into space; in areas free of ice solar, radiation penetrates into the Arctic

Ocean, is absorbed by the water and heats the ocean (the first 150 m). Hence, an increasing in the temperature of the water facilitates the melting of ice (this is a positive feedback).

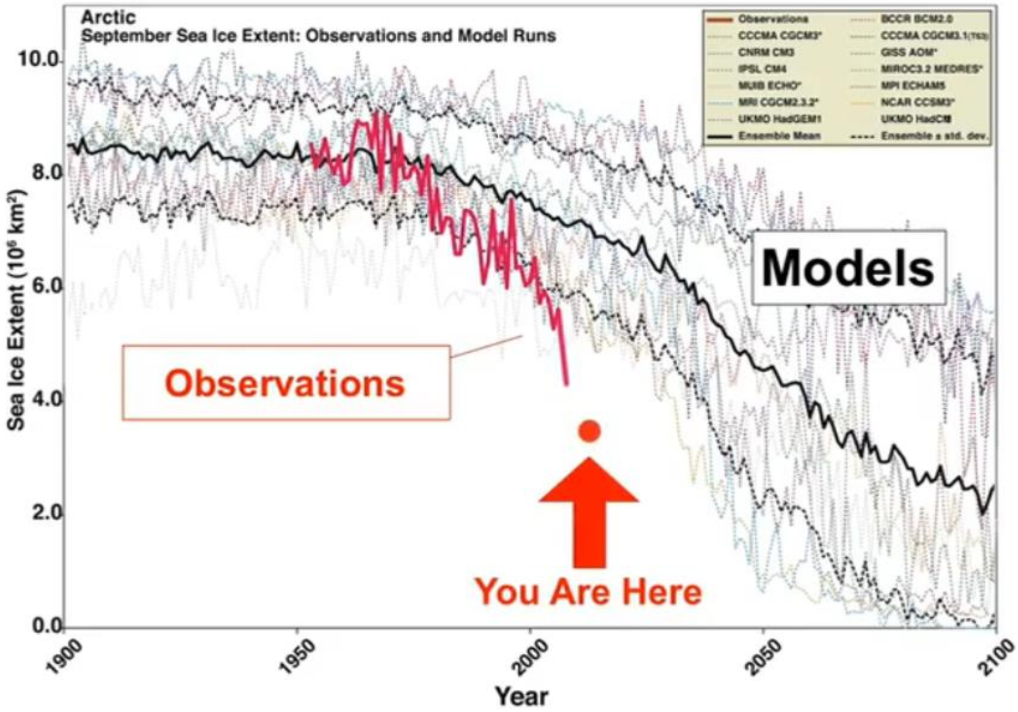


Figure 2.9. Match between model and observation

As far as the second feedback is concerned, an increase in temperature of surfaces covered by water implies an increase of the amount of steam of saturation in the atmosphere. A greater quantity of steam (a typical greenhouse gas) involves a greater absorption of the radiation emitted from the surface, as the graph below shows:

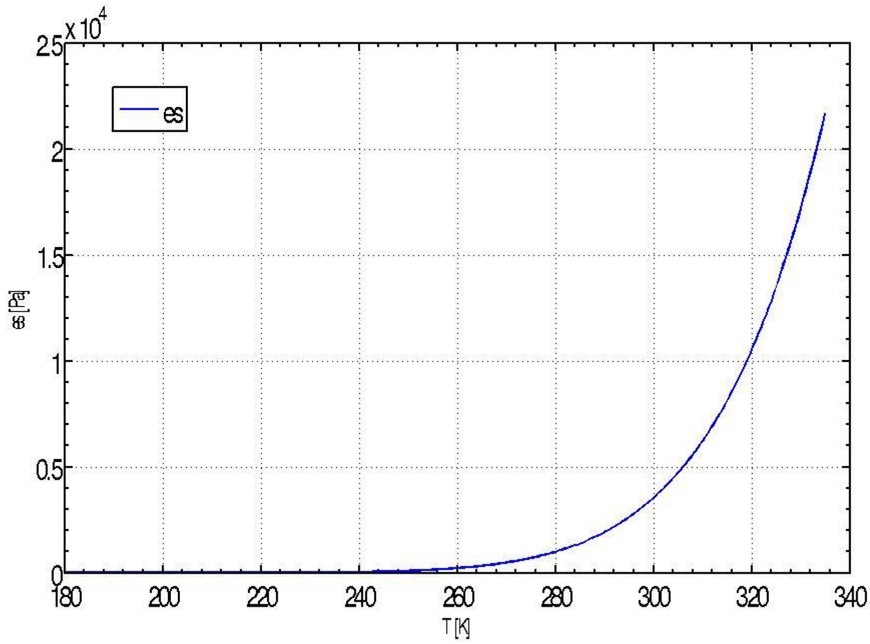


Figure 2.10. Graph of the steam in the atmosphere

This narrative presents another case of positive feedback (the increase of the temperature causes the increase of greenhouse gases which causes the increase of the temperature). Nevertheless, the question is much more complicate: What is the effect of this process *on* the cloudiness? What type of clouds are increased? Are they the same type or, do we have different clouds (base, height, optical properties)? What are the effects of these types of clouds? Do they increase the atmosphere absorbance (positive feedback) or do they increase the atmosphere albedo (negative feedback)?
This example is discussed to introduce a typical problematic issue that scientists are debating, since there is not yet a satisfying model able to interpret this feedback.
After this global introduction, the conceptual path zooms in on global warming and on the critical issue of how changes in the atmosphere composition (also due to anthropogenic causes) are circularly related to the temperature increase at the Earth surface.
Such a phenomenon is presented as the focus of the following experimental lessons.

2.1.2 Experimental Lessons (2 and 3)

Lessons 2 and 3 are two laboratory sessions characterized by the methodological choice of designing and implementing activities aimed at triggering peer-to-peer interaction, encouraging students to play with their ideas and giving examples of how to move from models to experiments and *vice versa*. In these two lessons the main aspects of the physics game of modelling are stressed and, within such a game, the back and forth relation between the composition of the atmosphere and the increase of the Earth's temperature surface is discussed in detail.
The two lessons foresee: i) an introduction of the fundamental physics concepts for analysing the phenomenology related to the interaction between radiation and matter; ii) the construction of models able to describe and interpret the previous phenomenology; iii) a re-analysis of the acquired knowledge on the interaction between matter and radiation in order to address specific problems related to CC, like GHE and its relation to GW.
More specifically, the students are, first of all, guided in getting acquainted with what happens to an object when it is exposed to a light source (sunlight or bulb). Results in physics education research support us in arguing that students tend to think that the temperature of the object will increase continuously and that, however, they have different positions with respect to how the change in temperature can depend on the colour of the object and on its material (Besson et al., 2010). For example, Besson and colleagues used an exercise in which an opaque object like a block of wood or a stone, and a transparent object like a block of glass, both with the same thermal capacity and same initial temperature, are exposed to sunlight. To a question about the temperature of the two objects, many students (35%) think that both objects reach the same temperature, 33% of the students think that both bodies reach a different temperature, 14% of those students tell that a transparent object needs more time to reach its final temperature than the opaque object (Besson et al., 2010). In the light of these results and, hence, expectations, the path foresees, as starting point, a sort of discussion guided by the teacher aimed at encouraging students to share with their classmates their knowledge and at discussing with them the reasonability of planning experiments explicitly addressed to study the temperature's profile of objects of different colours and materials.
Then, students are guided to construct a phenomenological and schematic model to introduce useful language for describing what happens to radiation when it interacts with an object. The model is simply based on a "conservation law" and it does not provide explanations for what happens at a

microscopic level. If you have an incident radiation that hits the object, one part out of the total amount of the incoming radiation is absorbed (a, coefficient of absorption), another one is reflected (r, coefficient of reflection) and another one is transmitted (t, coefficient of transmission). And, because nothing gets lost, we can write: $a_\lambda + r_\lambda + t_\lambda = 1$. Thanks to such a simple model it becomes possible to re-consider the experiments and to link the coefficients a, r, t to the properties (nature and colour) of the material and the wavelength of the incoming radiation.
The language (and the processes laying behind the language) allows some ideal bodies to be defined:

Table 2.2. Example of ideal bodies

		a(λ)	**t(λ)**	**r(λ)**
Blackbody	a body which absorbs all the radiations at the whole e.m. spectrum	1	0	0
Perfectly transparent body	a body which transmits all the radiation at a given wavelength	0	1	0
Perfectly reflective body	a body which reflects all the radiation at a given wavelength	0	0	1

A crucial point stressed in this part is that an object can be transparent for a given wavelength and opaque to another wavelength. This point is particularly relevant from an educational perspective, since several studies in physics education showed that also university students conceive properties like transparency as absolute properties of an object and not as a property that also depends on the wavelength of the radiation (Besson et al., 2010). Such a conceptual point is instead crucial for interpreting the GHE.
Finally the students are guided to re-process the acquired knowledge on the interaction between matter and radiation in order to move from experiments to models, and then to interpreter GHE and its relation with global warming in the light of the built models.
In the following, the two lessons are described in more detail:

- → **Lesson 2:** *Experiments on examples of interaction between radiation and matter (2.1.2.1)*
- → **Lesson 3:** *Experiments for the construction of a Greenhouse model (2.1.2.2).*

2.1.2.1 Lesson 2: *"Experiments on examples of interaction between radiation and matter"*

Summary

The interaction between matter and radiation is here investigated through a guided-inquiry (Fazio et al., 2012) aimed at leading the students through the development of simple experiments in which some objects are heated in the process of being exposed to a radiation source. In our specific case the objects are aluminium cylinders with different colours and the sources are bulbs with different spectrum.

In this lesson there are several conceptual points that students were asked to face explicitly:

- what characterizes thermodynamics behaviour or optic behaviour (e.g. to differentiate between heat and radiation);
- the concept of equilibrium (e.g. why an object exposed to sun reaches an equilibrium temperature and from what kind of properties the equilibrium temperature – or stationary temperature – is dependent);
- the concepts of absorbance (a), reflectance (r) and transmittance (t), as well as the Stefan-Boltzmann law and Kirchhoff's law.

In dealing with the previous concepts, it is emphasized that: *a-r-t* are properties which describe the interaction between matter and radiation; all bodies emit according to their temperature; in a stationary condition there is a balance between the incoming and the out-coming energy. Fundamental steps of this phase are to construct the phenomenological relation between absorbance of a body and its temperature and to stress absorbance as the crucial property for interpreting the thermal effects of radiation.

In lesson 2, the students are first of all guided to grasp the sense of the matter-radiation interaction by progressively construct the following relations and their physical meaning[2]:

(1) $E_{in} - E_{out} = \Delta U \rightarrow E_{in} - E_{out} = cm\Delta T \rightarrow R_{in} - R_{out} = cm\Delta T$

(2) $a_\lambda + r_\lambda + t_\lambda = 1 \rightarrow a_\lambda R + r_\lambda R + t_\lambda R = R_{in}$

(3) $E = \varepsilon_\lambda \sigma T^4$ [Kirchhoff law as the expression of the relation between absorptivity and emissivity $\rightarrow a(\lambda) = \varepsilon(\lambda)$]

First set of relations: from $E_{in} - E_{out} = \Delta U$ *to* $R_{in} - R_{out} = cm\Delta T$

The first balance reasoning, expressed by the set of equations (1), is presented by bringing it back to the first law of thermodynamics, that the students are supposed to know, and by making some assumptions about the physical systems that are being considered and about the type of interaction between them and the environment. The first law of thermodynamics is indeed expressed by the

[2] "E_{in}" and "E_{out}" of the first relation represents energy, instead "E" of the third relation represents the power emitted per unit of surface. We used the same symbol by varying only the subscript because students were useful to indicate the energy with the "E" letter and also the power expressed by the Stfan-Boltzmann law with the "E" letter.

equation: Q – W = ΔU (where Q is heat, W is work, U is internal energy). The first assumption is that the variation of the energy of the system is manifested only in terms of temperature variation of the system, $\Delta U = cm\Delta T$, that is we are considering systems and situations in which, for example, phase transitions and/or internal chemical reactions are not considered. In this case it also visible that the equilibrium condition is expressed by $\Delta T = 0$ and, in terms of energy balance, this means that the whole *incoming energy* is equal to the whole *outgoing energy* ($E_{in} = E_{out}$). The second assumption is that, in order to change the internal energy of a system, it is required that the system has to exchange energy with the environment. According to the first law that the students know, the system can exchange energy in different ways, heat or work. In our context, what is important to emphasize is the conservation of the exchanged energy, i.e. the energy entering the system minus the outgoing one are equal to the variation of internal energy. This allows us to say that the formulation $E_{in} - E_{out} = \Delta U$ does not stress how energy is exchanged (whether in terms of heat or work). This focus allows us to introduce a second hypothesis, namely that the energy exchange between system and environment occurs also by exchanging electromagnetic fields, that is by absorbing and emitting radiation ($E_{in} \equiv R_{in}$; $E_{out} \equiv R_{out}$) and our need to focus on the radiation exchanged. In this way the first principle assumes a form that lends itself to be used explicitly to make energy balances and to consider also the radiation as "exchangeable" energy. In this introduction of the set of relations (1) in terms of its relationships with the first principle two important things are highlighted:

- the emphasis is on the "energy balance", that allows us to speak of calorimetry not only in terms of thermal equilibrium, but also in terms of "process of energy exchange" (there is something in input, something in output and something that happens inside);
- the introduction of the "heating due to the radiation", that allow us to affirm that there is not only a heating due to heat or mechanical work.

Second relation: $a_\lambda + r_\lambda + t_\lambda = 1$

The second balance relation expressed by equation (2) is presented as a zoom in on the inner radiation. In particular it is stressed that this balance allows a new language to be introduced to establish what can happen to the incoming radiation when it interacts with an object.

A slab of some homogeneous substance is considered and $a_\lambda, r_\lambda, t_\lambda$ are introduced to express respectively the fractional absorption (absorptivity), reflection (reflectivity) and transmission (transmissivity) of the slab. The law of conservation of energy implies that: $a_\lambda + r_\lambda + t_\lambda = 1$.

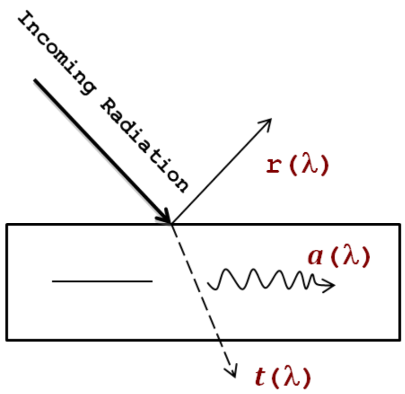


Figure 2.11. Slab of materials in interaction with an incoming radiation

What kind of information can one get from this balance? In this balance there is a very delicate physical issue: this relation can be analysed from two perspectives, optical and thermodynamic. From the "optical perspective", what matters are the fractional reflection and transmission (when usually I consider an optical model I put the accent on the reflected light and on the transmitted light). In this case the "thermodynamic perspective" is also needed. Indeed the fractional absorption has a thermal behaviour, it "heats" the body or, better, it changes the body's temperature.
Then, the crucial point of this relation is to make the students aware that here we are extending the radiation properties, from optical (and electromagnetic) to thermodynamic and this means to consider the radiation as an energy carrier able to heat a body.
In order to keep the balance, if we consider again the first set of relations (1) and we imagine that the slab is in a steady state (temperature doesn't change), we cannot forget that the slab also has to emit radiance:

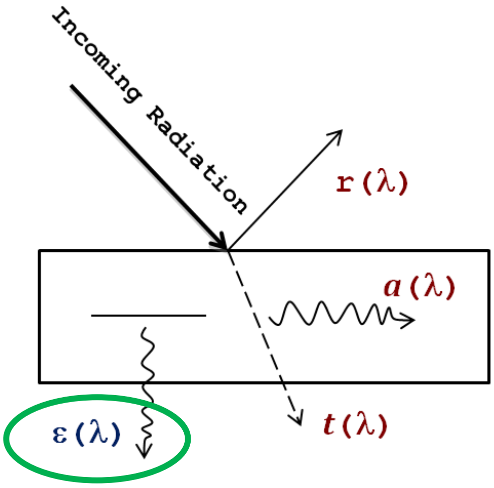


Figure 2.12. The role of emissivity

Such a claim introduces the third relation.

Third relation: $E = \varepsilon_\lambda \sigma T^4$
This relation affirms that all the material objects, only because of their temperature, emit energy, in the form of electromagnetic radiation.
In the history of physics, the first studies about the emitted radiation were based on an ideal body, called black body, which is characterized by: (a) complete absorption of all incident radiation (hence the term black); (b) maximum possible emission in all wavelengths in all directions. In other words, it is a complete absorber and it emits of radiation at any wavelength.
In 1879, Stefan empirically found that the irradiance of a black body was related to temperature by the law[3]: $E = \varepsilon_\lambda \sigma T^4$, where the constant σ = 5.67 x 10^{-8} W m^{-2} K^{-4}.
In 1884, Boltzmann derived theoretically this equation. Earliest accurate measurements of spectral irradiance are credited to Lummer and Pringsheim (1899). They observed the now well-known emission spectra for black bodies at several different temperatures shown in Fig. 2.13.

[3] As it is already anticipated, "E" is expressed in terms of power emitted per unit surface [W m^{-2}].

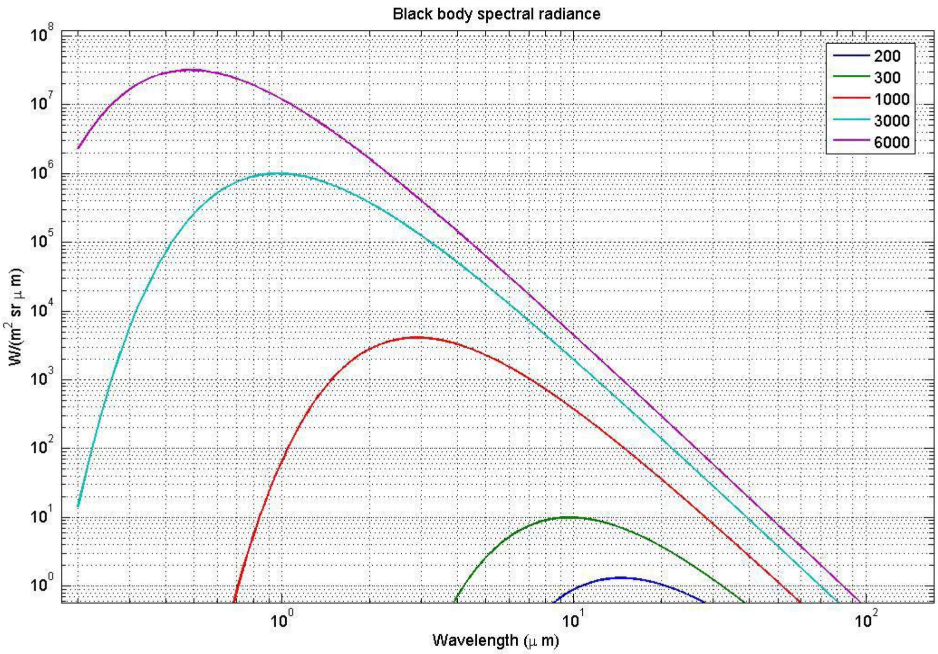


Figure 2.13. Emission spectra of a black body at different temperature

The spectral radiance emitted by a body of temperature T can be exactly reproduced as the product of two spectral quantities: the emissivity ε_λ and a function called Planck distribution $B_\lambda(T)$. With secondary school students, we didn't need to enter the mathematical formulation of Planck function. What is fundamental to stress is the importance of taking into account the fact that Planck function depends non-linearly from the temperature and that the emissivity is a quantity that can take values from 0 to 1 (when considering matter whose dimensions are much larger than the wavelength of interest).

What must be kept in mind is that the energy absorbed by a body depends on the incident electromagnetic waves and on the absorptivity of the slab, while the emitted energy depends on emissivity of the slab and its temperature.

So, focusing on the energy radiated by a body, the Stefan-Boltzmann equation give us the information that a body which has a temperature T emits energy[4] in an electromagnetic form at the rate in accord to the relation: $E = \varepsilon_\lambda \sigma T^4$.

[4] If we talk in temrs of energy we have to multiply by the surface.

MINDBUILDING: “The relationship between absorption and emission”

The absorptivity a_λ approaches unity as the medium (whose dimensions are here assumed to be large compared with wavelength) becomes optically thick. Generally the absorptivity changes with λ but one may define a **grey body**,that is a body that has a constant absorptivity, and therefore absorbs with an efficiency that is independent of wavenumber. In case the grey body is opaque (that is the transmissivity is zero), it will have also a constant reflectivity since: $a + r = 1$.

Consider two infinite plates that exchange energy only radiatively. One is a blackbody (b) and the other an opaque greybody (g). Suppose the plates are in thermal equilibrium – stationary conditions – so that they absorb and emit same amounts of energy. Suppose further that this equilibrium state is obtained with plates having different temperatures. One can write a balance equation for the absorbed and emitted radiance for each of the two plates:

blackbody: $\varepsilon \cdot S_g \cdot a_b + \varepsilon_b \cdot S_b \cdot r \cdot a_b = \varepsilon_b \cdot S_b$

greybody: $\varepsilon_b \cdot S_b \cdot a = \varepsilon \cdot S_g$

where*:* $S_i = \sigma T_i^4$ (*Stefan-Boltzmann law*)

We know that a black body is defined as a body that absorbs completely radiation incident upon it (i.e.$a_b = 1$) and whose emissivity is 1. Inserting these values in both equations and inserting the ‘g’ equation into the ‘b’ balance equation one obtains:

b: $aS_b + rS_b = S_b$
g: $aS_b = \varepsilon S_g$

The first equation is an identity (and therefore cannot determine the two unknown properties), while the second one states that there is a relationship between absorptivity and emissivity that depends on material property and on the temperature of the two bodies.
We now introduce a conducting medium between the plates: the medium drives the system out of equilibrium because energy flows from the plate at higher temperature to the plate at lower temperature. As soon as conduction takes place the radiation tries to restore its equilibrium by transferring energy radiatively from the colder plate back to the warmer plate: this process would violate the second law of thermodynamics. It follows that the **radiative equilibrium temperature** of the grey plate, defined as the temperature at which it emits energy at the same rate as it absorbs energy from the surrounding, must be the same as that of the black plate: therefore $S_b = S_g$, and equation ‘g’ reads: $\varepsilon\sigma T^4 = a\sigma T^4$.

The all-important result is obtained, which is called **Kirckhoff law:** $\boxed{\boldsymbol{\varepsilon = a}}$ **.**
Same reasoning can be applied to any arbitrary spectral range and we obtain: $\boxed{\boldsymbol{\varepsilon_\lambda = a_\lambda}}$

This simple equation has important consequences. It is in fact very difficult to measure directly the spectral emissivity of a body, while it is much simpler to measure its absorptivity.
Absorptivity assumes a very important and central role.

By matching the whole physical considerations made so far, students are hence asked to brainstorm to answer these questions: *In which ways do objects interact with radiation? What kind of properties can we define from the interaction?*

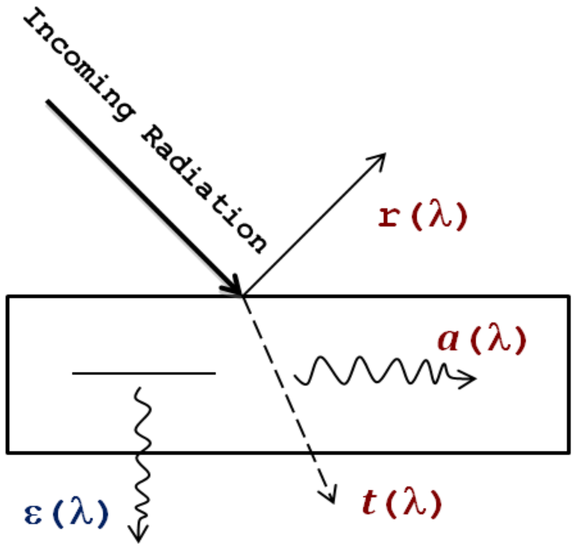


Figure 2.14. Matter-radiation interaction

When the radiation interacts with an object, the way in which the three indexes $a_\lambda, r_\lambda, t_\lambda$ change defines some qualitative features of the object. At a given wavelength, strong reflectors, for example, are generally weak absorbers (i.e., snow at visible wavelengths), and weak reflectors are strong absorbers (i.e., asphalt at visible wavelengths).
Students are then guided to think about a sort of classification of the objects following the way in which they interact with a particular kind of radiation. Indeed if an object behaves as a blackbody then $a_\lambda = 1$, and it follows that $r_\lambda = 0$ and $t_\lambda = 0$. If it behaves like a perfect window $t_\lambda = 1$, $a_\lambda = 0$ and $r_\lambda = 0$. Again, for any opaque surface $t_\lambda = 0$, so radiation is either absorbed or reflected: $a_\lambda + r_\lambda = 1$.
In the table below there are some examples discussed with the students.

Table 2.3. Example of materials and their properties

λ (micron)	***A***	***r***	***T***	**“Visible”quality**	**Materials (e.g.)**
All wavelength	1	0	0	Blackbody	?
0.5	0	0	1	Transparent	Perfect glass
0.5	0.9	0.1	0	Dark grey, opaque	Plastic
0.5	0.4	0.6	0	Light grey, opaque	Aluminium
10	0.9	0.1	0		Glass
10	0.5	0.5	0		Aluminium
10	0.98	0.02	0		Water

The following step has been to guide the students to recognise that the properties (a,r,t) are not absolute but “interaction” properties and for each object they are defined only at a fixed wavelength. In this sense, properties that are not “visible” to our eyes are introduced, namely properties that are not explored through “visible light”. In order to address such a crucial point, the electromagnetic spectrum is introduced by stressing that it includes electromagnetic waves at different wavelengths (or different frequencies), most of them not visible with our eyes. The visible range is only a part of it, that part that has wavelength values from around 400nm to 800nm.

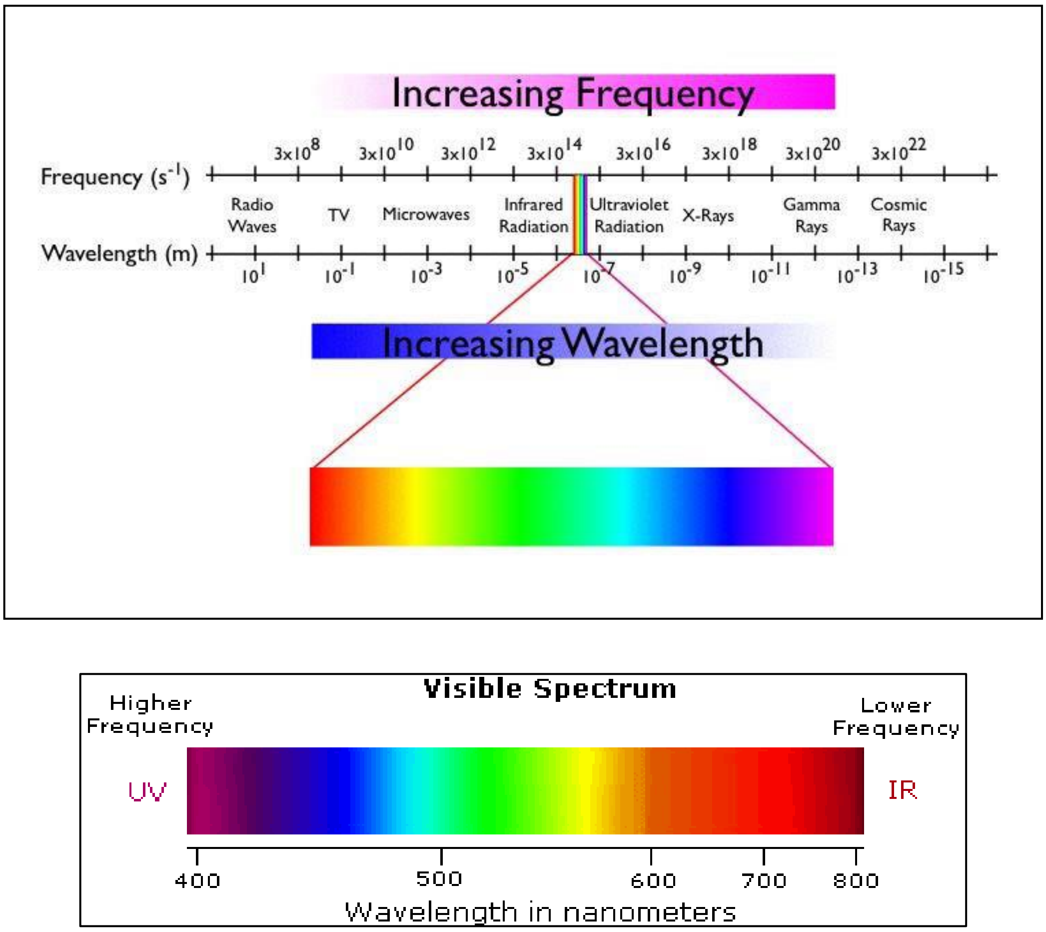


Figure 2.15. Electromagnetic spectrum

At this point we make a stop with students in order to reflect on the modelling choice we need to make to model the interaction, that is the choice to simplify the spectrum and to consider only two ranges of radiation:

– Solar or short-wave (SW) radiation, emitted by the Sun; these correspond to ultra-violet, visible and infra-red wavelengths between about 0.1 and 4 μm;
– Thermal or long-wave (LW) radiation, emitted by the atmosphere or the Earth's surface; these correspond mainly to infra-red wavelengths, between about 4 and 100 μm.

Students are hence guided to reflect on the implications of this is a strong simplification: on one hand it leads to loose, for example, the colours; but on the other hand it let to construct a model of interaction between Sun-Earth-Atmosphere without losing the physical essence that we need to interpret the greenhouse mechanism (as it is described in lesson 3).

To sum up, in this first part of lesson 2 a new language and new ways of looking at the interaction between radiation and matter are introduced so as to foster students to progressively focus their attention on the facts that:

→ properties like "being black, transparent" are interaction properties, i.e. they depend both on the object and on the incoming radiation;
→ all bodies emit according to their temperature;
→ in stationary condition (TD equilibrium) there is a balance between the incoming and the out-coming energy.

The new language and the new foci of attention are expected to guide the students to carry out and to analyse what happens in experiments in which some aluminium cylinders are exposed to different radiation sources (bulbs). The experiments represent the second part of lesson 2 and are carried out directly by students on the basis of a guide. In these experiments, two types of cylinders are considered: (i) aluminium cylinders that were coloured in different ways (black and opaque, white and opaque, polished aluminium) but they had the same thermal capacity (same materials, same mass, same volume and also same shape); (ii) plastic cylinders that are "colourless" and that had the same thermal capacity of the aluminium ones (but a bigger volume). Each cylinder has a hole which needs to insert the temperature sensor.

The cylinders are not only presented, but their physical properties are discussed. The most important concept that students need to pay attention before starting the experiment is the "thermal capacity". Students were asked to reflect what it means to have objects with the same thermal capacity and why it has been made this experimental choice. Indeed, if they heat the cylinders throughout "heat", for example by putting them in a box with water posed on a burner, they could deduce (from the law of calorimetry) that all the cylinders will be reach for sure the same equilibrium temperature. But, *what will happen when they heat the cylinders with the same thermal capacity through radiation?*

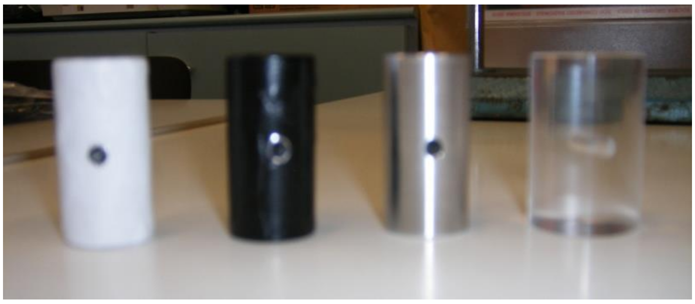


Figure 2.16. The cylinders

The radiation sources were composed by different kinds of bulbs with different electromagnetic spectra (e.g. incandescent bulb; fluorescent bulb; IR bulb; LED).

Students are divided into five groups and each group have: a couple of cylinders of different colours (e.g. 1 black al. and 1 white al.; 1 white al. and 1 polished al.; 1 black al. and 1 plastic), a bulb, 2 temperature sensors, 1 graph interface connected to a computer with a data collection program, 1 support for the sensors and 1 for the bulb.

Figure 2.17. The Instruments of the experiments

The experiments consist in gathering data of the temperature[5] variation of the cylinders versus time[6], during the whole process comprised of three phases: heating of the cylinders, when the bulb is switched on, stationary state after that the cylinders reached the equilibrium temperature and, finally, cooling of the cylinders, when the bulb is switched off.

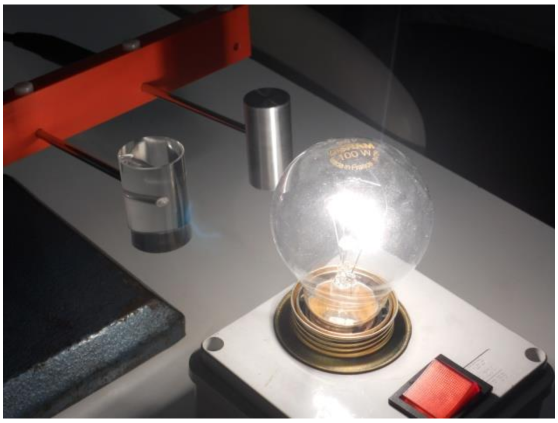


Figure 2.18. Example of experiment

During the experiments students are required to discuss in the group by following a set of questions (see annex F1) through which they are asked to:

– rethink of the properties and the laws treated in the first part of the lesson;
– reflect on the equilibrium through some qualitative examples;
– use some properties just introduced in order to explain aspects of the experiments they were carrying out;
– foresee the kind of graphs they could expected at the end, in relation with their different cylinders and bulb;

[5] Intended as the average temperature of the body.
[6] It was decided to set up data collection with one sample per minute.

– interpret the results they obtained at the end of the experiment, by comparing the expected graph with the experimental one.

The five experiments are organized as represented in the following figure:

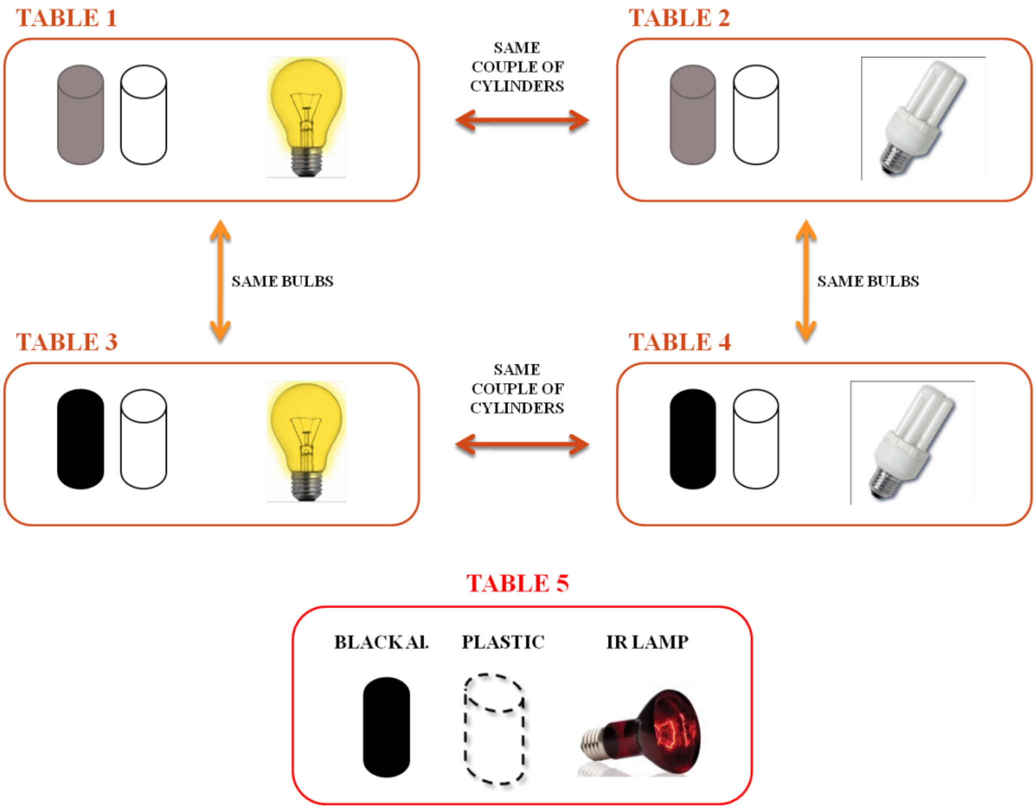


Figure 2.19. The five experiments

At the end of the experiments the groups are required to compare the graphs obtained by the different groups and to collectively think about the different previsions made by each group and the different interpretation they gave. Three kinds of comparison are required: (i) same objects but different bulb (table 1 vs. table 2; table 3 vs. table 4); (ii) different objects same bulb (table 1 vs. table 3; table 2 vs. table 4); (iii) completely different couple of objects and particular bulb (table 5 vs. the others).

The following figure is an example of the kind of graph students obtained from the experiments:

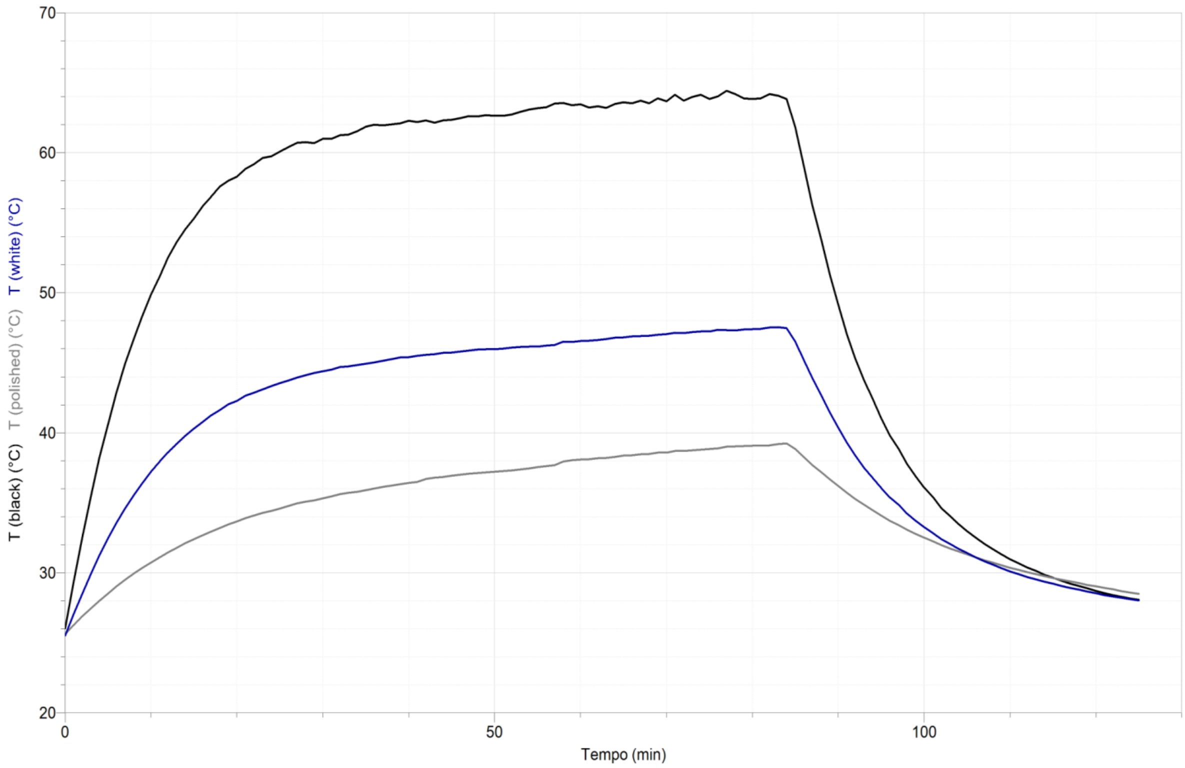


Figure 2.20. Graph of the three aluminium cylinders (black-white-polished)

In the discussions, what comes out from the students and is worthwhile to stress is that the graphs highlight that different objects reach different equilibrium – stationary – temperatures even if they are exposed to the same bulb. Frequently several students, during their peer-to-peer work, draw graphs like those reported in figure 2.21. In the figures, T_A represents the equilibrium temperature reached by the black object (A) and T_B the equilibrium temperature reached by the white object (B). For both these groups of students the decision appears debated and somehow controversial. Indeed, at a first moment they draw the two curves with the same profile (for A and B) but with two different equilibrium temperatures. Then, they change their mind, delete the profile of object B and decide that the two objects have to reach the same equilibrium temperature, but in a different way: the white object takes more time than the black one to reach the same equilibrium – stationary – temperature. *How can we then interpret the fact that objects with the same thermal capacity reach different equilibrium temperature?* This observation leads to stress the fact that the cylinders have however different colours, then we need to take into account different physical properties if we heat the object by "heat" or using the "radiation". In order to understand this delicate point, students are encouraged to focus their attention on the property of absorptivity and on the fact that the colour is related to the absorbance of a body.

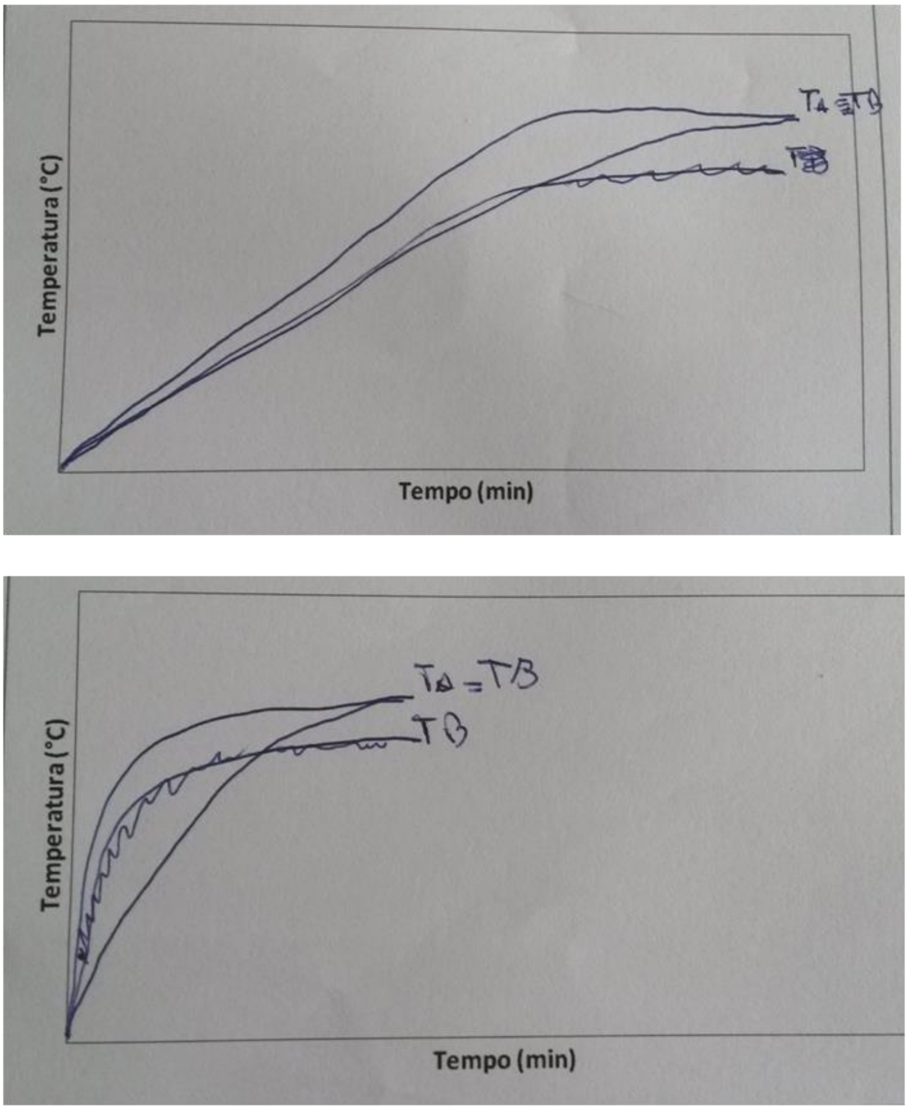
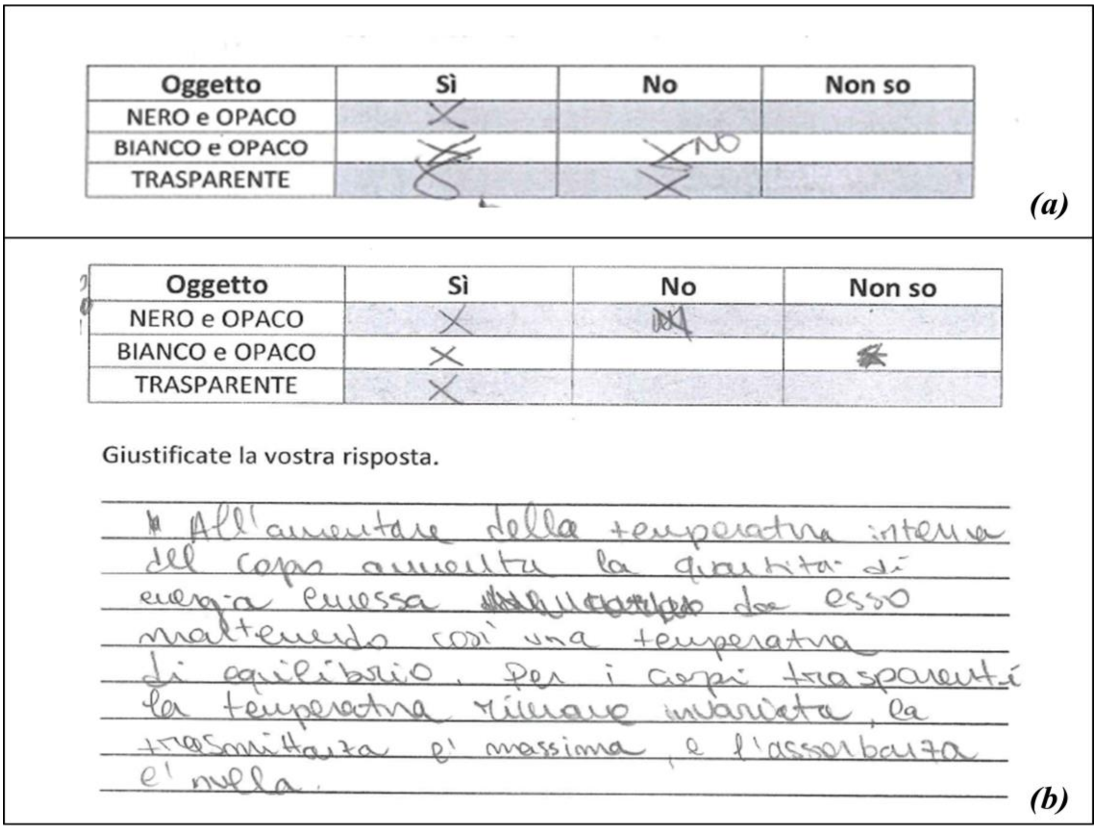


Figure 2.21. Students' graphs

A second aspect of the experimental graphs that is usually noticed by the students, concerns the profile of the graph: even though the bodies reach different equilibrium temperature, the profile of all the graphs is the same. *How must we interpret the achievement of the plateau (T_e)?* This observation led to discuss on the concept of emissivity and in particular on the relationship between absorption and emission.



(a)

Oggetto	Sì	No	Non so
NERO e OPACO	X		
BIANCO e OPACO	X	X NO	
TRASPARENTE	X	X	

(b)

Oggetto	Sì	No	Non so
NERO e OPACO	X	X	
BIANCO e OPACO	X		X
TRASPARENTE	X		

Giustificate la vostra risposta.

All'aumentare della temperatura interna del corpo aumenta la quantità di energia emessa da esso mantenendo così una temperatura di equilibrio. Per i corpi trasparenti la temperatura rimane invariata, la trasmittanza è massima, e l'assorbanza è nulla.

Figure 2.22. Excerpts from students' exercise on equilibrium temperature

Figure 2.22 shows a table of one group of students that, during the experiment, were discussing about the following situation: "three objects are exposed to the sunlight for a same indefinite time (long enough), the first object is black opaque, the second one is white opaque and the third one is transparent. Does they all reach an equilibrium – stationary – temperature?". From the table, again, this seems to be a debated issue. Students are not sure that an object exposed to a radiation source reaches an equilibrium temperature. The idea seems to be that, probably, the object can increase its temperature in an indefinite way. This could appear very strange, because just to refer to their common sense, all these students probably experienced in their life that an object cannot increase its temperature indefinitely. Nevertheless, it is well known that, when they reason in terms of physical properties, they find it problematic to recognize what are the properties they have to consider and how such properties can formalize daily life experiences. The first group (figure a) did not find a solution, whilst the second one (figure b) did it, after that the group's discussion got to focus on the concept of emissivity and on the relation among the absorbed and the emitted energy.
In order to fix this point in a collective discussion, the graphs obtained from the experiments have been considered and the profile of the graphs has been analysed, by "dividing" it into three parts (see Figure 2.23).

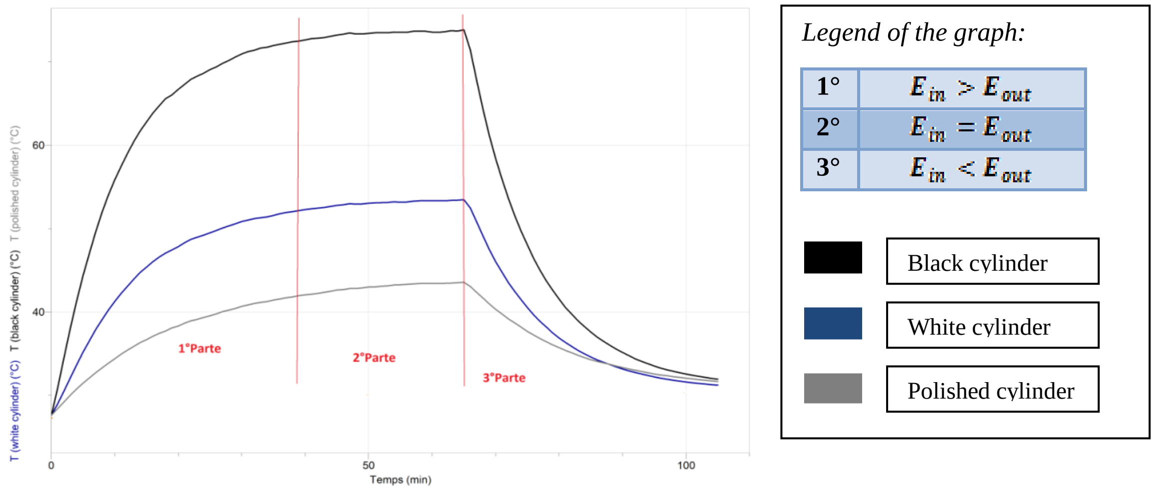


Figure 2.23. Graph of the three cylinders (black, white and polished) exposed to the same bulb

Thanks to the concept of emission, it becomes possible to provide an interpretation, in terms of energy balance, to the experiments carried out and in particular, to provide an interpretation of the three parts of the profiles:

– ***1st part "The increase of temperature":*** T increases because the energy absorbed in the time unit is greater than the power emitted by a body. Particularly, the reason for which the temperature initially rises is that the power emitted by the cylinder depends on the fourth exponentiation of his temperature (T^4) while the power absorbed is constant. in this way, the temperature of the cylinder rises until the "two power" are the same[7];
– ***2nd part "The stationary state":*** T remains constant because the body emits the same energy which it absorbs;
– ***3rd part "The decrease of temperature"***: T decreases because the energy emitted is greater than the one absorbed.

What it is particularly difficult for students is to remember the emission of a body.
The other important point to stress is the concept of transparency by using the experiment carried out by the group of students at table 5, which used the Plexiglas cylinder and the IR bulb.

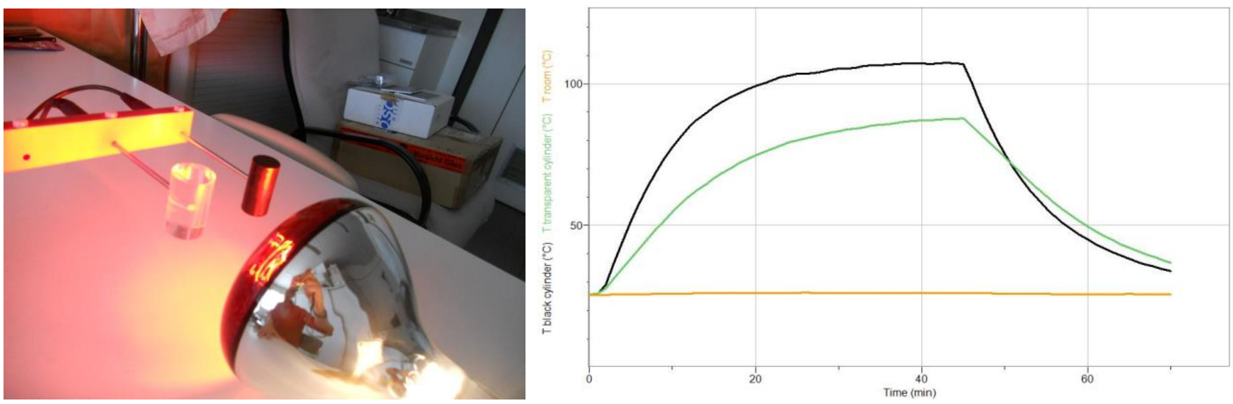


Figure 2.24. The black and the plexiglas cylinder exposed to the IR bulb

[7] Furthermore, the difference among the different cylinders' profiles is due to the fact that "*a*" depends on the frequency of the incoming radiation (as well as on the colour of the object), whilst "ε" depends on the frequency of the outgoing radiation (far infrared): in front of such a disequilibrium, the body reacts by increasing its temperature so as to arrive at emitting what it absorbs.

By referring to their common experience, students usually expect that the plexiglass cylinder, because of its transparency, does not reach a high temperature. By observing the graph obtained from such a group, they are usually very surprised from the fact that the Plexiglas cylinder reaches almost the same high temperature of the black one.
In this regard it is useful to reason on the graph of an experiment in which the plexiglass cylinder was exposed to three different types of bulbs:

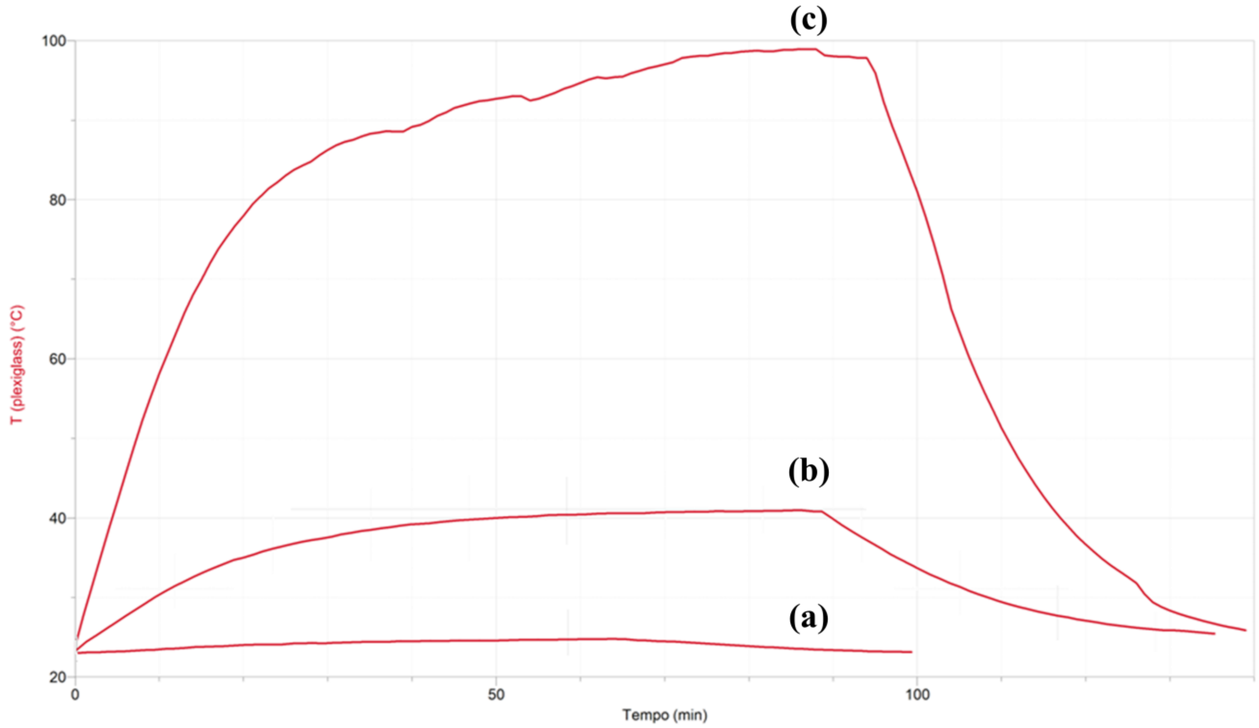


Figure 2.25. Graph of the Plexiglas cylinder exposed to three different radiation sources

The curve (a) represents the plexiglass cylinder exposed to the radiation of a fluorescent bulb. The curve (b) represents the plexiglass cylinder exposed to the radiation of an incandescent bulb. The curve (c) represents the plexiglass cylinder exposed to an infrared bulb.
This graph is very useful to show to students that the difference in variation of the T of the three curves can be seen as a difference in how the cylinder interacts with the three types of radiation, for instance in case (c) the absorption is much greater than in the other two cases. This example has helped students to rethink the concept of transparency and the use of word "transparent", indeed a Plexiglas cylinder that is "transparent" with respect to the visible light becomes "black" with respect to the infrared one.
To sum up, this second part of lesson 2 leads the students to construct a phenomenological relation between the absorbance (*a*) of a body and its temperature (T), through lab-experiments and activities. In particular the students are led to focus their attention on:

→ the property of absorbance as crucial concept for interpreting the thermal effects of radiation;

→ the fact that absorbance is not an “absolute” feature of an object, since it depends on the kind of radiation that interacts with the object itself;

→ the fact that also transparency is not an absolute feature and that is dependent on the absorbance of the object at different sources;
→ the importance of reasoning in terms of balance.

2.1.2.2 Lesson 3: *"Experiments for the construction of a Greenhouse model"*

Summary
The aim of lesson 3 is to guide students to construct a model of a "greenhouse", which can explain why and how a change in atmospheric composition can produce temperature rise on the Earth's surface. A very simple model is chosen based on a set of essential hypotheses, including: the Earth is modelled as a black body; the atmosphere is modelled as a uniform and homogeneous layer (metaphorically imaged like a sheet of plastic); radiation is assumed constant and average only on two wavelengths, in particular short waves for incoming and long waves for the outgoing; and the absorbance of the atmosphere is assumed to have only two values, according to the two wavelengths. In spite of these simplifications the model is argued to be suitable to enable students to get acquainted with reasoning in terms of energy balance and to understand, through some steps, the formal relation between atmosphere absorbance and earth surface temperature (Besson et al., 2010).
The significance and the power of this model is that it strongly and directly stresses that if the absorbance of the atmosphere (for long wave radiation) increases, then the Earth's surface and atmospheric temperature increases in order to keep the balance with the incoming radiation. This relation between absorbance and temperature has several implications. One is that absorbance can be interpreted as the bridge between anthropogenic causes (i.e. greenhouse gasses emissions) and the physical explanation of GW. Another implication of that relation is the opportunity it gives to exemplify, by means of physical phenomena, like the melting ices, the concept of feedback mechanism: the melting ice causes an increase of water vapour, carbon dioxide and methane gas (that are some of the major greenhouse gasses), so their emission in the atmosphere causes an increase of absorbance that in turn causes an increase of temperature (example of circular causality, so that causes and effects cannot be clearly distinguished).

At the beginning of this lesson, the ideas of the second lesson are rearranged, always from an experimental point of view, so as to emphasize the concepts of absorptivity and emissivity related to a specific experiment that "simulates" the GHE.
The physical reasoning is held by the balance relationships introduced and developed in the previous lesson:

(1) $E_{in} - E_{out} = \Delta U \rightarrow E_{in} - E_{out} = cm\Delta T \rightarrow R_{in} - R_{out} = cm\Delta T$

(2) $a_\lambda + r_\lambda + t_\lambda = 1 \rightarrow a_\lambda R + r_\lambda R + t_\lambda R = R_{in}$

(3) $E = \varepsilon_\lambda \sigma T^4$ [Kirchhoff law as the expression of the relation between absorptivity and emissivity → $a(\lambda) = \varepsilon(\lambda)$]

The balance reasoning, set out these relationship, will be extended to specific experiment of "simulation" of the GHE. These relationships are now used in experiments carried out to study the GHE. Like in the previous lesson, students are divided into five groups. Each group has the following materials: one box with, at the back, one black aluminium plate (simulation of the earth), one plastic lid (simulation of atmosphere), one bulb, one sensor of temperature put at the back of the aluminium plate, one interface linked to the computer for gathering data.
The experiment consists in gathering data about the temperature variation of the aluminium plate versus time, during the whole process that, new, goes through four phases: heating of the plate directly exposed to the radiation source without lid; steady state; re-equilibration after that a "transparent" lid is added (*Does the T of the plate incresase or decresase when you put the lid?*), and cooling of the system when the bulb is switched off.

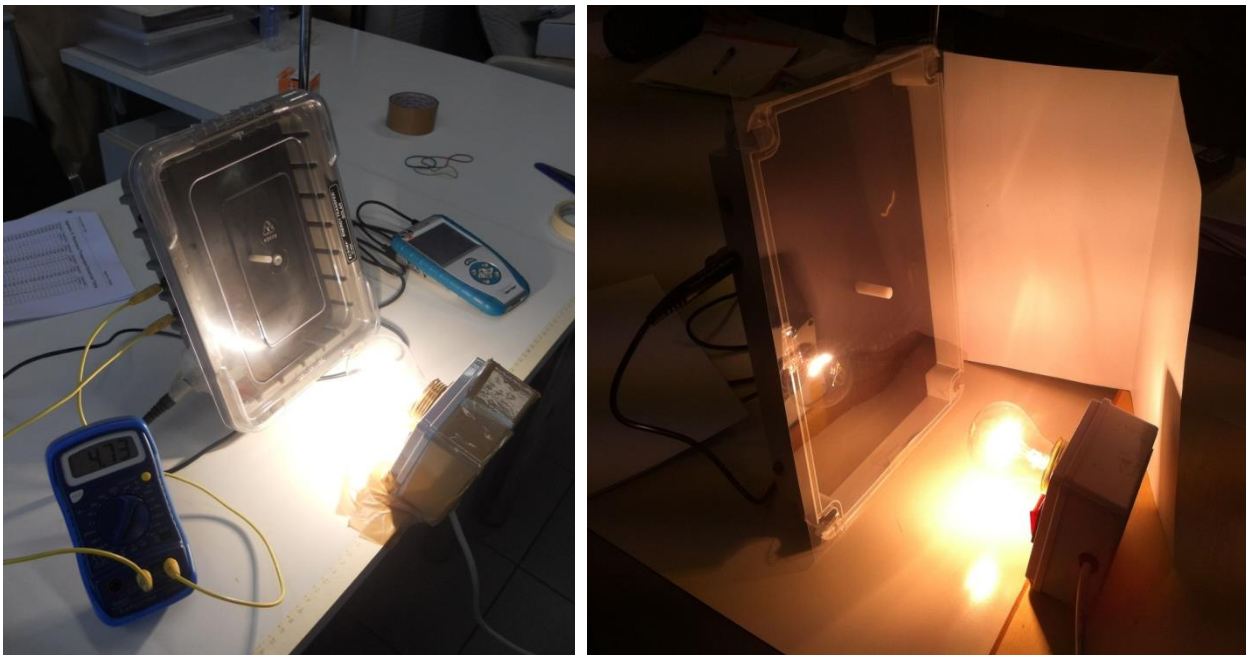


Figure 2.26. Example of the experiment on greenhouse effect

Before starting the experiment, students are guided to collectively reflect on the feature of the "box". The black aluminium plate is placed at the bottom of the plastic box, just to not touch the back of the box but to leave a very small space between the back and the plate. Again, the temperature of the plate is measured by means of a temperature sensor which is placed at the back of the aluminium plate. In this way the sensor is not directly exposed to the light of the bulb and revealed a realistic (average) temperature of the plate. The same measurements are repeated with the insertion of the plastic lid on the top of the box which it is posed in order to create a "greenhouse effect"[8].
During the experiments students are required again to discuss in the group by following a set of questions (see annex F2) through which they are asked to:

[8] Other several considerations helped to problematize the existence of convective heating and how it is possible to manage it.

– rethink the properties and the laws treated during lesson 2 and re-manage the competencies acquired during the previous experiments;
– apply their knowledge to interpret the experiment they are carrying out;
– imagine how to model the interaction radiation(sun)-atmosphere-earth depending by the variation of the absorbance of atmosphere ($0 \leq a_{ATM} \leq 1$) and earth ($0 \leq a_{EARTH} \leq 1$);
– predict and to draw graphs of the temperature of the plate versus time in the two cases, without the lid and with the lid;
– interpret the results they obtained at the end of the experiment, by comparing the expected graph with the experimental one.

The following figures are examples of typical graphs that students obtained from the experiment:

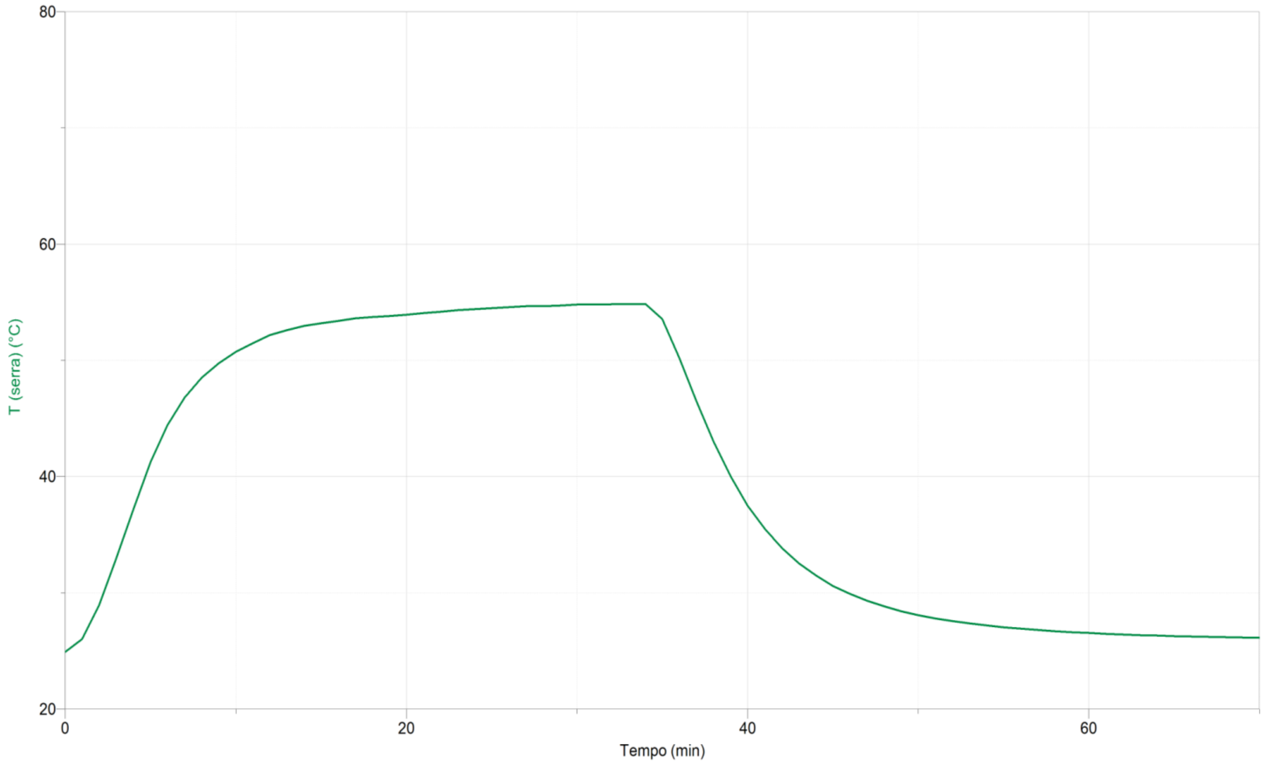


Figure 2.27. Graph of the greenhouse box without the lid

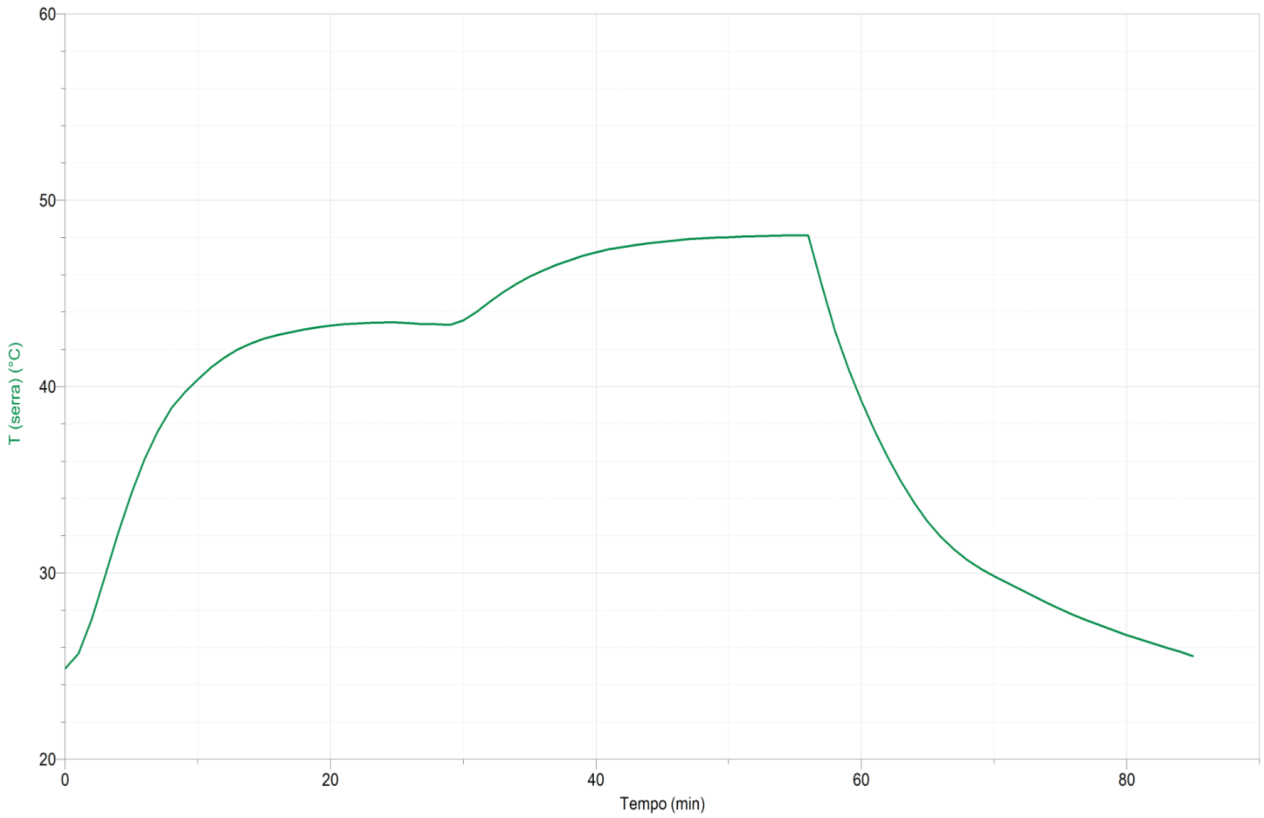


Figure 2.28. Graph of the greenhouse box with the lid in the second part

At the end of the experiments the groups are required to compare the graphs obtained and to collectively think about the different previsions made by each group and the different interpretation they gave.

In the collective discussions, the comparison of two kinds of previsions are typically the issue that more attracts the attention: some students foresee an increase of the temperature of the system after the insertion of the lid and other students foresee a decrease of the temperature of the system (an example of drawings from different groups id reported in Figure 2.29).

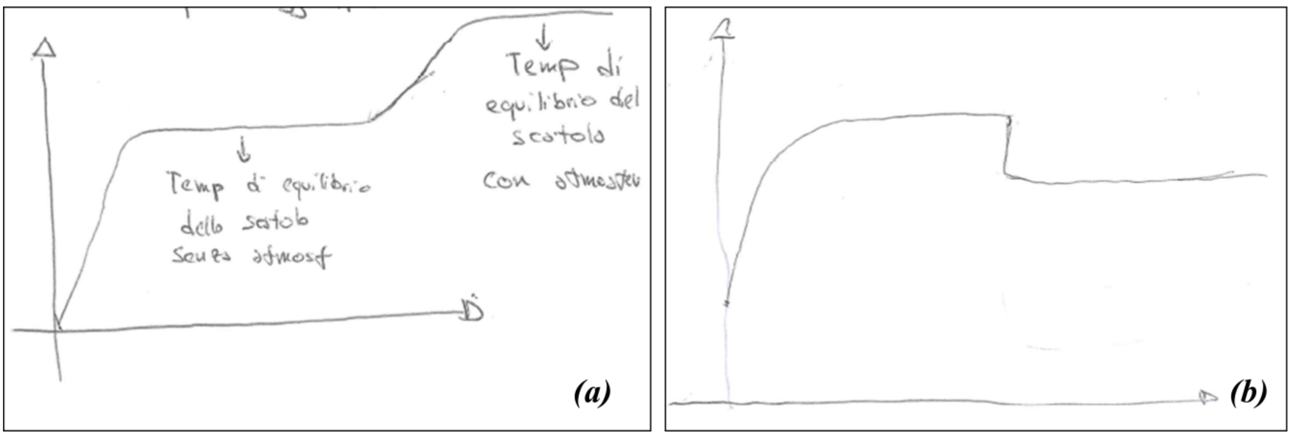
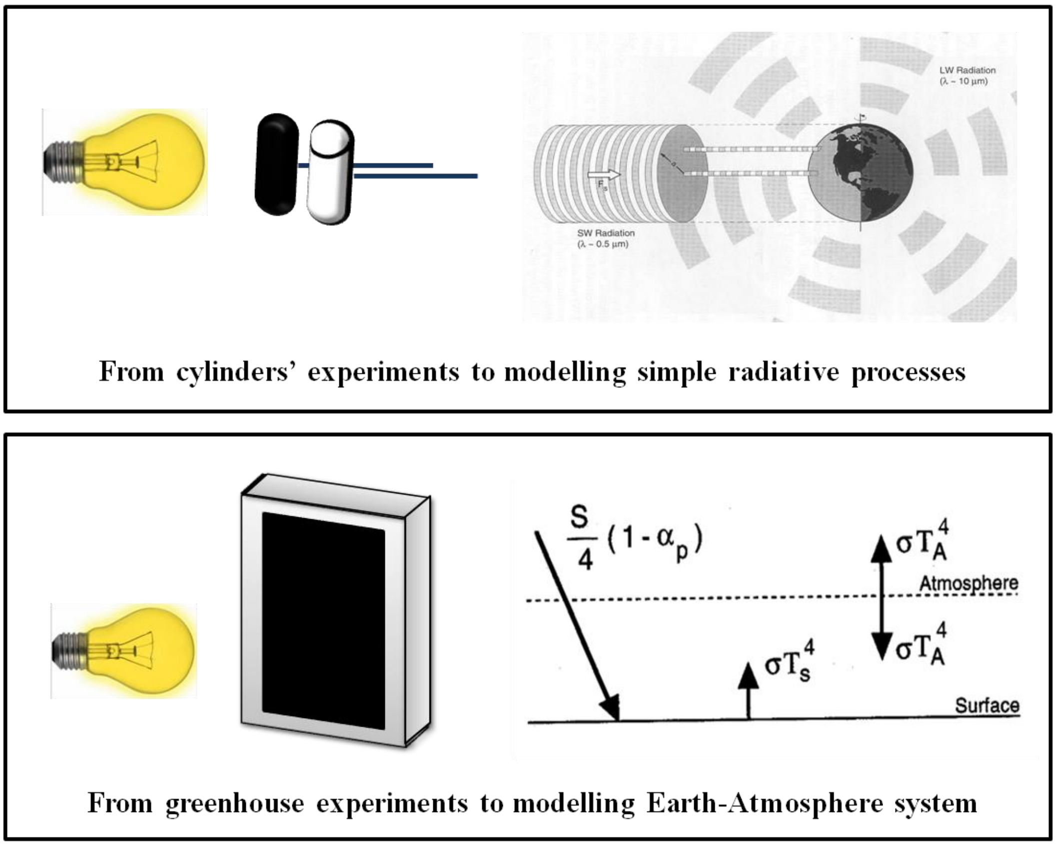


Figure 2.29. Excerpts from students' works

These different previsions trigger very interesting discussions about the feature of the atmosphere and its composition. Indeed, students who foresee the decrease think that the reflection (albedo) of the lid is much more than the absorption, so the presence of that kind of atmosphere reduces the temperature of the system. That kind of discussion is precious for a teacher since it allows the concept of feedback (positive and negative) to be explored in the last part of the lesson.
As already said, the sense of these experiments was to guide students toward the construction of a model of greenhouse able to explain how and why the presence of the atmosphere (or a change in the composition of the atmosphere) can produce a change in the value of the temperature of the earth’s surface. In this sense, this is the very essence of the conceptual path. Thanks to the experiments and the peer-to-peer activities, students are now ready for modelling. In order to do that all the experiments are re-analysed so as to stress how they can represent models of the interaction Earth-Sun-atmosphere. At first, the cylinders’ experiments are re-read to recognise, in them, the modelling of a simple radiative process Sun-Earth, where the cylinders represented the Earth and the bulbs the Sun. At second, the greenhouse experiments are re-read to recognise, in them, the modelling of the interaction between the Sun and the system Earth-atmosphere, where the Sun is represented by the bulb, Earth by the black aluminium plate and the atmosphere by the plastic lid (see Fig. 2.30).



From cylinders’ experiments to modelling simple radiative processes

From greenhouse experiments to modelling Earth-Atmosphere system

Figure 2.30. From experiments to models

As we already said, students are led to think that, in these models, an important choice to simplify the spectrum is made and only two range of radiation are considered:

- Solar or short-wave (SW) radiation, emitted by the Sun; these correspond to ultra-violet, visible and infra-red wavelengths between about 0.1 and 4 μm;

- Thermal or long-wave (LW) radiation, emitted by the atmosphere or the Earth's surface; these correspond mainly to infra-red wavelengths, between about 4 and 100 μm.

These two wavelength ranges represent spectral regions of significant black-body emission at temperatures of about 6000 K (a temperature representative of the solar photosphere) and 288 K (the Earth's mean surface temperature).

Let's move now to explore and develop the two models we used, by following the notes of Rizzi (Rizzi, 2014):

- **Model 1: balance of planetary climate**, that is a model of interaction between the Sun and a planet (Earth), without Atmosphere;
- **Model 2: balance of Earth-Atmosphere system**, that is a model of interaction between the Sun and the Earth with the introduction of Atmosphere.

Model 1: balance of planetary climate

The construction of the model starts by observing that the sun emits a nearly constant flux of energy (called luminosity): $W_O = 3.9 \times 10^{26}$ W.

Since space is effectively a vacuum and energy is conserved, the amount of energy passing outward through any sphere with the sun at its centre should be equal to the total energy flux from the sun (luminosity). If we assume that the flux density is uniform over the sphere, the average flux density S_d (irradiance of the solar emission) at a particular distance is:

$$S_d = \frac{W_0}{4\pi d^2} \quad (2.1)$$

When we consider the Earth and its mean distance from the sun (=1 astronomical unit or au), the irradiance gets a special name and it is called Total Solar Irradiance (TSI), whose value is approximately: S= 1370 Wm^{-2}. Of course, TSI shows high variability at many time scales.

What happens to TSI when it interacts with the Earth's surface? As figure 2.31 shows, the flux of SW radiation of irradiance *S*, intercepted by the planed, has a cross-sectional area πa^2. A fraction of the intercepted irradiance, the **planetary albedo** α, is reflected back to space by the planet's surface and atmospheric components. Thus, the fraction that is not reflected is: *(1- α)S*, is absorbed by the Earth's surface and distributed across the globe as it spins in the line of the beam.

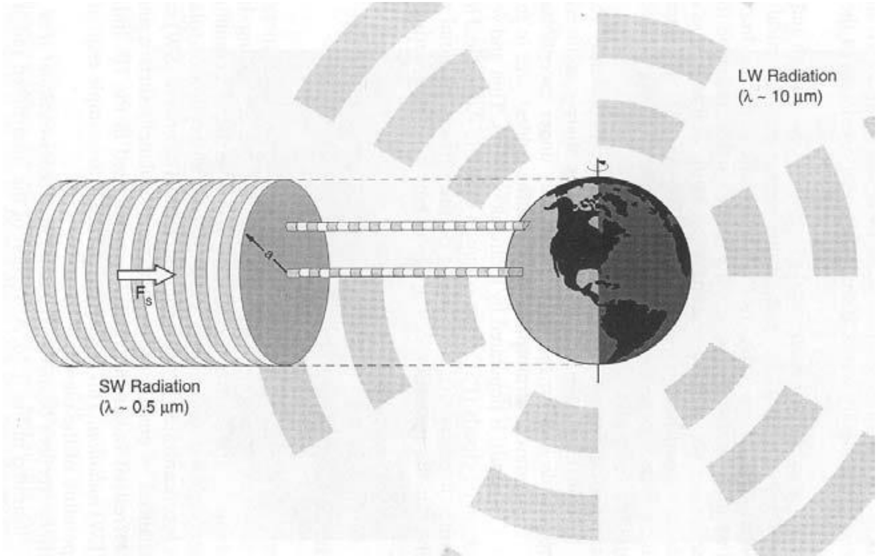


Figure 2.31. Long-term radiation budget for any planet (taken from Rizzi, 2013-2014)

Over timescales long, compared to those controlling the redistribution of energy, Earth (in absence of forcing external to the system) can be considered in thermal equilibrium, so that the incoming energy must be equal to the ongoing one. Consequently, absorption of solar radiation (shortwave - SW) must be balanced by emission to space from the planet's surface radiation (longwave - LW). This basic principle leads to a simple estimate of the long-term mean temperature of the planet.

In order to maintain thermal equilibrium, the Earth must re-emit to space LW radiation at exactly the same rate. If the emission to space of terrestrial radiation, also referred to as the outgoing LW radiation, is considered uniform over the globe surface, it can be described by the Stefan-Boltzmann law, that describes the energy flux in the time unit integrated over wavenumber that is emitted by a blackbody at temperature T. In this last step, we are assuming that Earth behaves as a black body and atmosphere does not have any role in the process of "equilibration".

Calculating the total LW flux emitted over the whole surface of the planet ($4\pi a^2$)[9] and equating the result to the SW energy absorbed in unit time by the planet results in the simplest energy balance equation:

$$(1-\alpha)S\pi a^2 = 4\pi a^2 \sigma T_e^4 \quad (2.2)$$

Where T_e is the equivalent blackbody brightness temperature of Earth. Therefore:

$$T_e = \left[\frac{(1-\alpha)S}{4\sigma}\right]^{1/4} \quad (2.3)$$

T_e provides a simple estimate of the planet's effective emission temperature.

In our case, in which we are considering Earth, an incident SW irradiance of S = 1370 Wm^{-2} and an albedo α_p = 0.30 lead to an equivalent blackbody temperature for Earth of T_e = 255 K. This value is some 30 K colder than the global-mean surface temperature, T_s = 288 K. The discrepancy between T_S and T_e shows that the model was too simple and is becomes plausible the hypothesis that such

[9] In this expression *a* is the radius of the Earth.

discrepancy is due to the presence of an atmosphere and to the different ways the atmosphere processes SW and LW radiation. Although nearly transparent to SW radiation the atmosphere is almost opaque to LW radiation. SW radiation therefore passes freely to the earth's surface, where it can be absorbed, but LW radiation emitted by the planet's surface is absorbed by the atmosphere, that in turn emitted in the same way in all the directions.
After the presentation of the model, students are guided to reflect on *what are hypothesis/choices at the basis of this model*, that is:

- the planet is considered in a stationary state so as to use a balance relationship;
- an average situation is considered, where the average is made over a long period when compared with the period of revolution of the Earth (this means that seasonal variations and, therefore, also daily variations can be neglected);
- Earth is modelled as a perfectly spherical ball (hypothesis on its geometric properties) and a black body (hypothesis on its physical properties);
- radiation is modelled as if it were irradiated by a light beam perpendicular to the cylindrical section (geometric assumptions);
- an overall average energy absorbed by the body is considered (e.g. given that the Earth is assumed as a spherical surface, the net energy entering the poles is less than that at the equator), as well as a global average energy emitted;
- the atmosphere is not taken into account.

The calculus of the surface’s temperature and its comparison with the experiments carried out with and without the plastic lid in the box lead the class to argue that, probably, the last hypothesis was to strong and it must be "unlocked" in a more refined model.
Although the big simplifications, such a model is still able to give real estimate of what would be the temperature of the earth in the absence of atmosphere (255 ° K). The question to explore with students is: *Why the model "works"?* To make a model means selecting what information are necessary to explain a certain situation. For example, if we think back to our experiment when we heated the cylinder with the light bulb, we are interested in the information "colour", whilst if we heated by putting it on a stove, we do not care the colour of the object, but its thermal capacity. Hence, in our modelling we selected the information that interest us to make an estimate of the temperature at the Earth's surface (in the absence of atmosphere), by explicitly explaining our choices/hypothesis, and then we can complexify the model.

Model 2: balance of Earth-Atmosphere system (A climate model with one atmospheric layer and a surface layer)

In this new model the role of an atmosphere is considered and it is modelled in two different ways. Firstly it is assumed to be a *blackbody* for LW radiation, but transparent to SW radiation[10]. Then, it is modelled as a *grey body* for LW radiation, but still transparent to SW radiation.
Let us start by assuming atmosphere as a blackbody for long-wave. In this case, the model is based on the following hypotheses:

[10] The feature of the atmosphere is important for establishing its role. If, for instance, it is considered an inert atmosphere, composed by gases like Oxygen and Nitrogen that do not interact with radiation, the atmosphere acts as a “transparent” body both at SW and LW radiation. In that case, following our model, it might be like to have no atmosphere.

- the incoming *net* radiation (S_{net}) in atmosphere is assumed to be equal to:
  $S_{net} = (1-\alpha_p)\frac{S\pi a^2}{4\pi a^2} = (1-\alpha_p)\frac{S}{4}$ where α_p is the planetary albedo, i.e. the part of radiation which is reflected by the atmosphere and by the surface Planet and, hence, $(1-\alpha_p)S\pi a^2$ is the net flux of energy that is absorbed by the Earth's surface and distributed across the globe's surface ($4\pi a^2$) as it spins in the line of the beam. As a consequence $(1-\alpha_p)\frac{S}{4}$ represents the *flow density* of the radiation coming from the sun and absorbed by the Earth, i.e. the energy that Earth absorbs per unit time and unit area;
- the Earth is assumed to behave, i.e. to emit radiation, like a black body by following the Stefan-Boltzmann law referred to energy emitted per unit time and unit area: $E = \sigma T_S^4$, where T_S represents the temperature of the Earth surface;
- the atmosphere is assumed to be transparent to the SW radiation whilst it absorbs all the LW radiation:

λ (micron)	**a (atm)**	**a (surf)**
0.5 (SW)	0	1
10 (LW)	1	1

- to assume that, at the first level of approximation, the atmosphere can be represented as a single layer, physically and chemically homogeneous.

With this model, the energy balance at the top of the atmosphere is the same as in the previous energy balance model. Since the atmospheric layer absorbs all of the energy emitted by the surface below it, in this model the only radiation emitted to space is from the atmosphere that emits like a blackbody.
So, why should this new model lead us to have a higher temperature at the Earth's surface? In order to investigate the implications of the presence of the atmosphere, let us unpack the various parts of the system (see Fig. 2.32).

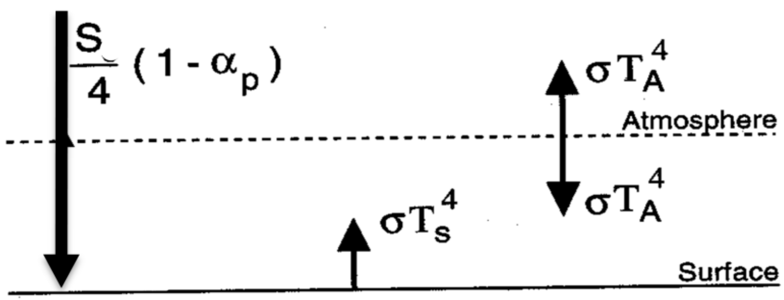


Figure 2.32. Earth-Atmosphere system

A further assumption is to consider the atmosphere as a layer in local thermodynamic equilibrium so we can assume to be in the conditions for the validity of Kirchoff law ($\varepsilon_\lambda = a_\lambda$).
Hence, the energy balance at the top of the atmosphere is:

$(1-\alpha)\frac{S}{4} = \sigma T_A^4$ (*2.4*)

At the surface of the Earth, the energy balance is:

$\left(1-\alpha_p\right)\frac{S}{4} + \sigma T_A^4 = \sigma T_S^4$ (*2.5*)

In the relation at the Earth's surface, the incoming radiation is the sum of two terms: the radiation coming from the sun and passing through the atmosphere (that is transparent for SW) and the radiation emitted by the atmosphere, modelled as a blackbody.
If we solve the two equations and, since we assume to be in the conditions for the validity of Kirchoff law (ε=a), we obtain that: T_S=303°K. This value of temperature is overestimated with respect to the real temperature surface.
It is reasonable to think that the limit of this model is that no radiation emitted by the Earth's surface is assumed to be transmitted directly into space, since it is completely absorbed by the atmosphere. Thus, let see what happens if we model atmosphere as a grey body for long-wave, and not as a blackbody.

λ (micron)	**a (atm)**	**a (surf)**
0.5 (SW)	0	1
10 (LW)	0≤a≤1	1

By complexifying the atmosphere, the two balance equations, at the top of the Atmosphere (2.4) and at the Earth's surface (2.5), change and can be written as follows.
At the top of the atmosphere, the energy balance is:

$\left(1-\alpha_p\right)\frac{S}{4} = \varepsilon\sigma T_A^4 + (1-\varepsilon)\sigma T_S^4$ (*2.4b*)

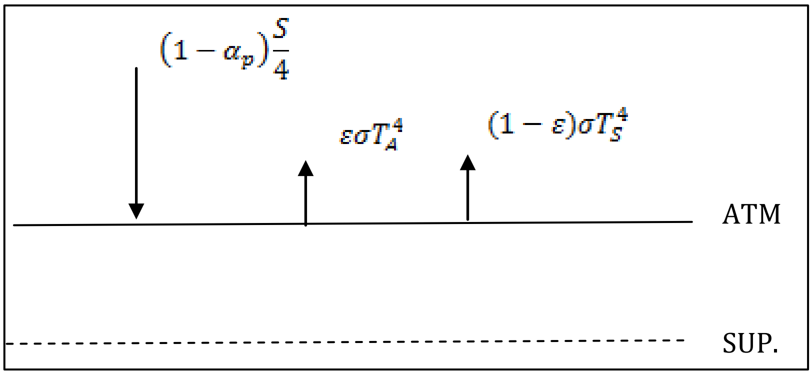


Figure 2.33. Energy balance at the top of the atmosphere

The first member of the equation represents the incoming radiation meanwhile the two terms of the second member respectively represent the two contributions of the outgoing radiation, in particular:

(*i*) the first term refers to the emitted radiation, at a given temperature[11], atmosphere modelled as grey body (for which emits according to the law $\varepsilon\sigma T_A^4$, con $\varepsilon < 1$); (*ii*) the second term refers to the radiation coming from the earth and transmitted[12] by the atmosphere.
The surface Energy balance is:

$$(1-\alpha_p)\frac{S}{4} + \varepsilon\sigma T_A^4 = \sigma T_S^4 \quad (2.5b)$$

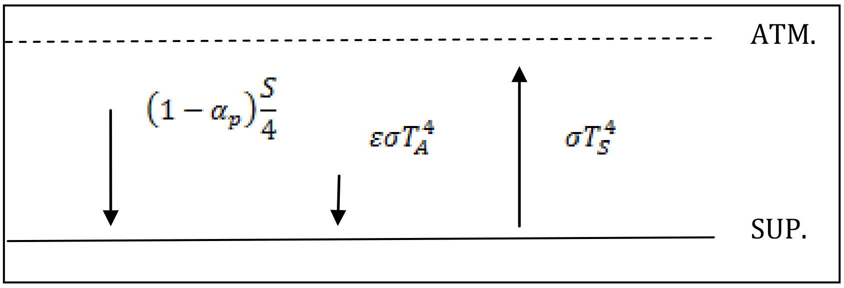


Figure 2.34. Surface Energy balance

The two elements of the first member of the equation respectively represent: *i)* the incoming radiation, and *ii)* the radiation emitted by the atmosphere at a given temperature and received by the earth. The second member of the equation represents the radiation emitted from the earth (assumed as black body).
The solutions of the system of equations, with respect to T_S and T_A, are:

$$T_S^4 = \frac{2T_e^4}{2-\varepsilon} \quad ; \quad T_A^4 = \frac{T_e^4}{2-\varepsilon} \quad ; \Longrightarrow \quad T_S^4 = 2T_A^4$$

Since we are in the validity of Kirchoff law (ε=a), we can write the two solutions dependent by the absoptivity (*a*):

$$T_S^4 = \frac{2T_e^4}{2-a} \quad (2.6)$$

$$T_A^4 = \frac{T_e^4}{2-a} \quad (2.7)$$

Given the solutions, it is possible to make a prediction of the temperature with respect to different values of the parameter *a*.
If the *a*(atm) at LW is equal to 1, and we are in the case of the previous model where the atmosphere at LW is assumed to behave like a black body. In this case, we get again T_S=303°K[13].

[11] T_S is the temperature at the Earth's surface and T_A the temperature of the atmosphere.
[12] The expression (1-ε) represents the transmittance (t).
[13] The limit of this situation is that none of the radiation emitted by the Earth's surface is transmitted into space. Everything that goes into the space is what is emitted by the atmosphere, which has its own temperature and emits into the space.

For a value of a(atm)=0.5, the temperature at the Earth's surface is T_S=274 °K, that is almost the real value. Again, for a value of a(atm)=0.7, the temperature becomes T_S=284 °K. Since the real mean surface temperature is close to 288°K, we can invert our reasoning and derive a value for a "mean grey atmospheric absorptivity":

$$a = \frac{2\left(T_S^4 - T_e^4\right)}{T_S^4} = 2 - 2\frac{T_e^4}{T_S^4} = 0.77 \quad (2.8)$$

To sum up, in table 2.4, we can observe that a greater value of a(atm) corresponds to a higher value of the surface temperature. This means, physically, that *if the atmosphere's absorbance increased, Earth has to increase its temperature in order to maintain the balance with the incoming radiation.* This is exactly the crucial point that the students are required to grasp.

Table 2.4. Variation of T_S dependent to *a(atm)* for LW

a **(atm) for LW**	$\mathbf{T_S}$
0	255.0 °K
0.5	274.0 °K
0.7	284.0 °K
1	303.3 °K

The strict relationship between absorptivity and temperature, highlighted by the model, leads the students to think about the fact that an increase in the absorbance of the atmosphere[14] can cause an increase in the temperature of the Earth's surface (and also in the Atmosphere), as well as an increase in the temperature of the Earth's surface or in the atmosphere can cause an increase in the absorbance of the atmosphere. This is particularly important because, despite the big simplifications of the model this relationship does not admit a simplified reading in terms of linear causality and open toward the idea of feedback.

What are the limits of this model?

At first, in this model it is assumed that the atmosphere is an homogeneous layer so it is not included in the model the fact that the gases which compose the atmosphere vary with altitude. Usually, gases are denser near the ground, although this is not valid for all the gases, for example ozone absorbs more in the high atmosphere. In general, the gases that absorb infrared decreases with altitude. In some classes, it is not difficult to complexify the model and consider the

[14] In the earth's atmosphere, the primary absorbers are water vapor, clouds, and carbon dioxide. Ozone, methane, and nitrous oxide are also radiatively active at wavelengths of terrestrial radiation, as are aerosols and CFCs. The radiative effect on atmospheric and surface warming of each of these components can be assessed fairly well. The combined effects, which must involve the positive and negative feedbacks between the various components, constitute a much more complex problem.
The change in time of the concentration of CO_2 is now well known and monitored. Very little is know on the increase in concentration of methane, which is a very powerful greenhouse gas, whose concentration depends on natural as well as anthropogenic processes and is stored in very large quantities in permafrost regions that are only now beginning to be studied (Rizzi, 2014).

atmosphere as a multi-layer. That would require to write a balance equations for each layer and, hence, to solve a more complicate equation system. Anyway, all the conceptual ingredients are already present and it could be a nice exercise that lead to have the temperature profile of the atmosphere (Rizzi, 2014).

Another hyper-simplification in our model is that, since the atmosphere does not have a uniform temperature and it varies with altitude, the atmosphere as a whole is NOT in thermodynamic equilibrium.

Students are guided to reflect on *what are hypothesis/choices at the basis of this model*, that are:

- We are assuming to have an homogeneous planet
- We are making predictions in global average
- We are assuming that the absorbance is average in only two intervals (short-wave and long-wave)
- Carbon dioxide is assumed uniformly distributed over the entire globe, but water vapor instead decreases going towards the polar areas and then decreases the absorbance
- There is a feedback effect (the melting of ice lowers the planetary albedo, so if you decrease the albedo increases the absorbance and this is a positive feedback, that goes in the direction to increase the effect).

Despite the big simplifications, we chose it since it appeared to us particularly suitable to let the students reasoning in terms of energy balance and to build progressively the formal relationship between the absorbance of the atmosphere and the Earth's surface temperature. The significance and the power of that model regard, in our opinion, the fact that it emphasizes, in an explicit and intuitive way, that if the absorbance of the atmosphere (for the long-wave radiation) increases, the temperature of the Earth's surface and atmosphere also increase in order to maintain the balance with the incoming radiation. This relationship between the absorbance and the temperature has several implications: i) absorbance can be interpreted as a bridge between the anthropogenic causes (e.g. greenhouse gases) and the physical explanation of global warming; ii) the relationship allows us to provide a more quantitative shape to the concept of feedback.

The next step in our path is to introduce students to the complexity of the Earth system and, in particular, to the need of moving "from real to virtual laboratory", so as to give an idea of the type of mathematical models that climatologists use today (Pasini, 2003).

By referring to the first lesson, the point that we stress again is that climate is a complex system, in the sense that it is composed of many (and different) sub-systems that interact with each other also through non-linear relations.

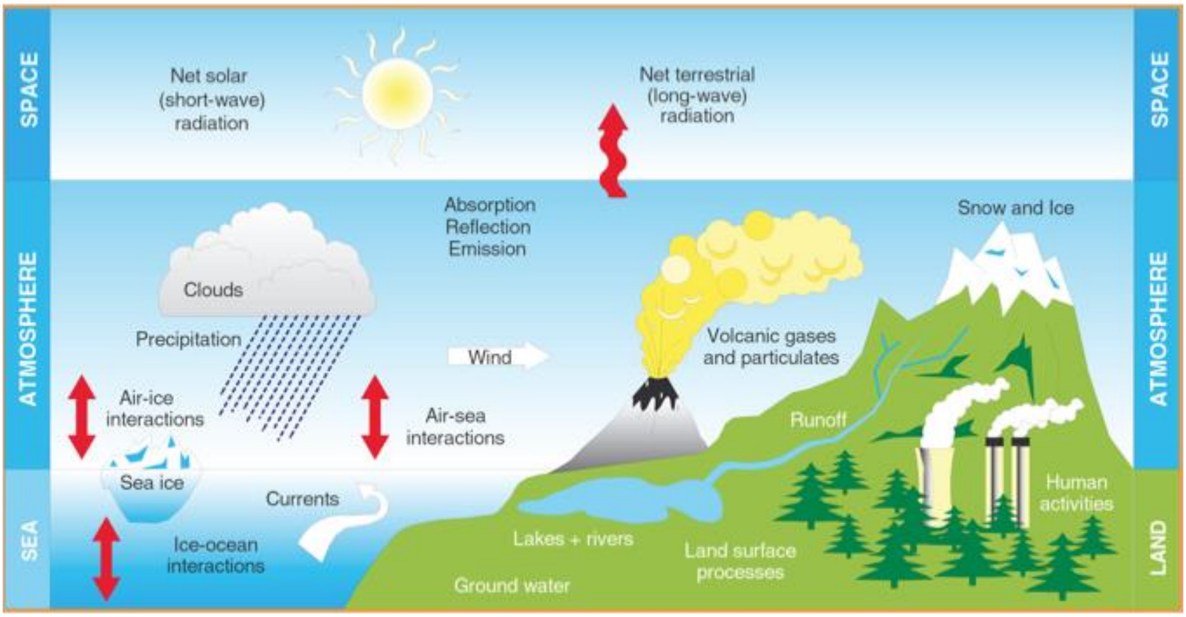


Figure 2.35. The Climate System

It is hence highlighted that, in a real laboratory, it is possible to analyse separately the individual pieces, creating controlled and simplified conditions, but: *Is it possible to put the pieces together and recreate the reality of climate?* As it is claimed by Pasini and Fiorani (2010), for large-scale processes in space and time, “it would mean to take a twin Earth”.

This is the argument that leads to make a transition to the virtual lab, reconstructing the processes according to our experimental experience and theoretical knowledge through the simulation of the behaviour of the real climate.

At first, this process of 'rebuilding' climate leads to not have a unique solution by different scientists. Despite this diversity, the current models lead to results similar to each other. In fact, the goodness of these models should be checked right on their ability to reconstruct the climate real past: “to assess what actions (forcing) external do vary and they did change the behaviour of the climate reality Climate recent and remote” (Pasini & Fiorani, 2010).

An important issue to be stressed is that the “reconstruction” of the pieces does not return the total system in a linear way, inasmuch the interaction between the parties of the system causes feedbacks, that could be *i)* positive feedbacks, if they contribute to increase the primary cause or ii) negative feedback, if they contribute to decrease the primary cause.

These considerations open towards the fourth lesson in which it will try to open towards the point of view of complexity (Pasini & Fiorani, 2010).

2.1.3. Lesson 4: “The epistemological perspective of complexity: Introduction to the basic concepts for looking at complex systems”

Summary

The aim of lesson 4 is to introduce some concepts typical of the perspective of complexity so as to refine the epistemological discourse and to address, from a new perspective, the behavioural barriers (see section 1.2.2.). In particular the notion of feedback is re-analysed to stress the epistemological distinction between linear and circular causality, previously introduced, where circular causality means that: i) causes and effects cannot be clearly distinguished; ii) small changes, in space and time, can produce big changes. Moreover, the concepts of time evolution, self-organization and multiplicity are introduced in order to discuss the notion of predictive power of a model and to stress that, in complex systems, the space-time scale of self-organization is different from the single sub-systems ones. Finally, the simple model of Schelling about social segregation is illustrated to analyse the relation between a system and its sub-parts in an example concerning the relation between individuals and society and to stress, again, that small (individual) changes can produce big social effects.

As already anticipated, the whole path has been designed on our hypothesis that the cognitive and emotional barriers (see section 1.2.2), as well as a sense of bewilderment and distrust of the population in the face of scientific controversies, are also the sign of the widespread idea that science should be deterministic and bearer of truth.

The lesson, by introducing students to the transition from classical physics (*physics of clocks*) to the physics of complex systems (*physics of clouds*), aims to introduce a new language suited to strengthen the epistemological competence and support the formation of critical thinking toward models and their deterministic power.

At the beginning of the lesson, by focusing on the relationship model-reality-experiment and by referring to the previous experimental activities, it is discussed to what extent the perspective of complexity leads to problematize the concept of causality. Indeed, the core problem is to show why, as soon as the system involves many co-related variables, it is needed to give up the classical view of linear causality, in which the cause comes before effect, small causes correspond to small effects and big causes correspond to big effects. In complex systems, it is not possible to distinguish cause and effect, even small changes can correspond to big changes in the evolution of the system, and *vice versa*. In order to argue such a point the concept of feedback (positive or negative) is reconceptualised in terms of circular causality so as to mark its difference with respect linear mechanistic causal processes.

Operationally, the lesson starts from the model presented in the previous lessons to explain the warming of the Earth's surface and it is re-analysed in terms of causal scheme. In particular, the relationship between the parameter a (absorbance) and the temperature *T at the Earth surface* is discussed as an example of circular causality: the increase in the concentration of greenhouse gases (and, therefore, the parameter a) can cause temperature increase, and the increase of the temperature feedback on the variation of the parameter a. For example, the melting of ice caused by the temperature increase at the surface of the Earth can lead both to an increase in water vapor (one of

the greenhouse gases) and to the release of methane due to broken layers of ice surface (IPCC, 2007). It is moreover re-discussed that, whereas there is nowadays a general agreement on the anthropogenic origin of the increase of greenhouse gases (IPCC, 2007), the effects of the feedback, like in the case of claudness, are topics deeply studied. Still connecting to the previous lessons, students are then guided to problematize the built model and the simplifications required by the study of a phenomenon in lab. In the laboratory it is indeed needed to isolate individual elements of the system so as to study specific phenomena or processes by separating them from the environment. For example, one can study the thermodynamic behaviour of air and its phase transformations. Nevertheless, in a physics laboratory we cannot reconstruct all the complexity of the atmosphere or of a climate system. It then uses mathematical models to be developed by the computer as a "virtual laboratory" (Pasini, 2003)[15].
Some examples of mathematical models are used to make the discussion on the concept of causality and on the concept of feedback more explicit and concrete.. For example, the "evolution of fishes in a lake" is considered and problematized with students. Such an example leads to deal with evolution laws (linear and not linear), logistic parabola, attractors, bifurcation points, Feigenbaum number, Nevier-Stokes equations, Lorenz attractor (Figure 2.36) and the concept of sensitivity to the initial conditions.

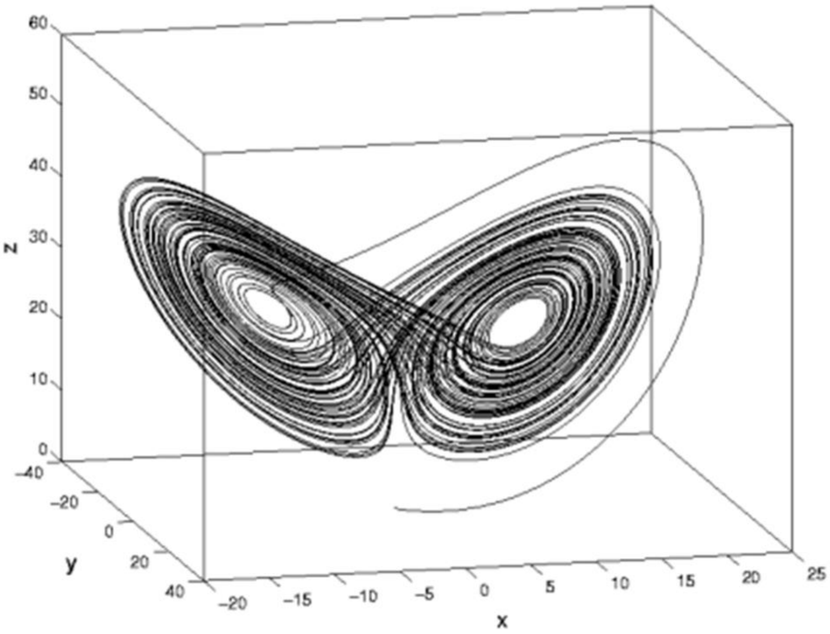


Figure 2.36. Lorenz attractor

In order to reflect on the exhaustiveness and on the predictive character of models, the idea of temporal evolution is introduced. From a complex perspective the concepts of causality and non-linear circular relationship need to be complemented by means of additional concepts as crucial as

[15] Mathematical simulations, by means of mathematical models, virtually recompose the system by reassembling the single "pieces" of reality, that have been separately studied in the laboratory. The "pieces" are reassembled by making them interact each other thanks to the "pieces" of theory that describes them and the individual equations validated in the lab-activity. Obviously, the variables developed through these models have a correspondent in the real quantities measurable in the system. That is why, when the model "runs" in the computer, it has been identified as a "simulation of the behaviour of the real system". This reflection leads students to think that the real-lab is a necessary condition but not sufficient when we are talking of complex systems.

the concepts of multiplicity, self-organization and unpredictability. On this point, students are guided to reflect that the model used in the previous lessons has a limitation because it does not consider the temporal evolution of the phenomenon. In order to extend such a limit, we showed the evolution of a complex physical system related to the turbulence by referring to the example of Benard cells (Figure 2.37): one horizontal layer of liquid is subjected to a gradient of temperature that causes a transmission of energy in heat modality; for a given value of the gradient, the energy transmission is not only by conduction but also by convection and it has instability.

Figure 2.37. Bernard Cells

By referring to such an example, it is made notice that complex physical systems, like the atmosphere, are not isolated systems, but they are in a continuous exchange relationship (matter and/or energy) with the outside and that they are constituted by a large number of elements interacting each other. The number of interactions is so high that, even if the laws are known locally (for example the laws of Nevier-Stokes equations for infinitesimal volumes of fluid), the details of the mutual interactions cannot be known. Under the conditions of instability of Bénard a small fluctuation is amplified by invading the whole system and stabilized (due to the exchanged energy with the outside world) by spontaneously creating a new molecular order. Then, at the presence of appropriate conditions, millions and millions of molecules move coherently and, following convective motions, are arranged according to regular structures which have a characteristic shape, the “Benard rollers” (Figure 2.38). Under certain characteristics of the fluid the "rollers" tend to interact and self-organize to form spatially precise hexagonal shapes called “Benard cells”.

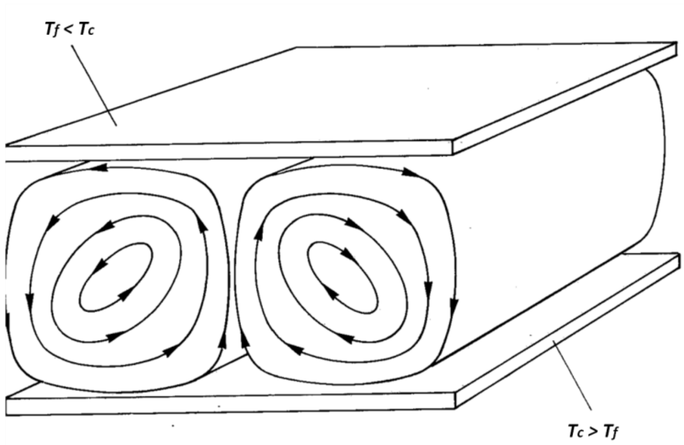


Figure 2.38. Bernard rollers

The organized behaviour is the result of the collective behaviour of a large number of molecules with a character of universality. That universality is independent from the details of the interaction, but rather it derives from feedbacks. The self-organization occurs on space-time scale different from that of the individual molecules, for instance, the Bénard cells are described on the macroscopic spatial scale of the order of centimetres and not the order of the molecular scale (around 10^{-8} cm), and on the macroscopic time scale of the order of seconds or minutes or hours and not on the order of the times of vibration of the molecules (around 10^{-15} s).

The behaviour of organized "Benard cells" is similar to the one that determines certain cloud formations associated with thermal rising and falling currents and it is the result of an extensive and unexpected molecular cooperation.

These reflections allow the teacher to discuss with students the relationship between the behaviour of the system as a whole and its parts, compared to the relationship individuals-collectivity and men-society (which is also a complex system characterized by circularity, multiplicity, unpredictability, self-organization).

Thus, this perspective leads us to consider in a different way the problem of the decision and the role of the individual within a community. Using the words of Prof. Zanarini (Zanarini, 1996): *"How is it possible that order emerge from the interaction of such a large number of people, each of that is the bearer of personal projects, desires, fantasies? In a classical perspective, the answer to a question of this kind is immediate: it is the overall rationality that imposes itself and its rules, that silence (at least within certain limits) personalisms, dissonances, conflicts. But this is a too simple explanation. We must once again remind the circular relationship between parts and whole and, at the same time, remember that each organization is also a self-organization. This does not mean that every organization is spontaneous and without any project, but rather that it is a living organization that, while it produces goods and services, also builds itself. This relationship is itself a circular relationship with the parts that make it up".*

In order to develop this point, a simple model of social system, i.e. the Schelling's model on the social segregation (Edmonds & Hales, 2005) is presented. The model assumes that individuals have weak personal preferences with regard to the colour of their neighbours (red and green, in the simulation). Each individual is assumed to be happy if he/she has the possibility to live close to at least one neighbour of the same colour. The "unhappy" individuals can move one step just to get "happy". The mathematical model shows that, even with such a weak condition, the evolution over time shows that ghettos are formed and a high degree of segregation is reached. With the students, this model has been introduced and discussed by using the computational simulation namely of NetLogo (Wilensky, 1997).

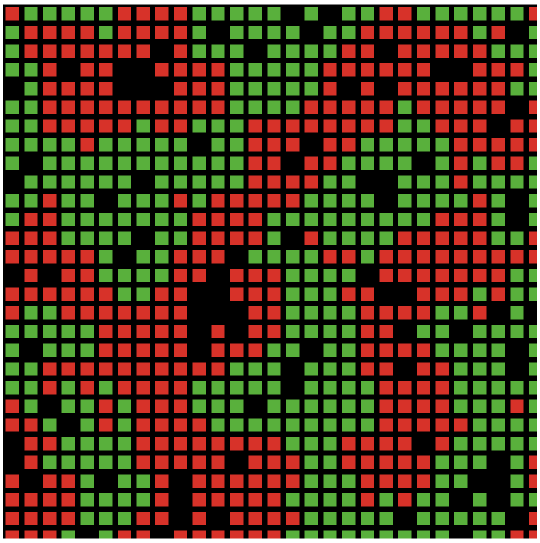


Figure 2.39. Example of configuration of segregation emerging in the Schelling's model

The model is very well-known since it is very simple and, also for that reason, very effective for showing that, weak rules of behaviour of individuals lead to the emergence of a collective phenomenon, of global nature, like segregation, not predictable from the behaviour of the individual.

2.1.4. Lesson 5: "Political and Economic scenarios: overview of climate treaties and proposals to cut emissions"

Summary

Lesson 5 provides a framework on political and economic scenarios related to climate change. It moreover illustrates the water and carbon footprints of common habits and daily activity, along with details on energy consumption of households appliances. The aim of lesson 5 is twofold: on a one hand, it aims to make students to understand the role of international climate agreements, and to acquire some knowledge about the current developments towards a global treatise on emission caps. On the other hands, students need to understand that not only policy makers have the power to influence the situation, but also citizens, that with their daily behaviour and habits have the ability to contribute significantly to climate change mitigation.
The core message is that human activity plays a crucial role, both with regard to the collective aspects, related to political and economic scenarios and the institutional choices, and individual aspects related to the behavior of the individual in his daily activities and in its interaction with the environment.

This lesson, according to its aim, is organized in two parts. The first part presents the international scene through an overview of the international panels on climate: i) the main stages of the prevention of CC (the current situation of the negotiations, the main reasons for disagreement and what countries nowadays play a key role in negotiations); ii) the environmental policies of countries which are outside the Kyoto Protocol and the reasons of their standing out; iii) The goals of "Europe 2020" and its plan to reduce CO_2 emissions in the European Union.
The second part presents the shift from the international actors to the individuals, from collective to individual actions. In particular it is discussed: i) how much the consumption of the people weighs in the general budget of emissions by showing some data on the production of CO_2 by different sectors (e.g. feed); ii) what actions of daily life have a major impact on the environment by illustrating some data relating to kilos of CO_2 produced by some actions of everyday life (e.g. use of cars, household appliances, electricity).
In the last decades the major global political institutions have tried to find political solutions to the problem of CC, that should be shared internationally to represent efficient actions for a global impact.
How did the concern about CC arise at a political level? What stages did this institutional, political and economic process follow? What are the future goals for the various countries? In Table 2.5 a list of the main conferences have been shown.

Table 2.5. The institutional steps of prevention to climate change

Years	**Conferences**
1979	The first World Climate Conference
1988	IPCC - Intergovernmental Panel on Climate Change
1992	UNFCC - United Nations Framework Convention on Climate Change
1995	(COP-1) First conference of the parties in Berlin
1997	Kyoto protocol
2010	Cancun agreements
2011	Conference of Durban
2012	Conference of Doha
2013	Conference of Warsaw

The first climate conference was held in Geneva in 1979 (World Climate Conference). It was a meeting between working groups in which the first data were analyzed to assess the existence of a climate problem and its size. After this first conference the IPCC (Intergovernmental Panel on Climate Change)was established, a supranational organization, comprised of distinguishing scholars from various fields who deal with periodic products of evaluation from different points of view.
Inside the IPCC there are three working groups: the first group is responsible for analyzing the scientific aspect related to CC; the second group is responsible for understanding the impacts of CC on natural and human systems; the third group is responsible for the mitigation of CC and the kind of strategies that can be put in place to prevent certain types of effects. Since its first establishment, the IPPC has produced five reports (1990, 1995, 2001, 2007, 2014). In its first report (1990) the IPCC officially declared that CO_2 contributes to the increase of the GHE.

One of the fundamental institutional step, also widely discussed and at the centre of acrimonious negotiations, is the establishment of the Kyoto Protocol in 1997. It was adopted in Japan on December 11th of 1997, but it got into action on February the 16th of 2005 after a long process of ratification. The Kyoto Protocol, in force until 2012, stipulated that industrialized countries had to reduce their emissions of the six greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride) in variables percentage depending on historical and political considerations that apply in each country. For Italy, the goal was the reduction of 6.5% of the emissions compared to 1990 levels by 2012. For a second group of states, including countries in the developing world, such as China and India, oil-producing countries, such as Saudi Arabia and Kuwait, and countries with subsistence economies, such as the Sudan, there were weaker (e.g. Pongiglione, 2012) obligations to reduce greenhouse gas emissions. A decade later, the results obtained from the implementation of the Kyoto Protocol are rather limited. First, the agreement has not been ratified by the United States of America and Australia, despite the strong contribution to the greenhouse gas emissions of the first of the two countries. In addition, most of the states that are committed to achieving the goals of reducing greenhouse gas emissions, set out in the Protocol have yet carbon emissions above the limits. Nowadays, China and India are among the largest emitters of CO_2 and are not subject to any restrictions.
Despite such difficulties, USA and China have got some commitments outside the Kyoto protocol. Indeed, the USA President is committed to reduce of 17% of emissions compared to 2005 by 2020 and China is committed to: i) reduce of 17% of emissions per person compared to 2010, ii) increase of 11,4% the use of renewable energy, iii) increase of 22,6% of reforestation.
The last overview of this part was on the goals of "Europe 2020" that are: i) to reduce emissions of 20% compared to 1990 (with a willingness to get to a 30% cut if the rest of the world engages in significant way), ii) to increase of 20% the use of renewable energy, iii) to increase of 20% of the energy efficiency. Students are guided to understand the big importance of these goals, because EU intends with its commitment to give a strong signal to other countries on the urgency of the climate issue and recognize its responsibility (principle of common but differentiated responsibilities).
As far as the second part is concerned, students are introduced to reflect on the role played by the individuals. First of all, some graphs of the impact of CO_2 emissions per sector have been shown and discussed (Figure 2.40).

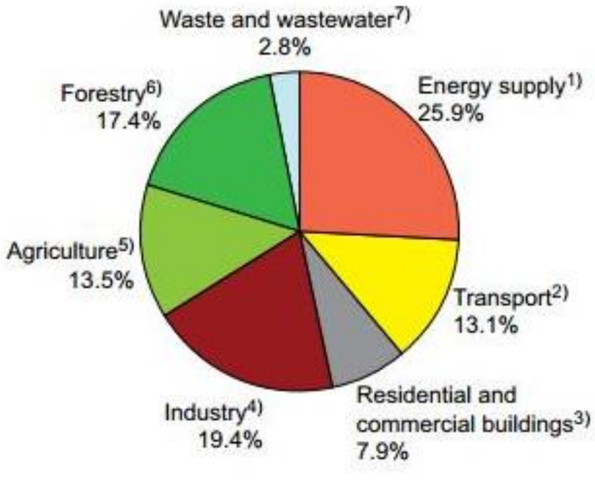


Figure 2.40. GHG emissions by sectors (2004)

In the analysis of this graph, the attention is paid on the energy consumption of buildings. In particular, this kind of consumption is explored by presenting an overview of energy uses in the residential and commercial sectors. We choose examples taken from the IPCC (http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter6.pdf) of US and China.

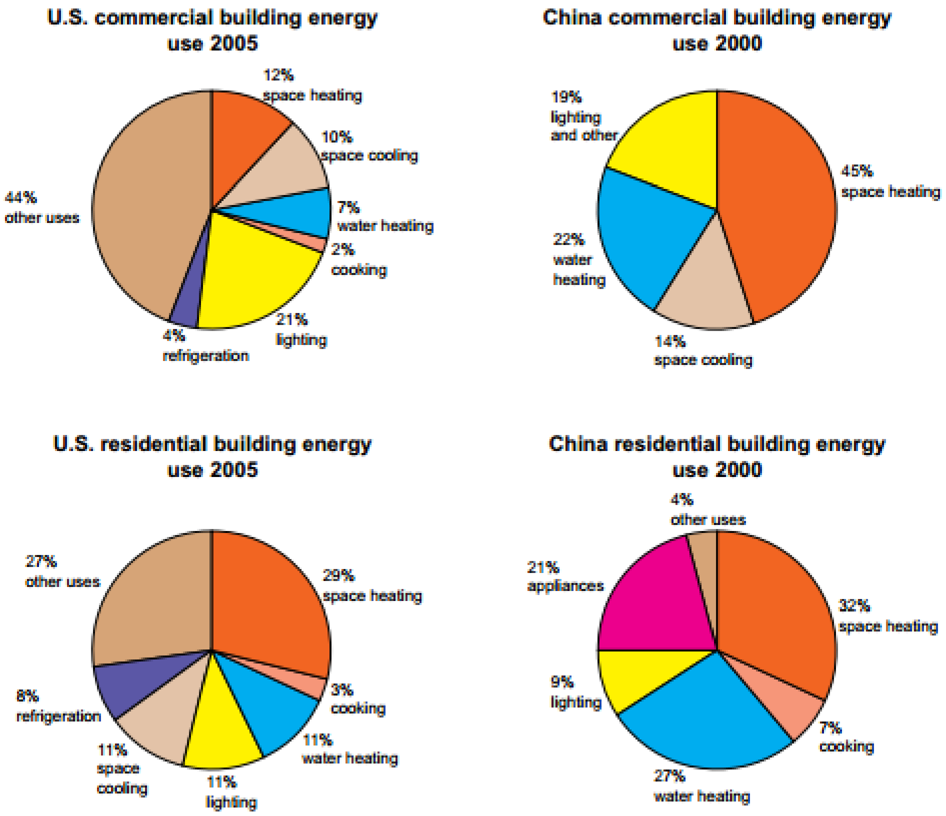


Figure 2.41. Comparison among commercial building energy and residential building energy in U.S. and China

The single largest user of energy in residential buildings both in US and China is space heating (29% and 32%). The larger uses in commercial buildings are much less similar between China and the US. For China heating is so far the largest end-use, whilst for US the largest use is other (plug loads involving office equipment and small appliances). Furthermore, lighting and cooling are similarly important as the third and fourth largest user in both countries.
The relevance of this example is that it stress to what extent most of energy is produced by using fuel. To produce 1 kWh of electricity, it is needed to burn almost 3 kWh of energy in terms of fuel, with the emission of 0.58 kg of CO_2.
The message that students are expected to grasp from this part of the lesson is that the role of individuals in its daily life is fundamental, i.e. the individuals behaviour, culture and consumer choices and their use of technologies are still the major determinants of energy use in buildings and play a fundamental role in determining CO_2 emissions. In the IPCC report there is a whole section dedicated to demonstrate that there is already a plethora of technological, systemic and management options available for buildings construction to substantially reduce GHG emissions, and there is

already the evaluation of the costs associated with their implementation (http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter6.pdf). Nevertheless, the impact at local political level is still very low.
A second example about individuals' behaviour is related to feed. Here, the notions of ecological, carbon and water footprints are introduced (http://www.footprintnetwork.org/en/index.php/GFN/). They respectively represent: the amount in acres of land (or sea) of biologically productive needed to provide the resources and absorb the emissions (*ecological*); the measurement of grams of CO2 emitted per kilogram of food product (*carbon*); the extent of gallons of water used per kilogram of food product (*water*).
The last and most famous example showed to students is related to transport (Figure 2.42).

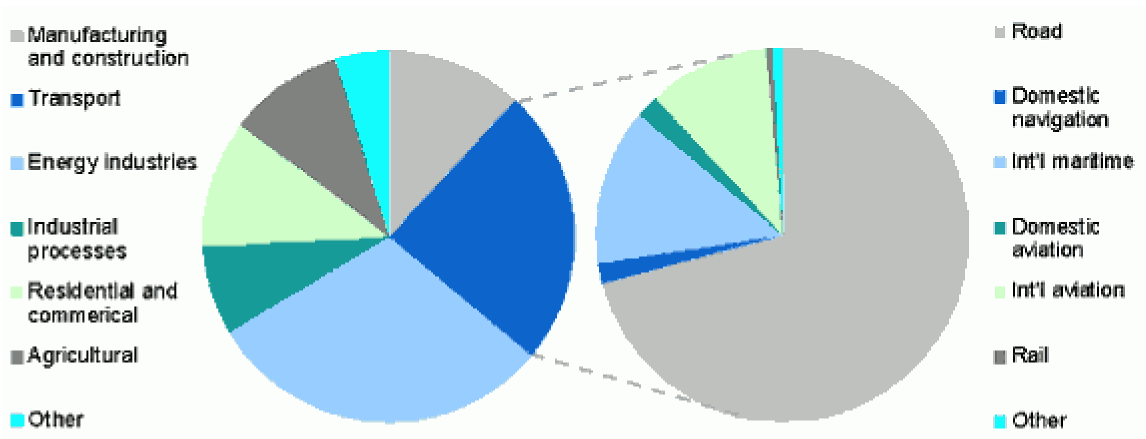


Figure 2.42. Greenhouse gas emissions in Europe for the transport sector (IPCC, 2007).

In Europe, for instance, road transport is responsible for one fifth of total emissions of CO_2. Between 1990 and 2007, greenhouse gas emissions have decreased in all sectors by 15%, whilst in the transport sector have increased of 36%.
In front of this scenario, EU is committed to pose objectives and strategies to cut emissions in transport sector. Particularly, associations of automobile manufacturers in Europe, Japan and Korea have committed to reduce: i) emissions from new cars to 140 g CO_2/km by 2008; ii) car emissions to 120g CO_2/km by 2012 (target not guessed); iii) car emissions to 95g CO_2/km by 2020. Moreover, EU is committed to increase consumer information on car emissions in circulation with a sort of "label" and to promote cars with low fuel consumption through tax measures (http://ec.europa.eu/clima/policies/transport/vehicles/index_en.htm).
To sum up, the last lesson is expected to pull the rope of the whole conceptual path and to act as a final summary on the central role of individuals in contributing to the variation of the atmosphere, in particular in increasing its absorbance.
The choice to construct our argumentations and our model around the relationship between the absorbance of atmosphere (*a*) and the variation of the Earth's surface temperature (with the consequently implication related to feedback) is for us a privileged point for exploring the human anthropogenic role in CC and for addressing the psychological barriers which prevent individuals to feel involved in the problem (see section 1.2.2).
In particular, that choice allows the first barrier (*not individual but collective*) to be dealt with because it is possible to recognize the central role of human actions in the variation of the parameter

a. Still, the choice allows to deal with the second barrier (*too big or too small*), because it shows the central role of the parameter *a* in showing examples of causal links and feedback mechanisms (i.e.: if *a* grows up, then T grows up; if T grows up T, then the glaciers are melting; if the glaciers are melting then *a* grows up). Finally, as for the third barriers (*too far*), the model, although it is very simple, has the potential of paving the way to introduce the epistemological perspective of complexity and it provides the opportunity to reflect on the problem of the nature of predictive models developed so far to study the evolution of complex phenomena.

2.2 The epistemological *fil rouge*

According to the overarching goals of our educational reconstruction, an epistemological *fil rouge* was explicitly implemented throughout the whole course in order to foster the progressive development of new and robust awareness about modelling, as well as about the causal schemes implied by the different types of models and modelling (Tasquier et al., 2015a).
In particular each lesson implemented a specific epistemological message consistent with the topic of the lesson.

2.2.1. Lesson 1: *The construction of "global lenses"*

The epistemological message of the first lesson concerned "the global lenses of climate science" from which specific real-world phenomena can be looked at: a systemic, non-reductionist approach.
The global lenses were built through the "contrastive" strategy of pointing out the differences between climate models, on one hand, and meteorological and mechanistic models, on the other.
In order to pass the epistemological message, the lesson was operationally organized around two modelling-choices: i) to emphasize that climate phenomena, by definition, concern a space and time scale bigger than the meteorological one and, because of that, their modelling implies a systemic, global approach that includes a new way of looking at possible future scenarios, from predictive to probabilistic and projective; ii) to introduce the notion of *feedback* by presenting and discussing real examples (e.g. melting of glaciers).

2.2.2. Lessons 2 and 3: *Zooming in on "isolated phenomena"*

The epistemological message of this part concerned the relationship, established by the process of modelling, between real-world, lab-experiments and theoretical knowledge.
Students were guided to recognize modelling as a process of *isolating* a particular phenomenon (greenhouse effect), identifying its conceptual skeleton as well as its potential for providing an interpretation of global change. By referring to such a specific case, students were encouraged to recognize that, even if models simplify the reality, they go behind a scale reproduction. They indeed are supposed to grasp the essence of real phenomena and this essence can be "intra-disciplinary", in the sense that it can require multiple lenses (optical, thermal and electromagnetic) to be captured (Besson et al., 2010).
Operationally, the lab-activities were carried out by implementing two modelling-choices:
- to situate explicitly the lab-experiments within the more complex and global problem so as to avoid students to see models as a scale reproduction and to get any impression of artificiality or hyper-simplification. In order to implement such a choice, students were systematically asked to answer questions like: *In this experiment we assumed that Earth is modelled by an aluminium cylinder, Atmosphere by plastic cylinder, Sun by a bulb. In light of our experiment, why can we do that? What features of these objects are we isolating and why?*
- to enable students to address the well-known difficulties related to the construction of the conceptual skeleton of the GHE. In particular students were guided to explicitly reflect on issues like: *What kind of properties do the models of black bodies of grey bodies express? What does it mean that we focus our attention on the property of this object of "being transparent or black"? In what sense is such a property dependent from how the object interacts with its environment? In*

what sense can we say that the property of being transparent or black is, at the same time, optical, electromagnetic and thermal?

2.2.3. Lesson 4: *The "epistemological perspective" of complexity*

The epistemological message of lesson 4 concerned the introduction of the perspective of complexity so as to refine the epistemological discourse on the global lenses of climate science, introduced in the first lesson.

Operationally, as crucial modelling-choices, basic words and concepts typical of the perspective of complexity were presented: *i)* the notion of feedback; *ii)* time evolution and the probabilistic and projective nature of non-linear models; *iii)* the relation between individual and collective behaviour in the application of the perspective of complexity to social systems.

The notion of feedback was re-analyzed in order to stress the epistemological distinction between linear and circular causality. Linear causality, typical of classical mechanistic dynamical models, implies that it is possible to distinguish between cause and effect and that small/big changes in causes lead respectively to small/big effects. On the contrary, by referring to simple math predator-prey models, it was shown that, in circular causality, causes and effects become not clearly distinguishable and small changes can produce big changes or *vice versa*. The case of melting glaciers was then reconsidered in the light of such a refined causal scheme.

As far as the concept of time evolution is concerned, simple examples like the Benard cells were taken into account and, focusing of them, it was discussed how a complex and open system, like atmosphere, can find, in time, new configurations (self-organization) due to a multiplicity of factors, that are: the inner composition of a system, the inner interaction between one sub-systems and another (the fluid molecules), feedback mechanisms, but also, and mainly, collective properties (that cannot be reduced to the sum of the individual behaviours). The introduction of concepts like multiplicity, unpredictability and self-organization was discussed so as to problematize the notion of predictive power of a model and to show that the space-time scale time of self-organization is different from single sub-systems ones: patterns of collective behaviour can be modelled at an appropriate space-time scale, but it is not predictable by the behaviour of single sub-systems.

At last, the simple model of Schelling about social segregation (Edmonds & Hales, 2005) was discussed so as to re-consider the relation between individual and collective relationship in society and to show how individual choices can produce social changes in a space-time scale typical of complex systems. This point paves the way toward the final lessons.

2.2.4. Lesson 5: *Reading the world with our "lenses"*

The epistemological message of lesson 5 concerned the effectiveness of the acquired physical and epistemological skills in looking at global change with a rational attitude. The complexity of natural phenomena was here used both as mirror and metaphor of the societal complexity.

Operationally, students were exposed to an overview of the most relevant international climate meetings, panels and reports. They were presented as a history of the political and economic choices taken from the Nations toward the purposes of the Europe 2020. In following such a history, students were asked to apply their new knowledge in interpreting the IPCC language (e.g. "climate change is very likely [90%] due to anthropogenic GHG increases") and they were guided

to recognize that, even if the issue of anthropogenic causes of CC is complex, it can be, however, rationally treated and addressed.
Special emphasis was given to the role/impact of individuals through: i) the analysis and discussion of IPCC data about the sources of CO2 emission related to individual behaviour (food, transport, house energy consumption, *etc.*); ii) analysis and discussion of tools used for evaluating the individual impact on CC (the notions of ecological, carbon, water Footprints).

In designing and implementing the epistemological *fil rouge*, we decided to avoid focusing our attention on the philosophical underpinnings on modelling. In the wake of Koponen (2007), we mainly emphasised the process through which models are methodologically built so as to make natural and complex phenomena understandable in the laboratory. We carefully stressed concepts/expressions like *empirical reliability, accuracy, limitations* and *usefulness* of models[16] and we consciously tried to avoid the realist philosophical underpinning that often orients science education, teaching and textbooks (Koponen, 2007). As we argued in the theoretical framework, such an epistemological stance, as well as being too partial for providing an authentic image of science, could mislead students who easily drop into a naïf hyper-realism. Such a strong epistemological position is worth being avoided since it can hinder a deep and rational engagement in understanding the scientific, political and economic implications of complex phenomena like climate change.

[16] In the literature we can found a support to our approach in these words: "Empirically reliable models make as direct as possible contact to what is detectable and measurable in experiments. The hallmark of empirical reliability is empirical success. Therefore, in order to learn to use models in physics, it is crucial to recognize that this learning needs to be done in the context of experiments and experimentation." (Koponen, 2007)

CHAPTER 3

Research Design

The designed path was targeted to upper secondary school students of grade 11th-12th-13th. Four teaching experiences were carried out. Each context had specific features and appeared suitable to pursue specific aims (section 3.1).
Throughout the various experiences many data were collected through progressively refined the data sources.
The whole research work has been strongly oriented methodologically and one of the research question just concerns such an issue: *RQ_4 - What analytic methods can be used to investigate the multiple dimensions of a teaching/learning classroom experience?*
The novelty of the methodological tools designed and used for data collection (section 3.2) is represented by the research question that they were targeted for:

> *RQ_3: How do secondary school students react to the produced materials? Are the materials effective for achieving the main goal of the research?*

Such a question was progressively declined dimension per dimension (chapters 4-5-6-7).

3.1 Contexts of implementation

Climate change, even though it has been recently included in the Italian curricula, remains an additional topic to be chosen only if desired by science teachers. Such a particular national situation allowed us to experiment the conceptual path into extra-school contexts, whilst it made it difficult to find a real classroom context. Thus, the conceptual path on CC was implemented in four different teaching experiences, different among them for the context (extra-school-PLS or classroom curricular classes), the period of implementation, the number of students , their age and the school level (see Table 3.1) .

Table 3.1 – Teaching experiences

Exp.	**Context**	**Period of implementation**	**Number of students**	**Age of the students**	**School level (grade)**
A	PLS (extra-school)	2012 (March-February)	10	18-19 y	12th – 13th
B	PLS (extra-school)	2013 (February-March)	19	18-19 y	12th - 13th
C	PLS (extra-school)	2014 (February-March)	21	18-19 y	12th - 13th
D	Classroom	2013 (January-February)	28	16-17 y	11th

The whole sample is comprised of 78 students.

Experience A. This experience represents our first pilot study in which we implemented the teaching path for the first time and in which we tested our data sources and methodology of data collection. The context of implementation was the Italian National Project, called PLS, which has the aim to orient students to the choice of University studies and to create connections between School and University. The lab-course represents an extra-school activities in which students are (auto-)selected on voluntary basis, i.e. they personally choose to attend the lab-course attracted by physics discipline or by the topic and they want to improve their level of awareness on it. This sample is comprised of only 10 students and they were around 18-19 years old, so some of them attended the 12^{th} grade of secondary school and some of them the 13^{th} grade. These students came from different schools and the most part of them met up each other for the first time during the course.

Experiences B and C. These experiences represent our last teaching interventions (chronologically), B in 2013 and C in 2014. The context of implementation was still the Italian National Project, called PLS. Like for experience A, the lab-course was an extra-school activities in which students were (auto-)selected on voluntary basis, i.e. they personally chose to attend the lab-course attracted either by physics discipline or by the topic. The sample was comprised of about 18-20 students per year and they were around 18-19 years old. Some of them attended the 12^{th} grade of secondary school and some of them the 13^{th} grade.

Experience D. This experience concerns an implementation in a real classroom context of a scientifically oriented secondary school in Bologna. The students were the youngest of our sample because they were 16-17 years old and they attended the 11^{th} grade. The class was comprised of 28 students. These students were not volunteer, their teacher chose to deal with CC issue.
As it was stressed at the beginning of this section, it was not easy to find a real classroom context. The context we found was not used to collaborations with research groups in science education and it was not easy to negotiate, for example, some issues related to data collection, which were deeply affected by the demands of the teacher and school. The main implication of this process of negotiation is that we did not give students the concept inventory on GHE as stated in the research literature.

The four experiences played different roles in the whole research work. The specific role of each experience is described in the next section (3.2) and then following the description of the data sources (3.3).

3.2. Research Questions and the role of each teaching experience in the analysis

Each teaching experiment played a different role within the whole research work.
The pilot-study (Exp. A) was the first teaching experience and it played a ‘leading’ role for different points of view. At first, it was the first test of the materials and the data sources. On the basis of the results of the pilot-study, the lessons were improved and the epistemological *fil rouge* revised (chapter 2). Such a sample had also the role to validate the data sources.
The experience D represented our classroom context and it was the most monitored of the teaching experiments. The data collected during this experience was the richest corpus that was analysed in depth along all the dimensions we considered. Experiences B and C played the role of enlarging the sample for questionnaires Q_1 and Q_2. Thus, they allowed us to carry out a semi-quantitative study about the impact of the path on the societal dimension.
The methods of data analysis are described in the following chapters (4-5-6-7), where various types of analysis are presented (see table 3.2).

Table 3.2 – Articulation of analyses' presentation and teaching experiences related

Chapter	Analysis	Experiences
4	Analysis of the pilot-study	A (pilot-study) B-C-D (classroom context and PLS)
5	Analysis of the conceptual dimension	D (classroom context)
6	Analysis of the epistemological and its implication with the other two dimension	D (classroom context)
7	Analysis of the societal dimension: correlation between and behaviour	B-C_D (classroom context and PLS)

From a methodological point of view, we had to cope with two types of problems raised by the ambitious goals we intended to pursue: i) how to assess the multi-faceted impact of a teaching experience that was designed to transform students' relationship with CC along different dimensions and ii) how to adapt the research needs to the constraints and habits of school settings.
In order to address the first type of problem, we organised the data collection and data analysis so as to focus initially on the single dimensions and later on the correlations among them. This strategy implied the development of analytic tools able to bootstrap from the data results related to each dimension but also analytic techniques that could make the results of each dimension comparable to each other.
As for the problem of coordinating research and school needs, the difficulties encountered were considered as "part of the game", indeed we were aware from the beginning that the work, given its multidimensional and complex nature, was very challenging for a real standard classroom and that we could not overload students with too many data collection processes. Because of these intrinsic difficulties, we decided to collect in each context only the data we need (e.g. we use the PLS experiences mainly for investigating the correlation between knowledge and behaviour). Furthermore, in front of data not particularly reach we paid a special attention to develop new analytical tools able to capture and interpret fine nuances of students' discourse respecting the criteria of validity, quality and rigor (Anfara et al., 2002; Hammer & Berland, 2013).

3.3. Data sources

During the teaching path different data were collected. The data sources were designed so as to take into account the different dimensions that are involved in the study (disciplinary, epistemological, societal).
In order to take into account the societal dimension we designed and implemented a pre-questionnaire (Q_1) and a post-questionnaire (Q_2) inspired on surveys in behavioural science. We collected information also from the interviews.
In order to take into account the disciplinary dimension we audio-recorded all the lessons and we collected information also from team's work of the students, interviews, questionnaires and written tasks.

Whilst, in order to take into account the epistemological dimension, we included particular questions in Q_1 and Q_2, we designed a proper questionnaire (Q_m) and we carried out individual semi-structured interviews, aimed at investigating: *i)* students' knowledge about modelling in Physics, *ii)* students' level of understanding of the specific models discussed in the course, *iii)* the quality of epistemological discourse.
Table 3.3 provides a map of when the sources have been used during the path and which of the three dimensions were investigated by each one.

Table 3.3. Data sources

MAIN DATA SOURCES	**MOMENTS OF SUBMISSION**			**CHECKED/TESTED DIMENSION**		
	B	**D**	**E**	**DD**	**ED**	**SD**
Pre-Questionnaire (Q_1)	X			X	X	X
Questionnaire on the idea of model (Q_m)		X			X	
Post-Questionnaire (Q_2)			X	X	X	X
Tutorials (team's work)		X		X		
Audio-recording lessons		X				
Notes from researchers		X				
Written task inspired by inventory from EU researches			X	X		
5 individual semi-structured interviews			X	X	X	X

Key: B: beginning of the path; D: during the path; E: at the end of the path
DD: disciplinary dimension; ED: epistemological dimension; SD: societal dimension

In not all the experiences we were able to use all the data sources, because of context constraints. Table 3.4 illustrates the match between the data sources and the experiences.

Table 3.4. Match between data sources and experiences

MAIN DATA SOURCES	**EXPERIENCES**	
	Pilot-study	**Others**
Pre-Questionnaire (Q_1)	A	B, C, D
Questionnaire on the idea of model (Q_m)	A	D
Post-Questionnaire (Q_2)	A	B, C, D
Tutorials (team's work)	A	B, C, D
Audio-recording lessons	A	D
Notes from researchers	A	D
Written task inspired by inventory from EU researches		D
5 individual semi-structured interviews	A	D

Pre-questionnaire and post-questionnaire

In order to investigate the level of students' involvement in CC and the quality of their information about the scenarios related to this issue, we designed a pre-questionnaire (Q_1) and a post-questionnaire (Q_2) inspired by surveys in behavioural sciences (see Annexes A and B).

The two questionnaires were administrated to students at the beginning of the first lesson of the course (pre-questionnaire) and at the end of the final lesson of the course (post-questionnaire).

The aim of the pre-questionnaire was to investigate:

– students' confidence, interest and concern about the issue;
– students' awareness about causes and consequences of GW and CC;
– the quality and the sources of their information;
– the level of trust/distrust about the information coming from media[17];
– something about their previous knowledge about some concepts;
– their previous idea of "modelling in physics".

The aims of the post-questionnaire were:

– to investigate if students had new arguments for reflecting on: *i)* their confidence, interest and concern about GW; *ii)* awareness about causes/consequences; *iii)* their personal life style;
– to check the evolution of their "idea of model";
– to get feedback on the course.

Questionnaire on the idea of model

In order to track what happened in the development of the idea of model in students' thoughts (the *fil rouge* pulled during teaching experiment), an intermediate questionnaire (Q_m) was administrated between the 3rd and the 4th lesson, i.e. after all the activities about the physical phenomena on Climate science (e.g. greenhouse effect) and before the lesson on complex systems. In Q_m (see Annex C) there were three open questions about:

– the evolution of their idea of model and modelling;
– the relation among model-experiment-reality;
– their perception about these two passages: a) from experiment to model; b) from real lab to virtual lab.

Tutorials (team's work)

During the two experimental lessons students worked in teams (around 4-5 students for each team) following specific tutorials (see Annexes F1 and F2). The teams worked together to conduct a physics experiment and to interpret the experiment by applying the physics concepts they were supposed to have learnt in the previous lessons. As already described in Chapter 2 (Section 2.1.2), in this kind of work the team was guided by a tutorial through which the students were required to:

- think about what they learnt in the previous lessons and write their answers to open questions and specific exercises (first part: *reflect*);
- drawn the profile of temperature versus time they expected to get in the experiment (second part: *foresee*);
- compare the prevision with the real graph and write how they interpreted the experimental results (third part: *interpret*).

[17] The questionnaire asked also some personal information about extra school interests, their expectations about the course and reasons of the choice of attending it

Interviews

The interviews were carried out a week after the end of the teaching experiment.

The aims of the interviews were:

- to checked if students were able to is the basis physical concepts they learnt in an conversational context;
- to investigate their idea of modelling in physics;
- to capture what they understood about the modelling of GHE in terms of balance and if they had perceived the link between GHE and GW;
- to have feedback about what they perceived and what they learnt from the lesson on complexity.

For carrying out the interview we constructed a protocol (see Annex E) organized as follow:

i) *First part:* students' idea of models and modelling in physics;

ii) *Second part:* students' idea of how models and modelling were addressed during the path;

iii) *Third part:* students' idea about complex models and the perspective of complexity.

Written task

The written task was designed in a collaboration with the teacher of experience D who wanted to use such a task to evaluate the students. This tool is a small weaker than we had hoped for collecting data along the conceptual dimension. Nevertheless, the school constraints did not allow us to give students the concept inventory on GHE as stated in the research literature. As sort of compromise, some questions of the written task were inspired by the concept inventory and they concern the main important disciplinary points stressed during the whole teaching experiment. The task was articulated in 13 open-ended questions (see Annex D).

CHAPTER 4

Pilot-study

4.1. Aims of the study and its specificities

The pilot study was designed to test both the materials and the data sources. In order to achieve these aims, a qualitative analysis was carried out[18], dimension by dimension.
Anticipating the results, the data analysis revealed both the positive aspects and weaknesses of the proposal (table 4.1).

Table 4.1. Positive aspects and weaknesses

POSITIVE ASPECTS	– The path is within the capability of secondary school students – Students seem to be able to consciously address difficulties highlighted in PER literature regarding modelling GW and GHE – Students developed arguments for moving critically across the various dimensions of the path
WEAKNESSES	– Some basic difficulties remained (e.g. the relation between heat and radiation) – The epistemological discourse of students about modelling was, and remained, rather weak

In the following paragraphs these results will be presented in more detail, dimension by dimension and through the comments of the students themselves.

4.2. Data Analysis and Results

4.2.1. Societal dimension

The analysis of the responses to the pre-questionnaire allowed us to obtain information on the specificity of the sample[19]. It was expected that, since they were volunteers, the group of students was not representative of a "typical class" of secondary school, and that they were already interested in environmental issues.
In fact, the pre-questionnaire showed this characteristic already emerging in the answers to the first question (Q1): "We often hear about climate change and/or global warming and, not infrequently, we discuss the reality of these phenomena. To what extent do you believe that these phenomena are real?" 4 out of 11 students answered by ticking the box "very much", 7 out of 11 ticked the box "enough" and nobody ticked the boxes "Little", "Not at all" or "I don't know". As we will see again in the analysis, the existence of a previous interest in the subject meant that involvement for the social dimension was expressed from the beginning.
On the level of involvement, the analysis of the fifth question (Q5) provides the initial information: "Is there something that you have changed and/or are changing in your lifestyle with regard to the issue of climate change?". To this question, 8 out of 11 students answered yes and only 3 out of 11 said no. The students that declared not having changed anything in their lifestyle justified their answers as follows:

[18] The sample of students was not significant from a statistical point of view. Only 11 students attended the course and only three of those agreed to be interviewed (one week after the course)..
[19] The students' names are invented (in the interests of anonymity).

"I'd like to do something but I don't know exactly what to do. I'm following this course in order to be able to understand what I can do". (Marco)
"I think it's because of my ignorance on the topic: anything I do could be right or wrong, given my knowledge of the subject" (Samuele)

Again in the pre-questionnaire, when they were asked about their expectations regarding the lab-course, Marco and Samuele answered:

"With this course I hope to achieve a strong knowledge of the issue of global warming, its causes and effects. I think this is a problem which is not given enough consideration and the course seems like a good way to try and understand it properly, and try to understand what each of us can do" (Marco)
"With this course I expect to get a better knowledge of the subject, seeing as how it's an issue that is tackled little from a scientific point of view (or otherwise) in my school, and I suppose by schools in general. In this light, I really appreciate the multi-disciplinary approach that this project takes" (Samuele).

These students showed interest in the subject and also that they perceived the importance of the issue, by expressing their need to acquire more knowledge in order to achieve proper and aware involvement in the issue.
The analysis of the post- questionnaire[20] provided information on the extent of change in the ideas of students regarding their perception of the causes and consequences of global warming. The first estimate of this change is given by the answer to the fourth question (Q4): "Thinking about what you have heard about climate change and global warming, do you think you will modify something in your lifestyle in the future?". To this question, 6 out of 9 students answered "yes" and 3 out of 9 students answered "no". Students who responded that it would change their lifestyle justified their answer in this way: *"Even before the lab-course I had started to be careful in this sense, now however I will be sure to pay it a lot more attention"*.
The analysis also demonstrated further evidence of change or evolution in awareness. At the beginning of the course, most of the students believed that:

- the emission of greenhouse gases by livestock had less importance in contributing to global warming (9 out of 11 students);
- ozone depletion and general air pollution had a greater importance in contributing to global warming (9 out of 11 students).

At the end of the lab-course, 6 out of 9 students had changed their mind on the first point, and 7 out of 9 students on the second. This result is also important from a disciplinary perspective. The confusion between the greenhouse effect and other phenomena is a critical point. The disciplinary treatment of such a point led to an increase in the awareness and a relocation of the greenhouse effect in relation to other environmental issues. If, as mentioned, the presence of a strong societal dimension already favoured disciplinary involvement , in this case we can see how the opposite is also true: the knowledge gained in building disciplinary knowledge about the greenhouse effect has

[20] There were only 9 answers to the post-questionnaire because two students were absent during the last meeting.

favoured a shift of attention towards the societal dimension, relocating and clarifying some issues on which there is often confusion.
In the second part of the questionnaire, the open questions allowed students to express themselves more freely. Here are some examples of their responses:

> *"I certainly tackled the scientific aspect of the subject in a more indepth way and I will probably think more about environmental issues in future before doing things, for everybody's sake" (Francesco)*
> *"I already knew about the issue before the course. Of course, now I know how to view the problem as I have understood better how to react to the information given on the topic" (Matteo)*
> *"Before this course I didn't realize how real the problem was" (Samuele)*

Despite the particularity of the group of students, it is still possible to highlight the fact that there has been a change in their way of looking at the issue. Particularly, in looking at their comments, possible reasons for this change have been identified within two special needs:

i) the need to improve their knowledge about the scientific explanation of the phenomenon in relation to political/economic scenarios:
"I found the laws of physics really interesting, regarding the ability of a body to absorb, transmit and reflect radiation…[…] It has certainly increased my knowledge of the topic and my concern about a problem that is difficult to resolve, for many reasons but particularly for politics and economics" (Marco)
"The political implications are the most engaging part of the subject, […] the simple experiments were both exemplary and useful" (Marco)

ii) the need to give "concrete" analysis of the phenomenon
"I found the demonstration of climatic change and its effect on the earth, complete with photographic images, very interesting" (Andrea)
"The debates were interesting and the experiments gave a practical back-up to the theory" (Fabrizio).

4.2.2. Disciplinary dimension

The main aim of the disciplinary analysis was to investigate whether students understood the basic physics concepts involved in the explanation of the phenomena of GW and CC, and *whether*/*how* they were able to manage the topics addressed during the lab-course. Some specific questions led the analysis (table 4.2) and allowed us to select data by focusing on the crucial points of the conceptual path and also on the conceptual difficulties well-documented in the research literature (chapter 1, section 1.2.1).

Table 4.2. Leading questions for the analysis of the disciplinary dimension

Did students understand the main crucial concepts of the conceptual path?
Were there difficulties or elements of confusion in the understanding of any concepts?
Were students able to autonomously manage the knowledge they learned, e.g. by making some links among the addressed topics?

In order to explore this dimension, the data collected during the team's work, post-questionnaires and interviews were analyzed[21].

Two important points emerged from the data collected during the team's work. The first is that students did not seem to encounter particular difficulties in interpreting the concepts of absorbance, reflectance and transmittance. This is possible to see, for example, from the answers to the tutorial on the cylinders experiment. In the first part, students were asked to define some characteristics of the bodies (e.g. opaque body) through the concepts of absorbance-reflectance-transmittance. The response of group 4, for example, was: "An opaque body is an object with an absorbance level between 0 and 1, reflectance between 0 and 1 and transmittance of 0; thus the balance is a+r=1 (a piece of wood, for example)". Students were able to correctly answer by using the a/r/t relationship and also by giving an example.

Another exercise required the establishment of the relationship between the final temperatures of two objects (one opaque and one transparent) with the same thermal capacity and the same initial temperature, exposed to the same radiation source. Students responded: "T (opaque) > T(transparent) because an opaque body has a higher absorbance level than a transparent body".

What remains unstated, either because it was considered irrelevant in answering these questions or because it was too sophisticated for them, is the dependency of the parameters a, r, and t on the incident wavelength. This aspect was awarded extreme importance during the lab-course, since the difficulties of viewing these parameters as "interaction parameters" (i.e. parameters that are dependent on both the properties of the body exposed to electromagnetic radiation and the wavelength of the radiation itself) are well-documented in the research literature.

The second awkward point regards the usual problem concerning the concept of heat. Even though all the students had already studied thermodynamics at school, the concept "heat" is used with a certain levity and, in this case, was confused with the concept of radiation. In the question in which students were asked to interpret a graph representing the evolution of the temperature of a body exposed to the light of a bulb as a function of time, and explain why the body reached a certain equilibrium temperature, students of group 3 responded: "As the body temperature increases, so does the heat transmitted by the body itself. In this way, a balanced temperature is achieved". And yet, during the experiment of the greenhouse box, when students were asked to interpret a graph which shows the profile of temperature *versus* time of the aluminium plate (greenhouse box) during its exposure to the radiation of a light bulb, the same students responded: "The black body absorbs and then retransmits heat, which however clashes with the transparent cover that, having minimum absorbance (as it's not totally transparent) re-emits towards the black body, eventually increasing the temperature". In both answers it is possible to see how students use the word "heat", surely the best-known and most familiar for them, instead of the word "radiation", attributing in their

[21] Since there were only three interviews, they were not statistically significant of the sample but were useful in providing confirmation of specific points already documented in the research literature.

reasoning the same physical meaning. This is further confirmation of some existing results in the research literature on the difficulties students encounter with the concept of heat.
The data collected in the post-questionnaire emphasized a point already highlighted in the analysis of the societal dimension, i.e. the fact that after the lab-course most of the students were able to distinguish between global warming and other phenomena. As already mentioned, 7 out of 9 students grasped that the ozone hole and general air pollution are another type of phenomena, indeed many students reported: "I was convinced that global warming and the hole in the ozone layer were two closely-connected phenomena".
The data emerging from the post-questionnaire, although less rigorous in its scientific language than data collected from the tutorials, highlighted that students worked out their own personal reinterpretation of their content knowledge; indeed the students answered the questions in an authentic way by quoting the disciplinary content addressed during the course without any direct instruction to do so in the questions.
In the analysis of the interviews we tried to explore the problematic issues that emerged in the previous analysis. Particularly, we tried to extract feedback about students' reaction to the explanation of the greenhouse effect through reasoning in terms of energy balance[22].
The interviews confirmed the fact that the concepts of absorbance-transmittance-reflectance were not problematic for students, but something new also emerged: the interviewees had problems positioning the concept of emission in their reasoning. Regarding this, below is an extract of a student interview, where it is possible to see how he/she arrived at distinguishing between reflection and emission:

> Student: *well, in the case of Earth, we made some hypotheses that were, I mean we talked about, the radiation striking Earth which is partly absorbed and partly transmitted, I mean, more reflected than emitted…*
> Interviewer: *Why is 'reflected' different from' emitted'?*
>
> Student: *because 'emitted' is the point of departure of radiation, because it is first absorbed and then emitted… then afterwards we studied the specific details of absorbance, of the property that light radiation has on bodies […] of the characteristics of absorbance, transmittance and reflectance […]*

In the answers above, the student demonstrates a temporal causal linear reasoning to distinguish between emission and reflection: "because transmittance is the starting point of radiation; because after absorbing it, it emits". In this reasoning, there is something "before" and something "after", a "cause" - the absorption of radiation - and an "effect" - its emission. Nevertheless, the student tries to build his/her own reasoning in order to explain the phenomenon of the greenhouse effect in terms of energy balance instead of in terms of trapping radiation:

> Interviewer (I): *What relationship is there between explaining the greenhouse in terms of trapping of radiation and between explaining it in terms of energy balance?*
> Student (S): *[…] so, what relationship is there between trapping and balance? Well…if the Earth receives radiation… the rays emitted from Earth after absorbing those of the Sun will*

[22] This point also touched the epistemological dimension.

be trapped by the atmosphere…that is, more than trapped..I'd say absorbed… that then in turn will re-emit them
I: *And why?*
S: *because the atmosphere is a mass… and so if it absorbs it heats up*
I: *So, in effect, you can explain the greenhouse effect and earth warming only in terms of energy balance and not of trapping!*
S: *yes… you just need to think of the atmosphere as a body*
I: *Exactly.. the atmosphere isn't a cover that blocks, but a body that absorbs and emits…. This is a vital issue*

The key point that allowed him/her to tackle the reasoning in terms of balance was to consider the atmosphere as a body that interacts and, therefore, absorbs and emits radiation.
Another point that emerged from the interviews, and that confirmed the result of the post-questionnaire, was that the models discussed during the course represented the *core-idea* for distinguishing between global warming and other phenomena such as the ozone hole and pollution. Regarding this aspect, here is an excerpt from another student interview:

- **distinction between global warming and the ozone layer depletion**
  "Before the course, I thought it [the cause of GW] was a thinning of the atmosphere... so, because it was thinner, more radiation could enter and the Earth overheats ... but then I realized that the atmosphere also accumulates and re-emits radiation [...]" (Andrea)

- **distinction between global warming and general pollution**
  "[…] the heating is due to the fact that the particles that make up the atmosphere, which are greenhouse gases and which are increasing, absorb and consequently raise the environment temperature" (Andrea)

From this excerpt it is also possible to see how there is a temporal linear causal mechanism when he/she spoke of the absorption and emission of radiation by the atmosphere, even if the concept of emission is better described than that by the previous student.
To sum up, as a general result from the analysis, it emerges that most of the students:
– understood and were able to interpret the concepts of absorbance, transmittance and reflectance;
– encountered difficulties in distinguishing the concept of radiation from the concept of heat;
– were able to distinguish between global warming and other phenomena.
As a more specific result which is not applicable to the whole group, it appears that the three interviewed students showed some difficulties in gaining confidence with the reasoning of energy balance, as they had not been able to achieve temporal-causal reasoning. However, despite their difficulties, these students were still able to create a personal path[23] to try to tackle the argument. Particularly, two points seemed to have played a key role in shifting the reasoning from thinking of the greenhouse effect in terms of "heat entrapment" to terms of "energy balance": *i)* to distinguish

[23] This is supported by the diversity in their thinking and the candor of their words. Even though they do not strictly adhere to the terminology,, they do not simply regurgitate the original words of the tutors, but provide a reinterpretation that triggers different reasoning strategies by each of the three students.

between reflection and emission, even though maintaining a temporal causal reasoning, and *ii)* to consider the atmosphere as a body that actively interacts.
Reasoning in terms of energy balance represents a critical point and also poses a problem to solve: the students are used to reasoning with a temporal linear causal approach and, in the face of phenomena and models that require new types of reasoning, they seem to prefer to temporally follow the path of radiation (incoming and outgoing), attributing a "before" and an "after" [24]. Probably for this reason, the concept of emission is the most difficult to interpret and place in the global reasoning[25].

4.2.3. Epistemological dimension

The three interviews appear particularly interesting for the fact that all three students have shown a deep and worrying lack in their physics education; in particular students had no idea about what a physical model is, because they had never spoken about it during their physics lessons at school:

> *"[A model] is a reproduction of a real phenomenon in the laboratory by means of appropriate tools to its measurement and made in order to obtain data as much as possible related to reality ... and computational accuracy [...] [Thinking of the models made in physics] I can think of an electrical circuit." (Francesco)*

> *"By 'model' I mean experiments ... thinking of my studies, the word model has never been used except for some experiments in the laboratory ... examples of models do not come to my mind" (Andrea)*

> *"The model is, I think, an example, in the sense that even in everyday life, the model is something from which you take example in physics ... and I would give the same meaning … the model is an experiment, then an example …" (Fabrizio)*

Such a weakness is also easy to find in most textbooks that pay increasingly less attention to the modelling processes in physics.
Returning to the results of the study, the fact that students did not have any idea about what a model in physics is, made our attempt to gradually introduce them to the game of modelling and complexity a fairly ambitious goal. However, epistemological weaknesses did not preclude active disciplinary involvement and the activation of a process of reworking their personal content knowledge. We believe that this was very much influenced by the great interest of this particular group of students in the societal implications of the issue.

4.3 Findings and open issues

With the case analysis, we asked what contribution the pilot study can make to answering the following questions: *What kind of role could be played by the disciplinary, epistemological and*

[24] This result is in agreement with results on causal reasoning obtained in a teaching experiment on thermodynamics (Levrini et al., 2014a; 2014b).
[25] The concept of issue requires a perspective in terms of balance, while the concept of reflection leads us to look for temporal process (there is a change in the type of causal reasoning that is necessary to understand it).

societal dimensions in fostering a deep involvement of students on complex issues such as climate change? What changes should be made to the entire proposal in light of the pilot-study experience in order to tackle a real classroom context?

From the data analysis emerged some general points (for example: use/abuse of the concept of heat, the lack of awareness of the processes of modelling and role models in physics) which are particularly important for an effective understanding of the phenomenon of climate change.

Nevertheless, the existence of a strong societal dimension triggered in students a meaningful process to gain access to the disciplinary dimension despite these difficulties. This process allowed the students to develop their own personal path, both to understand the physics contents (e.g. the explanation of the greenhouse effect in terms of energy balance) and to evaluate the role of individual behaviour in the variation of environmental parameters of fundamental importance in the greenhouse mechanism (e.g. the role of the absorbance of the atmosphere at different wavelengths). The interaction between these two dimensions has started a process of change in students' ideas and ways of looking at the problem. This change has resulted particularly difficult and not deeply rooted, due to the lack of a prerequisite general discourse on modelling which is necessary to confidently tackle the conceptual path and to be able to grasp the peculiarities of an epistemological perspective of complexity.

We believe that the maturation of the knowledge necessary for the development of critical thinking, which has lasting repercussions on (and awareness of) individual and social behaviour, may be achieved only through a proper integration of the three dimensions.

In light of these results, the goal we set for ourselves as we move from the pilot-study experience to the next step is therefore to foster in students an activation of the three dimensions. Particularly, the choice to find a normal classroom context and to explore this experience indepth is made in order to guarantee a "neutral" context from the societal perspective (because they are not volunteers).

On the basis of the results of this pilot-study, it will therefore be necessary to review the materials in order to provide a deeper epistemological dimension. Specifically, it is fundamental:

- to make stronger and more evident the epistemological *fil rouge* on the models and modelling (chapter 2, section 2.2);
- to revise (in form and content) the lesson on complexity to make it suitable even for students who have not had the opportunity to develop a previous awareness on the perspective of complexity and its epistemological features (chapter 2, section 2.1.3).

We believe that future experiences using the new restructured materials will allow us to verify their effectiveness in helping students to overcome behavioural barriers that currently prevent them from feeling involved in the issue of climate change. Such an issue is for us a topic of primary importance for the development of a scientific citizenship even though it is particularly distant from traditional methods of designing school curricula, because of their transversality and intrinsic complex nature.

At the very least, the pilot-study guided us in revising our investigative tools. The most significant change consisted in the insertion of explicit questions aimed at indepth investigation of the epistemological dimension (chapter 3) regarding both the idea of models and the perspective of complexity (chapter 7).

Such considerations and changes based on the pilot-study are strongly coherent with our initial conjecture (chapter 1).

CHAPTER 5

Analysis of the conceptual dimension

The aim of this part is to show the results of the data analysis carried out to see *if* students achieved conceptual understanding of the physics knowledge addressed throughout the whole path. In particular we analyzed in details the written task, realized at the end of the activities.
The task was designed in collaboration with the class teacher since that was his tool for evaluating the students. The questionnaire construction took place through a process of triangulation between the teacher and the scholars who participated in the project and it was built to match, as much as possible, the needs of the teacher and the school and needs coming from the research.
According to the evaluation habits and the standards of the school, the task had a multiple choice format and was articulated in 13 questions (see Annex D). In evaluating the threshold of sufficiency the score of 7/13 represented the minimum. Each question had 4 choices. The students were informed that, for each question, there was only one right answer. In case they recognised more than one correct answer they had to choose the more complete one. This aspect represented a conscious methodological choice in the design of the written task, since we wanted to check if students grasped a rich meaning of the physics concepts addressed during the course and if they were able to see all the nuances stressed by the different perspectives in which the concepts were addressed.
The crucial topics around which the task was articulated were identified by the researchers. The topics were chosen both because they were the crucial points highlighted by the research literature, either because they were the crucial points around which the conceptual path was built. The design of the task was also inspired by the concept inventory on GHE.
The graph below (figure 5.1) provides a global view of students' scores. One point was attributed to each correct answer. Only 24% of students failed the task and the 76% of students were successful (reached the sufficient level of performance represented by 7 correct answers out of 13).

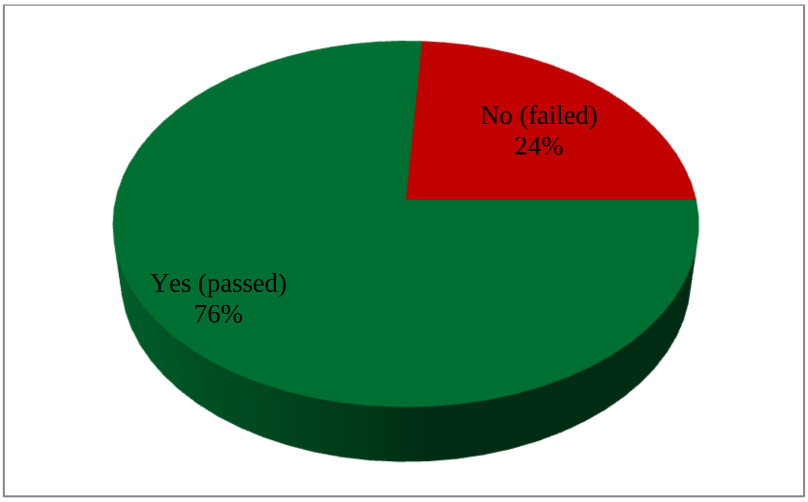


Figure 5.1. Class score (written task)

The graph below (figure 5.2) shows the distribution of the scores over the students:

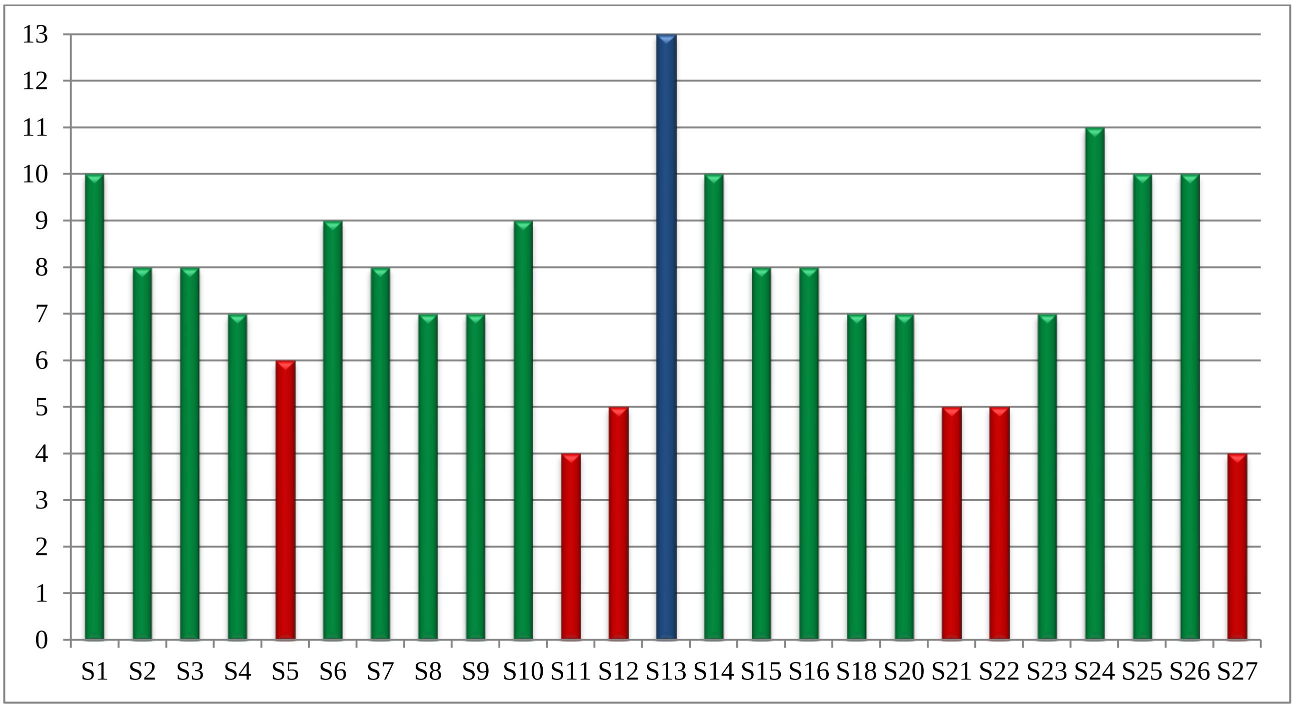


Figure 5.2. Students' score (written task)

The colours in the graph mean: blue-bar the excellence, green-bar students who achieved a sufficient or competent level of performance and the red-bar students who achieve a low level.
Looking at the graph, it is interesting to highlight that only 6 out of 25 students failed the task. Among the students who passed the task, only one achieved the maximum and other 5 out of 25 students achieved a competent level of performance. So, most of the students have been situated in a mid-range.
Both the teacher and the school were very satisfied of students' performance that went beyond teachers' expectations. Nevertheless, as already mentioned, this task had a double role: on one hand it had to feedback to the school system (to students, teacher, school, parents) about the project; on the other hand it had to feedback to our research about students' conceptual understanding.
As for the research feedback, the written task was hence analyzed in order to answer RQ_3 and RQ_4 (*RQ_3: How do secondary school students react to the proposed materials? Are the materials effective in achieving the main goal of the research?RQ_4: Which analytic methods can be used to investigate the multiple dimensions of a teaching/learning classroom experience?*) applied to the analysis of the disciplinary dimension.
In order to provide the "disciplinary contribution" to the answer to the RQs, the analysis was carried out by focussing on the questions and was oriented by the graph reported in Figure 5.3.

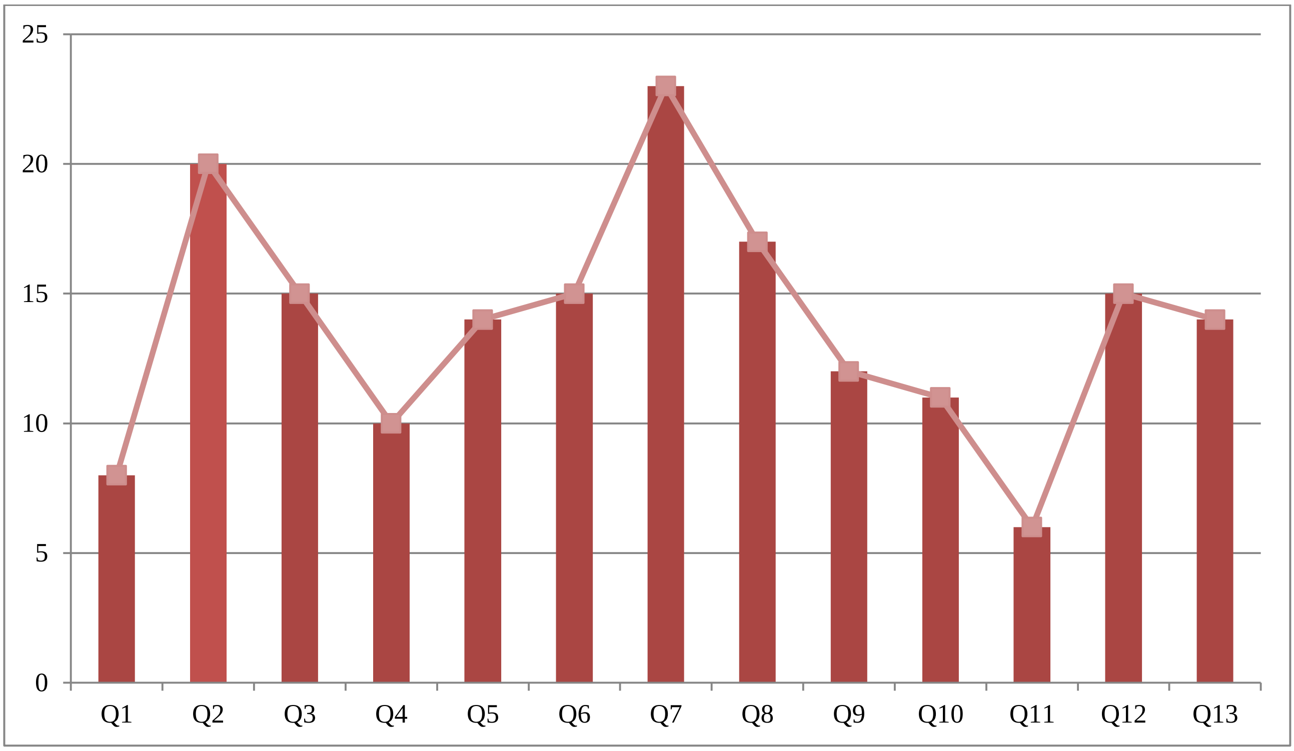


Figure 5.3. Map of students' answers

The graph was interpreted by grouping the questions which touch similar focal/crucial points: properties of matter-radiation interaction (Q2-Q3-Q4-Q5-Q8-Q9); emission radiation (Q1-Q10); differences between heat and radiation (Q10-Q11); "information" questions (Q6-Q7-Q12-Q13).

More specifically, the group of questions Q2-Q3-Q4-Q5-Q8-Q9 concerned matter-radiation properties. Particularly, Q2 required a student to recognize that GHE is phenomenon of matter-radiation interaction and that it depends "both" from the properties of the radiation and from the properties of the atmosphere. In Q3 the point was to distinguish between "amount of radiation" and "percentage of the total inner radiation" and to recognise that the fraction of radiation which is absorbed is part of a balance of the inner radiation. Q4 required a double ability: to reason about radiation both in terms of wavelength and frequency, and to recognize that the atmosphere was not transparent for the overall electromagnetic spectrum. Q5 required to interpret the properties of transparency, opacity, etc. in terms of absorbance, reflectance and transmittance. Q5 required to apply the previous properties by focusing of a real problem. Q9 regards again the concept of transparency and it required a student to give up the idea of transparency as an absolute concept and to accept its dependence on the kind of radiation.
The group of the two questions Q1 and Q10 focused on the emitted radiation and on the problem that originates when the emission is disregarded in the balance reasoning. Q1 seemed a simple question because it concerns the "definition" of a black body. But, behind its apparently simplicity, it required to focus both on the absorbance and the emittance in order to give a complete description of the black body behaviour. The same occurs with Q10, where, if the emitted energy is not considered, it is not possible to explain the equilibrium (or the stationary condition). Furthermore, Q10 was grouped also with Q11 as ensemble of questions focused on the differences between heat and radiation. Q11 required to give up the idea of explaining the GHE by trapping the heat in the

atmosphere and to accept the reasoning in terms of balance between inner radiation and ongoing radiation.
The last group of questions was composed by “information questions”. They were grouped not because of their topic but because the informative nature of the question. Q6 and Q7 required only to recognize the balance relationship and the graphs seen during the course. Q12 and Q13 aimed only to verify if students knew the term feedback and the typical temporal scale of climatology.
In the following sections, the analysis group by group is presented.

5.1. Properties of matter-radiation interaction: Q2-Q3-Q4-Q5-Q8-Q9

Figure 5.4 shows that the questions in which students met fewer difficulties are Q2 and Q8, whilst those in which they had more difficulties are Q4 and Q9.

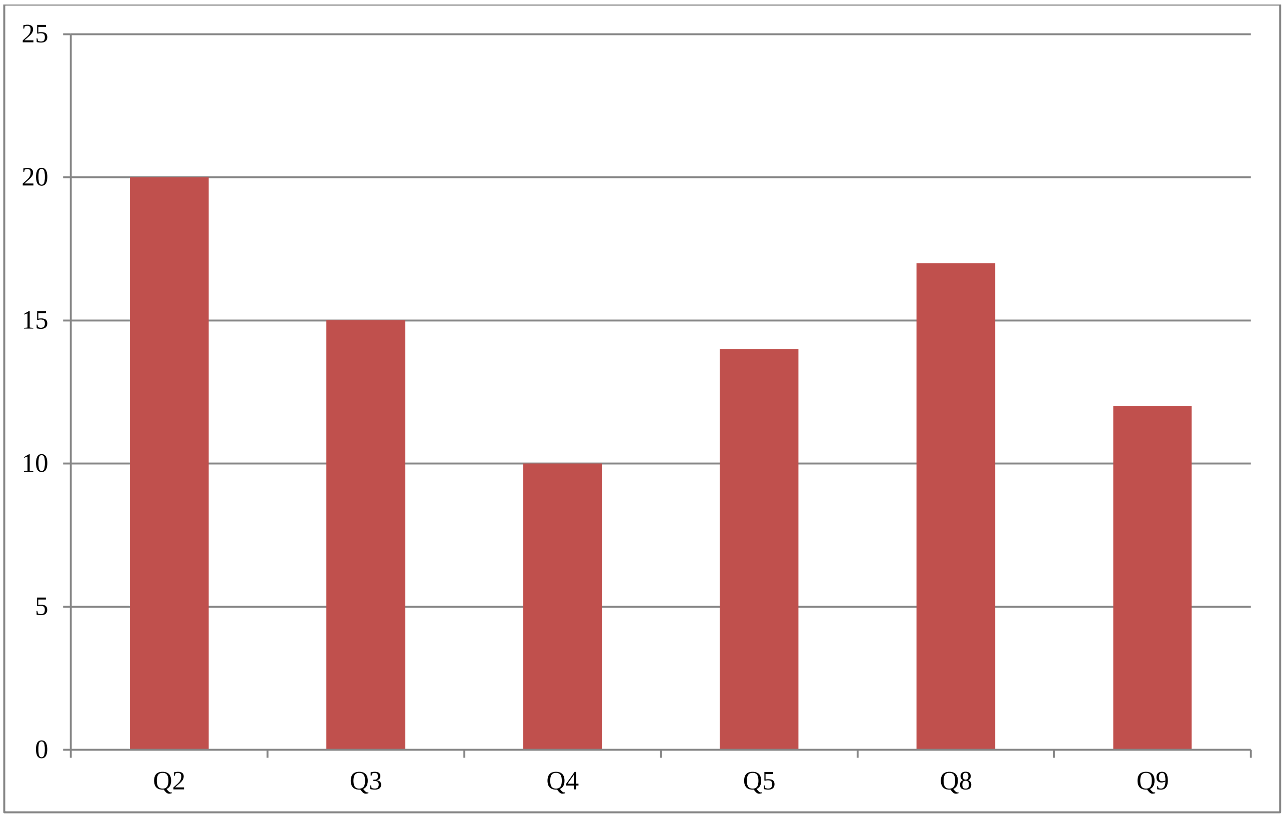


Figure 5.4. Questions on properties of matter-radiation interaction

Let’s go through question by question in order to interpret students’ different level of performance.

Question 2

Q2 was targeted at investigating if students grasped the idea that the matter-radiation properties are interaction properties, which depend both from the nature of the matter and from the kind of radiation (as it was highlighted by the experiment with the cylinders, chapter 2). Furthermore, the question makes a link between the importance of such a concept in the explanation of greenhouse effect.

Question 2: *"The physical phenomena which cause the greenhouse effect depend …"*

A1. both on the properties of the radiation and the properties of the gases that make up the atmosphere

A2. only on the properties of the incident electromagnetic radiation

A3. only on the properties of the gases that make up the atmosphere

A4. none of the above answers is correct (justify this choice)

Students' reactions to this question appear to be very positive: 20 out of 25 understood that we were talking about interaction properties.

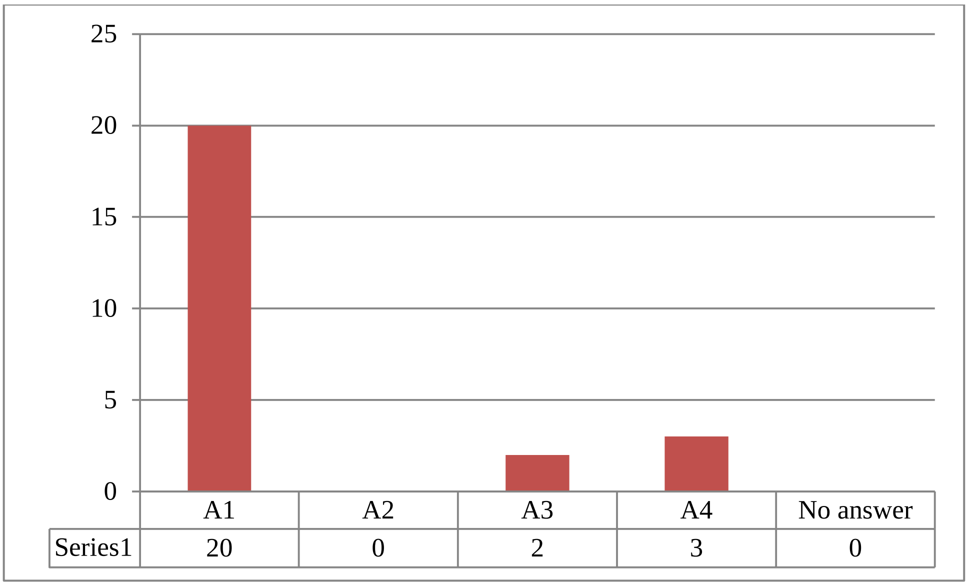


Figure 5.6. Students' answers for Q2

Q2 verifies students' comprehension/awareness about the two points: i) the "interaction feature" of the properties that are not recognize as absolute; and ii) the important value of such "interaction feature" in explaining greenhouse effect.

Question 3

Q3 was targeted at investigating if students grasped the concept of absorbance, its role in the balance relation of an inner radiation (chapter 2, section 2.1.2) and its relationship with transmittance and reflectance.

Question 3: *"What is the absorbance?"*

A1. the amount of radiation absorbed by a body
A2. the percentage of the total radiation that is absorbed by a body
A3. a characteristic property of opaque bodies
A4. the opposite of transmittance

Students' reaction to this question appear to be situated in a mid-range: 15 out of 25 recognized in the answer to the role of the absorbance in the balance equation of an inner radiation.

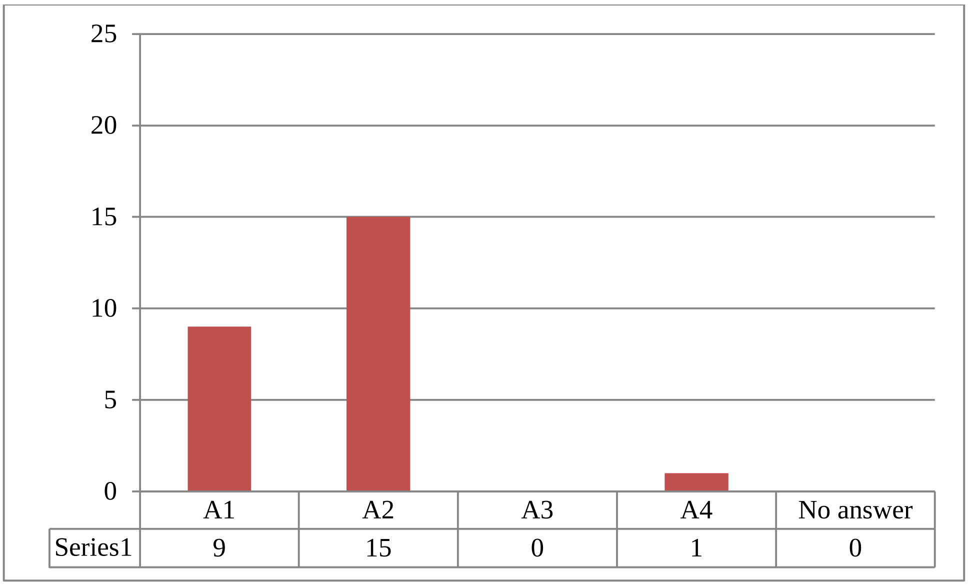


Figure 5.7. Students' answers for Q3

All the students' minus one who did not choose the correct answer focused their attention on answer A1.

Question 4

Q4 was targeted at investigating if students are able to manage with the interaction properties, the feature of the object and the radiation spectrum by combining the part in a unique reasoning and by applying their reasoning in a situation in which "new words" are used.

Question 4: *"The atmosphere is considered a:"* **A1. opaque body for the low-frequency radiation and a transparent body for the high-frequency radiation** A2. opaque body for the high-frequency radiation and a transparent body for the low-frequency radiation A3. opaque body for both the low-frequency radiation that for those high frequency A4. a transparent body both for the low frequency radiation that for those high frequency

Students' reaction to this question achieved not a high performance, only 10 out of 25 recognized the correct answer.

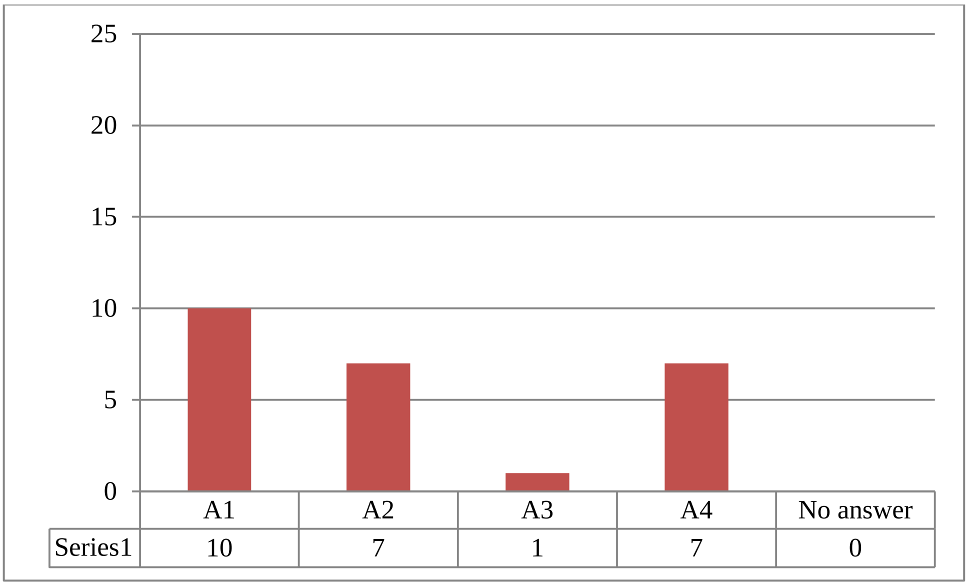


Figure 5.8. Students' answers for Q4

The students who did not correctly answer this question were essentially distributed over two answers:

- those who responded "on the contrary" compared to what type of radiation the atmosphere is opaque rather than transparent. They probably confused wavelength and frequency.
- those who responded that the atmosphere is a transparent body. They probably consider only a shortwave radiation, like the solar radiation, or did not appropriate the dependence of transparency also on the type of ingoing radiation.

Question 5

Q5 was targeted at investigating if students were able to pass from the value of the properties of transmittance in a certain situation to the "qualitative feature" that the body should show.

Question 5: *"A body with transmittance = 0 is defined as:"*

A1. grey body
A2. opaque body
A3. translucid body
A4. transparent body

Students' reaction to this question appears in a mid-range of performance, 14 out of 25 recognized the correct answer.

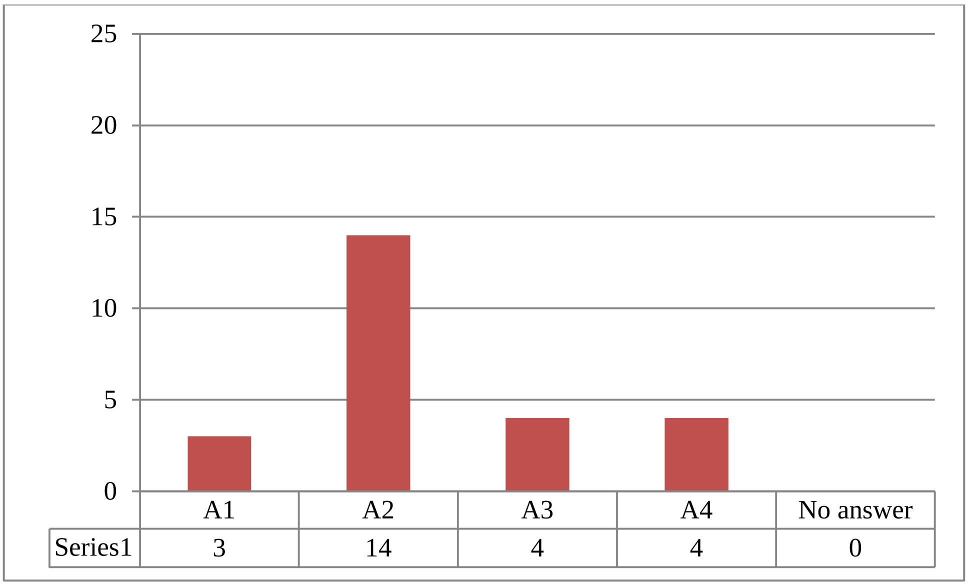


Figure 5.9. Students' answers for Q5

Question 8

Q8 was targeted at investigating if students were able to apply what they had learned to a real problem. Students were required to recognize that, if two bodies have been heated by using radiation source, the colour of the object influences its absorbance and then its temperature.

Question 8: *"An opaque object A (e.g. a block of wood or stone) and a transparent object B, having the same thermal capacity and the same initial temperature equal to Ti, have been exposed to sunlight for the same time t. The temperature TA and TB of the two objects at the end of the exposure time will be:"*

A1.TA = TB
A2. TA > TB
A3. TA < TB
A4. You can not determine the relation if you do not know the mass of each object

Students' reaction to this question appears to be very positive, 17 out of 25, recognized the correct answer.

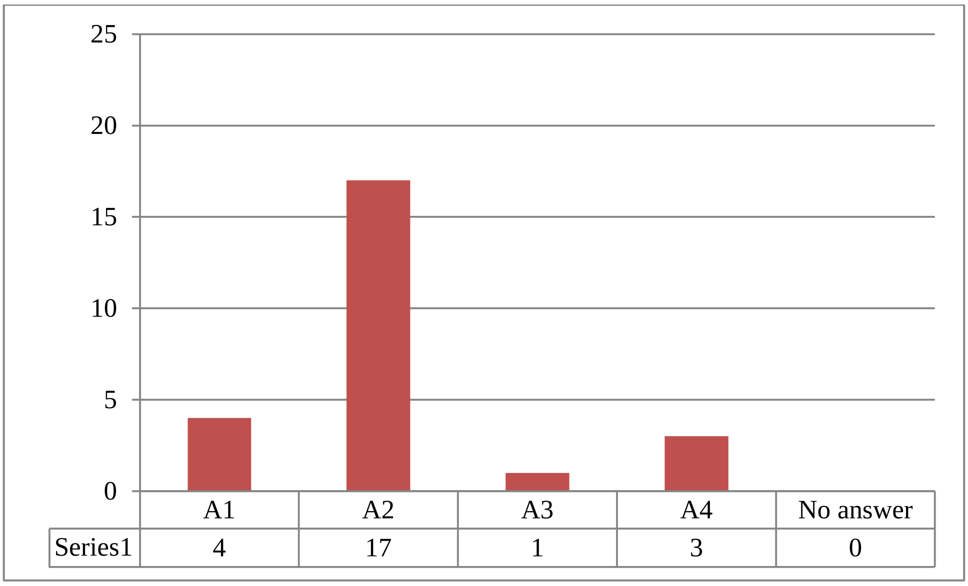


Figure 5.10. Students' answers for Q8

Q8 appears to be an easy question for students, even if they were required to elaborate their knowledge and to apply it in a real situation.
The problem proposed in this question was evocative of a similar problem which was dealt with during the experimental lessons.

Question 9

Q9 was targeted at investigating if students accepted transparency as an interaction properties depending on the wavelength (i.e. away from the common sense associated with that word).

Question 9: “A block of plexiglass (plastic) is:”
A1. transparent to any type of radiation
A2. transparent for visible radiation
A3. opaque to infrared radiation
A3. opaque to ultraviolet radiation

Such a topic results to be something still difficult to accept for them, indeed only 12 out of 25 recognized the correct answer.

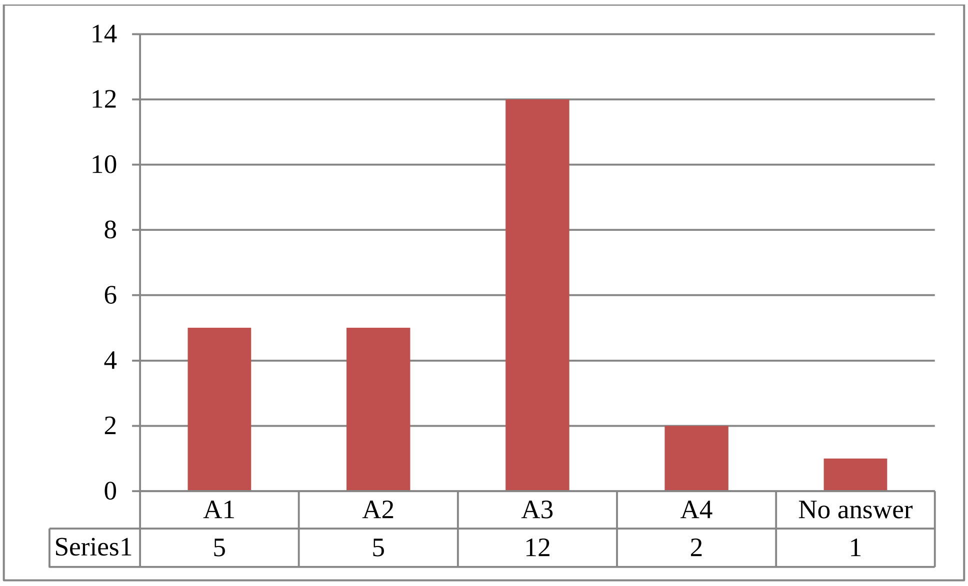


Figure 5.11. Students' answers for Q9

Students found it difficult to manage in a more complex context the concepts of *opacity* and *transparency*, although these were two points which were strongly stressed throughout the project. Such a difficulty is causes by the fact that there is the greatest discrepancy between common sense and scientific thinking. The words *opaque* and *transparent* are much used in everyday language. Students showed to not have re-arranged their knowledge and to not have correlated these words to the scientific concepts of absorbance, reflectance and transmittance.

5.2 The concept of emission radiation (Questions Q1 and Q10)

The questions Q1 and Q10 concerned the concept of emittance and, from the overall picture (Figure 5.3) they appear to be problematic.

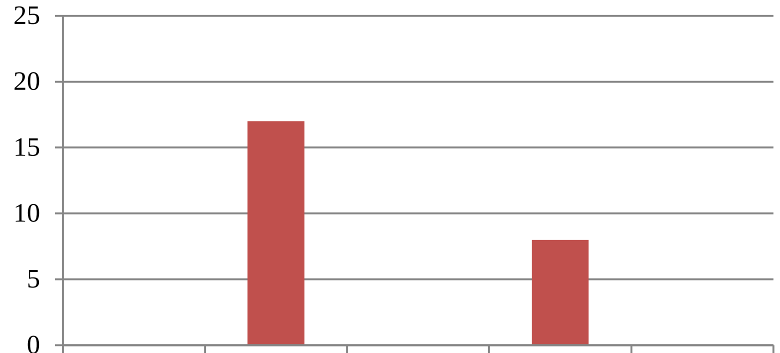
Question 1

Q1 aimed to investigate what is a black body. Apparently, it could seem an “information question” in which it is required to remember the definition, but it represented one of the challenging question of the task.

Question 1: *"What is a Black body?"*

A1. A body which cancels all the radiation
A2. A body which absorbs all the radiation
A3. A body which emits all the radiation
A4. A body which absorbs all the radiation and emits

The result of this application is particularly interesting, only 8 out of 25 students answered exactly, the other 17 out of 25 provided a wrong answer, but the wrong answer is the same for all the 17 students "A2. A body which absorbs all the radiation".



	A1	A2	A3	A4	
Series1	0	17	0	8	

Figure 5.13. Students' answers for Q1

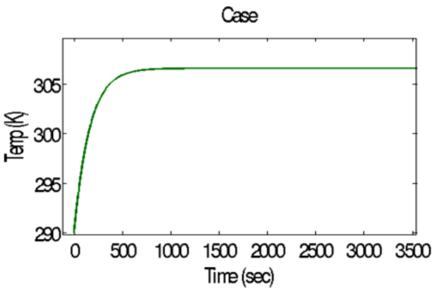
The A2 option is not completely wrong because it highlights one feature of a black body. However, it disregards the critical point that we stressed plenty of times during the path: a black body also emits in function of its temperature. Here we can probably see, again, the strength of common knowledge that, driven by the word “black”, does not accommodate the idea that, for example, the sun is a black body.

Question 10

This issue can be further highlighted by the responses to the question Q10, where awareness of the concept of emission assumes a key role to answer correctly.
In this question students were asked to explain why a graph (temperature vs. time), which represents an object heated through radiation energy, shows a temperature plateau.

Question 10: *"This graph (Time-Temperature) represents an object which is heated by radiation. Why does the graph show a temperature plateau?"*

A1. Because the object reaches the equilibrium temperature with the lamp
A2. Because the temperature of this specific object can't overcome this limit
A3. Because in that point the energy emitted is the same of the energy absorbed
A4. Because the lamp can not provide more heat than that



The correct answer was A3 and 11 students answered well, but the same number of students ticked A1 as correct answer. This distribution shows the fact that students still reasoned in terms of thermal equilibrium between heat exchanges and not in terms of energy balance where both the emission process and absorption are crucial.

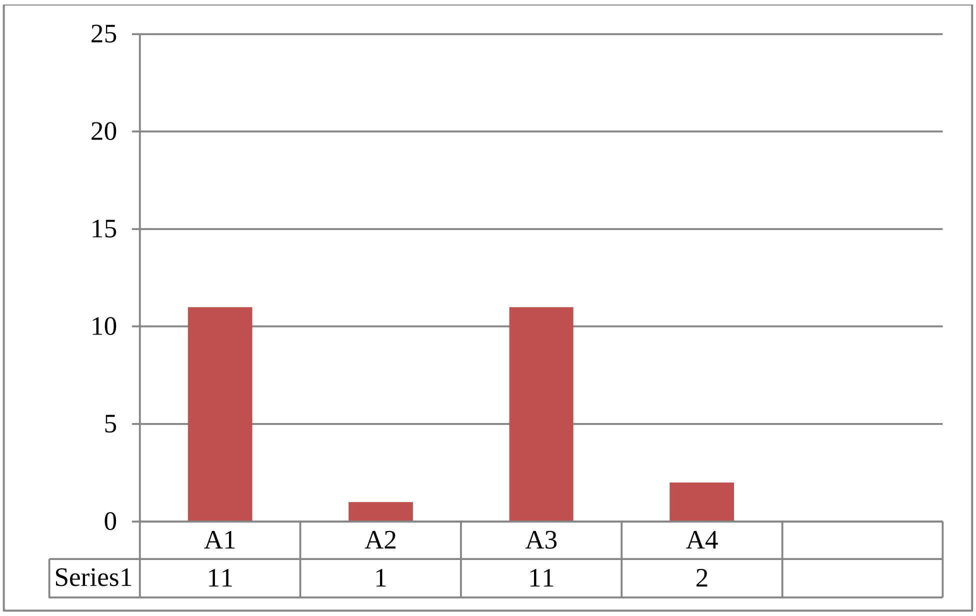


Figure 5.14. Students' answers for Q10

5.3. Difference between heat and radiation (Q10 e Q11)

Both question Q10 and Q11 aimed to investigate if students grasped the difference between heat and radiation. Q10 was already explored in the previous section because played a double role, i.e. the importance of considering the emittance and the importance to distinguish between heat and radiation.

In Q11 were explicitly required to recognize if the greenhouse effect depends on “heat trapping” or on equilibrium radiation balance.

> **Question 11:** *“What is the effect of greenhouse gases in the atmosphere?”*
>
> A1. They trap the heat absorbed from the earth producing an overheating
> A2. They produce a decrease in the thickness of the upper atmosphere, increasing transparency for high-frequency radiation
> **A3. They cause an increase the absorbance of the atmosphere for the low-frequency radiation**
> A4. They cause an increase the transmittance of the atmosphere, increasing the amount of radiation that strikes the earth

Q11 was the question in which the lower result has been achieved, only 6 out 25 students recognized the correct answer.

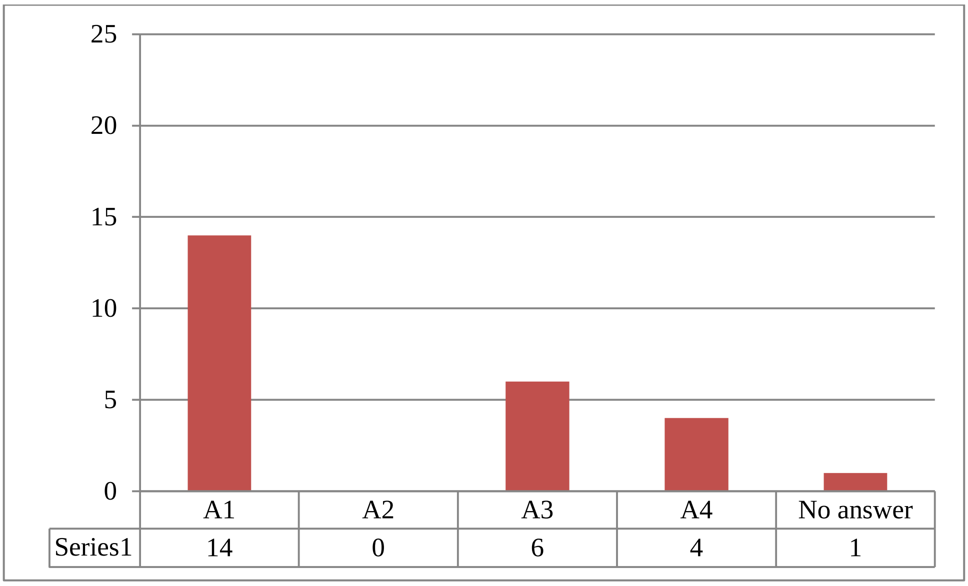


Figure 5.15. Students' answers for Q11

Q11 represented the most difficult question because required to have really “internalized” the crucial physical points. Behind such a difficulty there is a naïve image and an epistemological obstacle that, although well known and explicitly addressed, the path was not able to destroy (chapter 7).

5.4. “Information” questions

In this section four questions (Q6-Q7-Q12-Q13) are grouped. They do not concern the same topic, but have the same feature of being “information” questions (see Annex D).
The first two questions aimed at checking f if the students were able to remember information about the physical laws addressed during the course (Q6), and about the graphs discussed during the lab-activities in which different-coloured cylinders were exposed to a radiation source (Q7). The other two questions were designed with a *definition formula* that aimed to explore two of the main features of climate science: one concerned the idea of feedback (Q12), and the other one concerned the aspect of the typical time scale of climate events (Q13) .

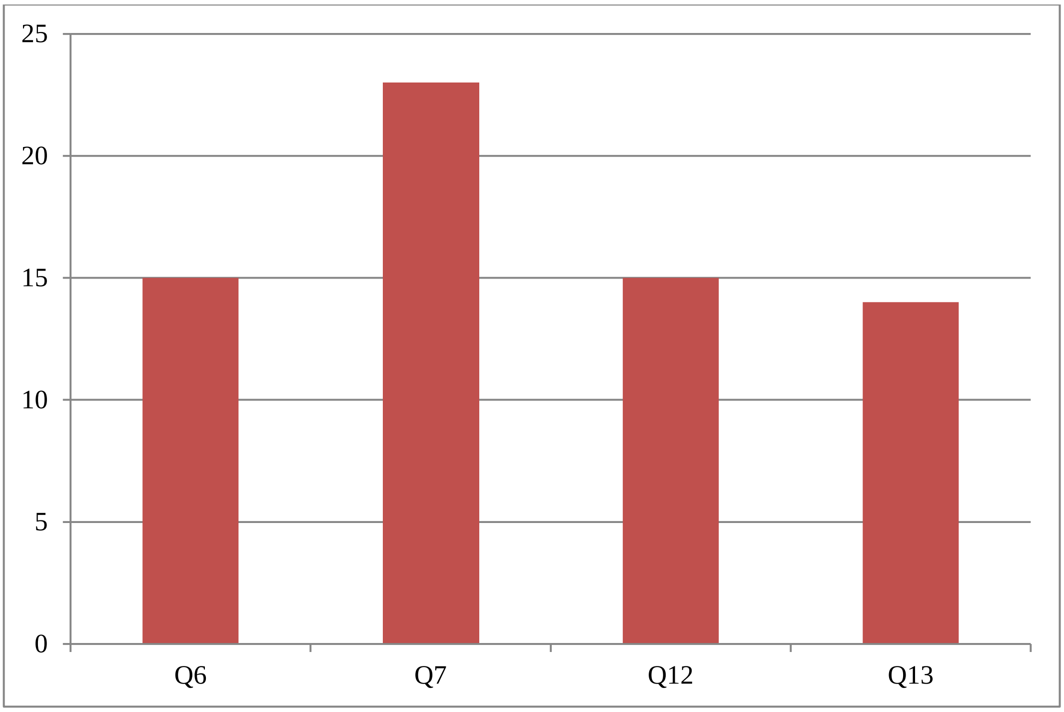


Figure 5.16. Informative questions

Figure 5.16 shows that only Q13 created some difficulties. The students which answered incorrectly generally focused on the spatial scale. This is quite normal for students who have studied at school classical mechanics, in which the time is reversible and most attention is given to the spatial evolution.

5.5. Discussion of the results

The analysis shows that students seem to basically understand the disciplinary content knowledge, but they didn’t seems particularly able in managing the concepts in an autonomous way or in recognizing them in new situations with respect to the contexts where they were presented.
This is a clear signal that the new knowledge is not particularly robust. The content reconstruction developed along the whole teaching experiment changed something in their way of seeing physics, put it could be only a starting point because there weren’t the prerequisites for being more than this.

This students are particularly young for this path, in fact in their physics curricula they did not deal with thermodynamics (e.g. they have done only thermology and calorimetry). Again, they have not really solid physics basis, because some of the concepts of the path were completely new for them (e.g. frequency, wavelength) and also because during the year they addressed a lot of extra curricula projects, so they did not have enough time for the reorganization and the settling of their knowledge.
From the analysis it appears moreover that the students were able to provide right answers in most of the contexts similar to what they knew whilst they had difficulties in handling the same concepts in new contexts. This is a clear signal that the students were not used to explore multiple contexts and multiple definitions (Levrini & diSessa, 2008) and that their attitudes toward an evaluation task was part of the didactical contract (Brousseau, 1986).

Finally, we want to stress one again that the data collected for the disciplinary dimension are more weaker than the data collected for the other dimensions because of the constraints of the school. Such a lack in the data obliged us to make a methodological effort to try and use the data of the written task for our research purposes and to interpret the students' conceptual achievement from this data. In this regard, we analyzed the questions by grouping them according to the kind of problem that the research literature suggests investigating.
To sum up, as positive results the analysis showed that the students understood the properties of absorbance, reflectance and transmittance, and that they did not overlap the process of reflection with the process of emission. Instead as open problems, the analysis highlighted that students continued to show difficulties in managing the concept of emission and in making confusion between heat and radiation.
This process of analysis allowed us to understand what problems the path helped resolve and which problems still remain open. Nevertheless, the analysis did not allow us to thoroughly investigate the nature of these unresolved problems.

CHAPTER 6

Analysis of the societal dimension

The aim of this part is to show the results of the data analysis carried out to see *if* this kind of teaching experience was able to generate a behavioural response in the students and *if* this response could be related to a kind of knowledge.
Particularly, in order to carry out this analysis we took into account both the experience with the classroom context (sample D, chapter 3) and the two experiences with the volunteer students who attended the lab-course within the PLS (samples B and C, chapter 3). We analyzed in details the pre-questionnaire (Q1) and the post-questionnaire (Q2). As already explained in chapter 3, the questionnaires were inspired by international surveys (Eurobarometer, 2009; Yale Project on Climate Change Communication – YPCCC) and include both societal/behavioural questions and questions on knowledge[26].
The two questionnaires were analysed in order to answer RQ_3 and RQ_4 (*RQ_3: How do secondary school students react to the proposed materials? Are the materials effective in achieving the main goal of the research?RQ_4: Which analytic methods can be used to investigate the multiple dimensions of a teaching/learning classroom experience?*) applied to the societal dimension.
In order to carry on the analysis for this dimension some open questions leaded the work:

- *Is it possible to find a correlation between students' knowledge and their behavioural attitude towards climate change?*
- *If so, what kind of analytic tools can be designed to investigate whether and how there were such correlation?*
- *What kind of general inference can be done from our case?*

Although the work is empirically-oriented, it still aims to achieve goals that reach beyond the specific area to which the empirical study refers: i) to provide a contribution to the methodological problem of designing analytic tools in order to investigate whether and how students' knowledge and behaviour evolve; ii) to provide new arguments for exploring the effect of mutual interaction between knowledge and behaviour.
Prior to the presentation of the analysis (6.4), it will be described: what we intend by knowledge and what is the actual debate on that (6.1); some details about the nature of the questionnaires (6.2); the methods we developed in order to identify patterns of knowledge and patterns of behaviour (6.3).

6.1. The international research scene about knowledge and behaviour

Over the past several years many international studies pointed out that there is a complex relationship between knowledge related to CC and related socio-scientific issues and the development of a behavioural attitudes towards them. Indeed, several researches suggest no strong link between a person's general environmental attitudes and knowledge, and his or her willingness to undertake pro-environmental actions (Boyes & Stanisstreet, 2012). Moreover, the literature on public understanding of CC indicates that, despite there is a widespread awareness of the issue and a general concern, there is however a limited behavioural response (Lorenzoni et al., 2007).

[26] The analysis has been realized in collaboration with Dr. Francesca Pongiglione (Facoltà di Filosofia, Centro Studi di Etica Pubblica, Università Vita-Salute San Raffaele) and it is the basis of the paper "Correlation between knowledge and behaviour related to climate change issue" (pre-print).

Many models of pro-environmental behaviour exist (Ajzen & Fishbeim, 1980; Fietkan & Kessel, 1981; Hines et al., 1986; Burgess et al., 1998). With respect to such models there is an open-ended debate in the literature, indeed several studies point out that most pro-environmental behaviour models are limited because they consider humans as rational beings who make a systematic use of available information and because they fail to take into account the complexity of the relationship among individual, social, and institutional constraints (Blake, 1999; Kollmuss & Agyeman, 2002).
Recent sets of research, mostly by sociologists and psychologists but also by philosophers and environmental educators, have tried to address these limitations and to investigate what kind of barriers prevent individuals to engage with environmental issues such as CC (Lorenzoni et al., 2007; Defra, 2008; Norgaard, 2009, Weintrobe, 2012; Tasquier, Pongiglione & Levrini, 2014b). Much research has been run in this field, but the debate is still ongoing, as barriers vary across population groups and may change over time according to life stage and other individual circumstances.
What it is instead rather shared among the scientific community, is the existence of a gap between knowledge and behaviour (Kollmus & Agyeman, 2002), since behaviour is influenced by many factors besides knowledge. Indeed, it is a common belief that knowledge about CC is not enough for generating a behavioural response. This has been suggested by many studies regarding environmental issues according to which knowledge about CC is simply not the key-factor able to have people change their behaviour about it (Norgaard, 2006; 2009; Strauss, 2008), and “scientific literacy” can actually even obstacle the behavioural response (Kahan et al., 2011). This is apparently also suggested by numerous surveys conducted mainly in Europe (Eurobarometer, 2009) or in the United States (YPCCC) which report a widespread awareness of CC and even a certain degree of self-reported knowledge, but a scarce behavioural response. Yet, more specific questions from the same surveys revealed a quite poor understanding about some basic climate dynamics. Recently it has been argued that lack of knowledge about causal relationships within climate dynamics (i.e. what causes CC, and what are the consequences of it) can hinder the behavioural response, as the individual is not able to understand its role as causal agent and therefore does not even know how to take action properly (Pongiglione, 2012). Another study (Kaiser & Fuhrer, 2003) suggested that what people lack is procedural knowledge, i.e. detailed information about what an individual can actually do in her daily routine to help mitigating climate change. A UK-based experiment somewhat confirms this view, as people involved in the study reported to have particularly enjoyed to receive tailored knowledge about how to reduce their environmental impact (Nye & Burgess, 2009).
We built our hypothesis taking both theses: the one concerning the importance of a “causal” kind of knowledge and that regarding the need of a “procedural” one.
The fact that knowledge does not act on behavioural change is due to a number of factors (e.g. Jensen & Schnack, 2006; Kollmuss & Agyeman, 2002; Lorenzoni et al., 2007). In our study, we particularly focus on one hypothesis that environmental education at school is often proposed to pupils in two extremely ways. On one hand, it is explored as a final part of biology or physics course and it is strictly technically addressed, hence it is not socially contextualized. On the other hand, it is part of environmental organization projects and it is most oriented to sensitize students to environmental issues without any particular insight on the scientific knowledge. None of the two ways addresses the issue of what knowledge can affect behaviour and how.

6.2. The questionnaires

In order to answer the RQs, we focused on the Pre-questionnaire (Q1), given to the students just before the first lecture, and the Post- questionnaire (Q2), given at the end of the last lecture.
The purpose of the first questionnaire was to investigate the students' level of knowledge and risk perception of CC and the actions taken on it (if any). The second questionnaire was aimed at investigating whether the level of comprehension regarding CC had changed and improved, and whether the information received made students willing to change something in their behaviour and how.

Pre-Questionnaire (Q1)

The first question of Q1 addressed to students concerned their beliefs in the existence of CC. Answers could range from "very sure" to "not at all sure" with two intermediate answers ("quite sure" and "not so sure") and the "don't know" response. If their answer was "not at all sure", they were asked to motivate it (as to find out why they were skeptic about the phenomenon). Such introductory question has been adopted in many surveys regarding CC knowledge (such as Eurobarometer surveys, or YPCCC), just for acquiring a general idea regarding participants' awareness of and belief in CC.
Question 2 and question 3 concerned the causes and the possible consequences of CC. The purpose of these questions was to understand whether students had a fair idea regarding the very basic causal relationships within CC, and were able to indicate the elements that mainly contribute to cause it and the possible effects it may generate. Also the YPCCC surveys addressed analogous questions, listing many phenomena as possible causes and consequences of CC and asking people how much they thought such elements to be somewhat involved in CC. Eurobarometer surveys included just a few questions about CC causes and consequences, that generally revealed a widespread confusion. In question 2 we listed a series of environmental issues (some responsible of CC and some not): the accumulation of greenhouse gases produced by single individuals; the accumulation of greenhouse gases produced by industry; livestock holdings; the ozone hole; deforestation; pollution[27]; nuclear power; other. Students were asked to what degree they thought the factors listed were causes of CC, with the following levels: very much/somewhat/little/not at all/don't know. We also asked to briefly motivate the answers given.
Question 3 (about the consequences of CC) was left open, without predefined answer; we also asked to specify which possible consequences (if any) worried or scared them mostly. We were generally more interested in verifying the level of understanding about the *causes* of CC, since our hypothesis is that this is the crucial point on which knowledge is more confused or lacking (as shown also by Eurobarometer and YPCCC surveys). Furthermore, only knowing what causes a phenomenon allows the individual, with her behaviour, to prevent it, while focalizing only on the (disastrous) consequences of it may just generate helpless fear, without a hint on how to deal with it (e.g. Norgaard, 2006; Strauss, 2008). In general, the idea is that the understanding of the possible consequences of CC (as much as for every other issue alike) can be an element that sometimes motivates people to prevent it, but without a clear understanding of what causes it no action is possible.

[27] "Pollution" was originally meant as general environmental pollution (from waste, for example). Yet most students understood it as emissions (by transport means, industries, etc.) and therefore was not considered a crucial element in evaluating students' knowledge level.

Question 4 was about the current behaviour related to CC. Specifically, students were asked if they were currently taking action on CC (answer were simply "yes" or "no"). Then, if their answer was "yes", they were directed to question 4.a., that asked to specify what practically were they doing (open question). If they answered "no", they were asked, in question 4.b., to specify why. Two options were given: "I would like to do something, but I don't do it because….."; and "I'm not taking action and I would not do anything, because…".

General questions about people's current behaviour on CC are very common in CC surveys. Both in Eurobarometer (such as the Standard Eurobarometer, 2011) and in YPCCC (Americans' Actions to Conserve Energy, Reduce Waste, and Limit Global Warming, 2010) interviewees were asked if they had personally taken any action to fight CC. Instead of giving predefined answer, we left question 4.a. open, in order to understand whether students could generally indicate actions that actually help mitigating CC, or if there was a certain degree of confusion also about the actions that most contribute in preventing it (commonly expressed by actions such as "recycling waste").

The aim of question 4.b. was to find out the reasons for not taking action. A 2008 Eurobarometer survey has addressed this question, that allowed to individuating some of the main barriers to direct engagement in CC prevention. What had emerged in that case (through predefined answers, though) was that people lamented the scarce efficacy of individual action, the current inaction of bigger actors (governments, industry) and also a lack of information about what specifically could be done by the individual (Special Eurobarometer, 2008; 2009). We did not give any predefined option for answering this question, as we wanted students to express what was hindering them.

Post-Questionnaire (Q2)

Four questions were address in the final questionnaire (delivered at the end of the last lecture). In question 1, students were asked whether their opinions about CC had changed and in what sense. In question 2, students were asked whether their opinion about climate change's *causes* had changed. Specifically, there were listed again the various elements from the first questionnaire's question 2 (see above), and students were asked, for every single element of the list, whether their opinion regarding the importance of such element in causing CC had changed or not. They were asked to motivate their answer, in order to understand if they had achieved a fair level of comprehension of climate dynamics. Question 3 asked again which they thought were climate change's consequences, and how scared of them they were. Question 4 was about behaviour: students were asked whether they would modify something in their lifestyle as a result of what they had heard during the course. Those who answered "yes" were asked in 4.a. to specify how they will change their behaviour; those who answered "no", were given in 4.b. two options: "I would like to do something, but I will not do it because…" and "I will not do anything, and I would not because…".

6.3. Methods

Students' answers to the questionnaires were analysed through a bottom-up iterative process, aimed at discovering ways to reveal whether and how students' level of knowledge and behavioural attitudes evolved from the beginning to the end of the course.

The method that we used in our investigation concerns a phenomenological search for emergent patterns which can provide insight into students' level of knowledge, on one hand, and students' behavioural attitudes, on the other hand.

Operatively, the analysis allowed us to identify some *operative markers* which could reveal *whether* and *how* students i) enriched and refined their level of knowledge, ii) improved their behavioural habits; and *if there are* and *what kind they are* correlations between level of knowledge and behavioural habits. The markers concern two kinds of patterns: patterns of knowledge and patterns of behaviour.
The patterns have been identified through a process of triangulation among the researchers[28]. The identification of such markers allowed us to track the evolution of the whole group of students along the two dimensions investigated.
The consequential steps of analysis were carried out. The first step aimed to separately analyze the two types of sample in order to see similarities and differences between the two groups. Such a first picture of the whole corpus of data showed that both the group of students of the classroom and the group of students of PLS improved their level of knowledge and behaviour. The analysis highlighted that, as a global regularity, between the two samples there were some differences in the level of achievement both in knowledge and in behaviour, but that such differences were not in the amount of change. The group which achieved a lower level started from a lower level and the "gradient" of improvement looks like the same of the group whose reached a higher level starting from a higher level. Such result lead us to make the choice to consider the sample all together, for the next step of analysis. The second step, represented the substantial part of the analysis, aimed to analyzed the changes occurred in the patterns of knowledge and behaviour, separately, and to investigate the correlation between the two.
Prior to follow the steps of the analysis the patterns of knowledge (6.3.1) and behaviour (6.3.2), designed for interpreting students response, will be explained.

6.3.1. Knowledge patterns in Q1 and Q2

P1: the student is not able to correctly assess the importance of the factors listed in provoking CC. Specifically, tends to consider the ozone hole and nuclear power as very important factors, while severely underestimates the role of individual emissions, of deforestation and of livestock farming. Arguments given in open questions concerning consequences of CC and GHE are poor for both logic and content, show a widespread confusion and the general inability to distinguish between causes and consequences.
P2: the student is not able to correctly assess the importance of the factors listed in provoking CC. Specifically, tends to consider the ozone hole and nuclear power as important factors, but often not both, sometimes opting for a wiser "don't know" response. There is a general (but not excessive) underestimation of the role of individual emissions, of deforestation and of livestock farming. Arguments are logically coherent, but there can be severe conceptual mistakes. At times there is remaining confusion between causes and consequences.
P3: there are remaining mistakes in assessing the importance of the factors listed in provoking CC, giving too much importance to either the ozone hole or nuclear power, and underestimating the role of individual emissions, of deforestation and livestock farming. Arguments are logically coherent, the student is able to distinguish well between causes and consequences of CC and to correctly

[28] Each scholar who participated in the study searched for the emergent patterns by analyzing sample per sample and then, after a first phase, the scholars exchanged their work in order to check if they have identified the same patterns. The work was repeated several time and the special cases were collectively discussed. This process of triangulation has carried on to the progressive refinement of the patterns. Finally, the work have been validated from an external scholar.

mention some climate change's consequences. Contents are quite good, with some remaining mistakes.

P4: the student is able to assess correctly the importance of factors contributing to CC with some minor over- or underestimations. Both arguments and contents are good; there can be some minor mistakes.

P5: the student is able to assess correctly the importance of factors contributing to CC. Both arguments and contents are good.

In Q2 students' improvement can be measured both with an advancement of level, that bring them to a higher pattern among those already listed, and with an improvement in assessing the importance of climate change's causes, which they express by changing opinion on some of the factors listed in question 2, but not coupled with an improvement of the arguments in open questions. Such patterns are indicated adding a "X" to the existing ones (P1X, P2X, P3X, P4X, P5X).

P2X: it represents a sort of "threshold pattern" of knowledge. While it merely shows an improvement in Q2 from either P1 or P2, and therefore it is still indicating a low level of general knowledge, the improvement in assessing the importance of climate change's causes is a sort of turning point.

6.3.2. Behavioural patterns in Q1 and Q2

O: the student does not give any answer.

A: the student does not take action on CC (nor is willing to in Q2) as he/she thinks that individual efforts are ineffective.

B: the student does not feel like changing lifestyle and habits for preventing CC (nor is willing to in Q2)[29].

C: the student would like to do something for CC, but does not know what to do.

D: the student says he/she is taking action/willing to take action on CC, but then either indicates actions that are not very consistent with the problem (such as recycling waste), or declares (especially in Q2) things such as "I will consume/pollute less".

E: the student says he/she is taking action/willing to take action on CC, and mentions a general emission reduction or awareness raising among friends and family, but not specific actions.

F: the student says he/she is taking action/willing to take action on CC, and mentions *one* concrete action that is able to help mitigating CC (i.e. a reduction in the use of car, energy saving at home, decrease in consumption of meat and not seasonable food, home insulation, etc.).

G: the student says he/she is taking action/willing to take action on CC, and mentions *two* concrete actions that are able to help mitigating CC (i.e. a reduction in the use of car, energy saving at home, decrease in consumption of meat and not seasonable food, home insulation, etc.).

H: the student says he/she is taking action/willing to take action on CC, and mentions *three or more* concrete actions that are able to help mitigating CC (i.e. a reduction in the use of car, energy saving at home, decrease in consumption of meat and not seasonable food, home insulation, etc.).

[29] O, A, B do not represent levels of behavior, they represent merely different motivations given by students fo not engaging in environmentally responsible behavior, without one reason being better than the other.

Behavioural patterns are the same in Q1 and Q2, and students often migrate from one to another. The only pattern that is not existing in Q2 is pattern “C”.

6.4. Data analysis and results

The analysis is presented by showing at first the results on knowledge (6.4.1), at second the results on behaviour (6.4.2) and then the correlation between knowledge and behaviour (6.4.3).

6.4.1. Knowledge

The following graph shows the knowledge patterns resulted in Q1 (blue column) and in Q2 (red column) – KQ1-KQ2 – in both samples (48 students). Patterns are located on the X axis, and progress from pattern P1 (which represents the lowest level) to P5X (which represents the highest).

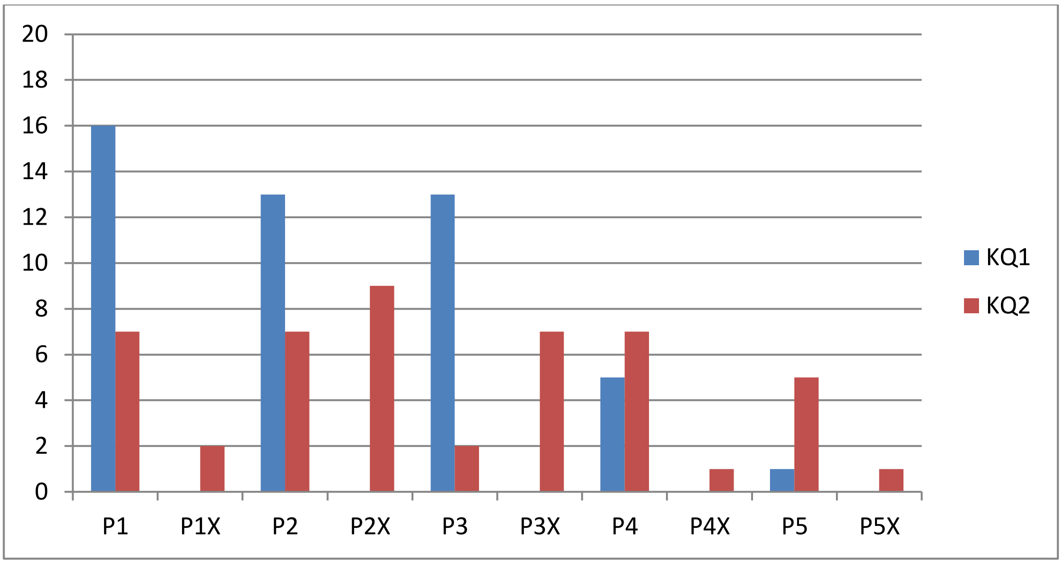


Figure 6.1. Distribution of KQ1-KQ2 (Classroom + PLS)

What emerges from this graph is that the lowest-level patterns (P1 and P2), that where highly populated in Q1, are significantly less populated in Q2. Students that place themselves in P1 and P2 in Q1 are about the 60% of the total sample, and about 33% of them remain in a low level also in Q2 (P1, P1X, P2). This means that lowest-level patterns’ population has almost halved in Q2.
Students with a medium-to-good knowledge level in Q1 (P3 to P5) are about 40%, and those with a medium or high level in Q2 (P2X to P5X) are about the 67%. P2X, which represent a sort of “threshold pattern” is considered a medium level of knowledge.
The two samples had significant differences in knowledge. Students belonging to the non-volunteers group show a generally lower level of knowledge in Q1, and displayed in Q2 a lower improvement, as it is apparent in the following graph, if compared with the graph of figure 6.1:

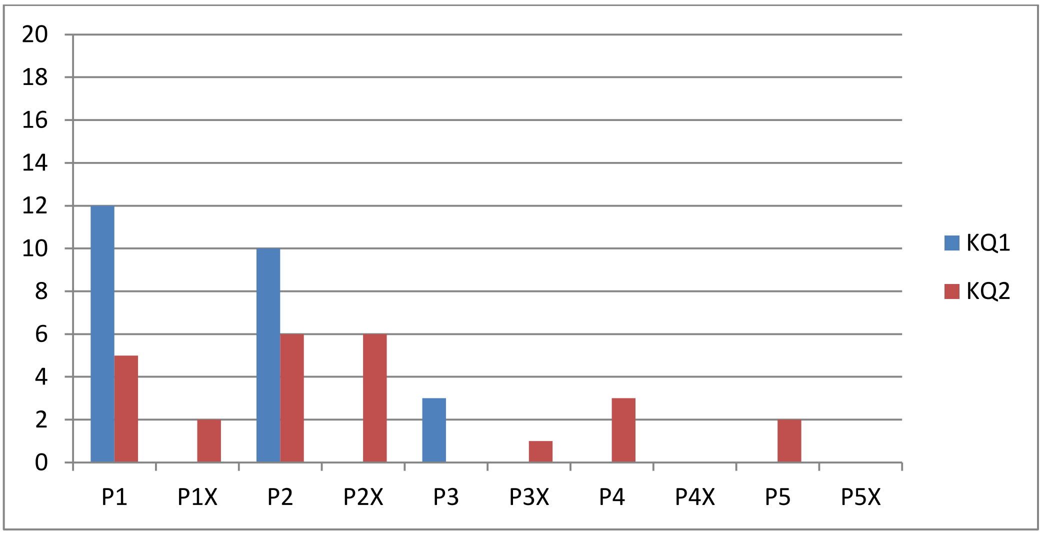


Figure 6.2. Distribution of KQ1-KQ2 (Classroom)

Students from the PLS groups (those who volunteered) start from a more advanced level, due at least to a previous interest in the topic, and generally improve more in Q2 (see figure 6.??). Just 7 students were in either P1 or P2 in Q1, and only 3 are still in those levels in Q2, while most students place themselves in medium or high pattern in Q2 (20 out of 23):

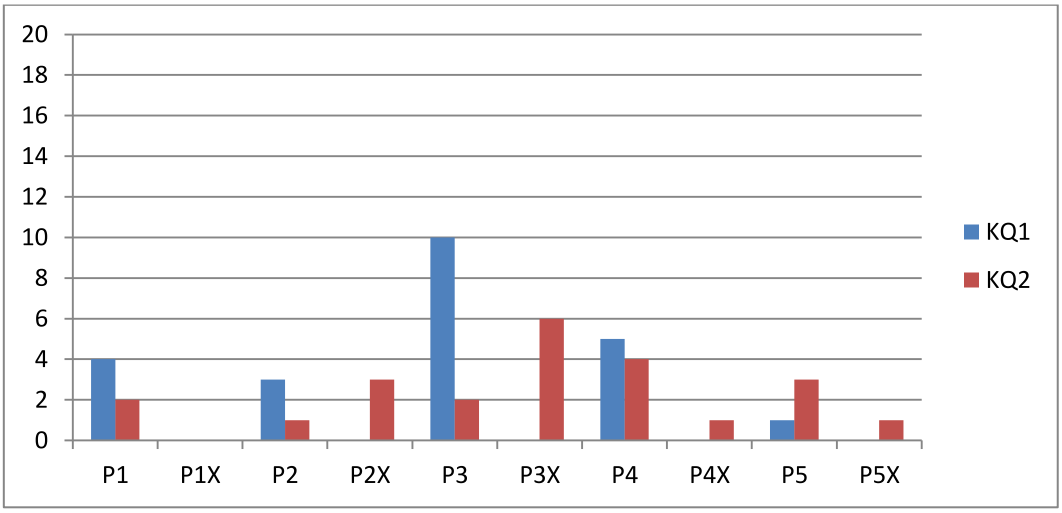


Figure 6.3. Distribution of KQ1-KQ2 (PLS)

The following graph shows the correlation between knowledge patterns in Q1 and Q2 in both samples:

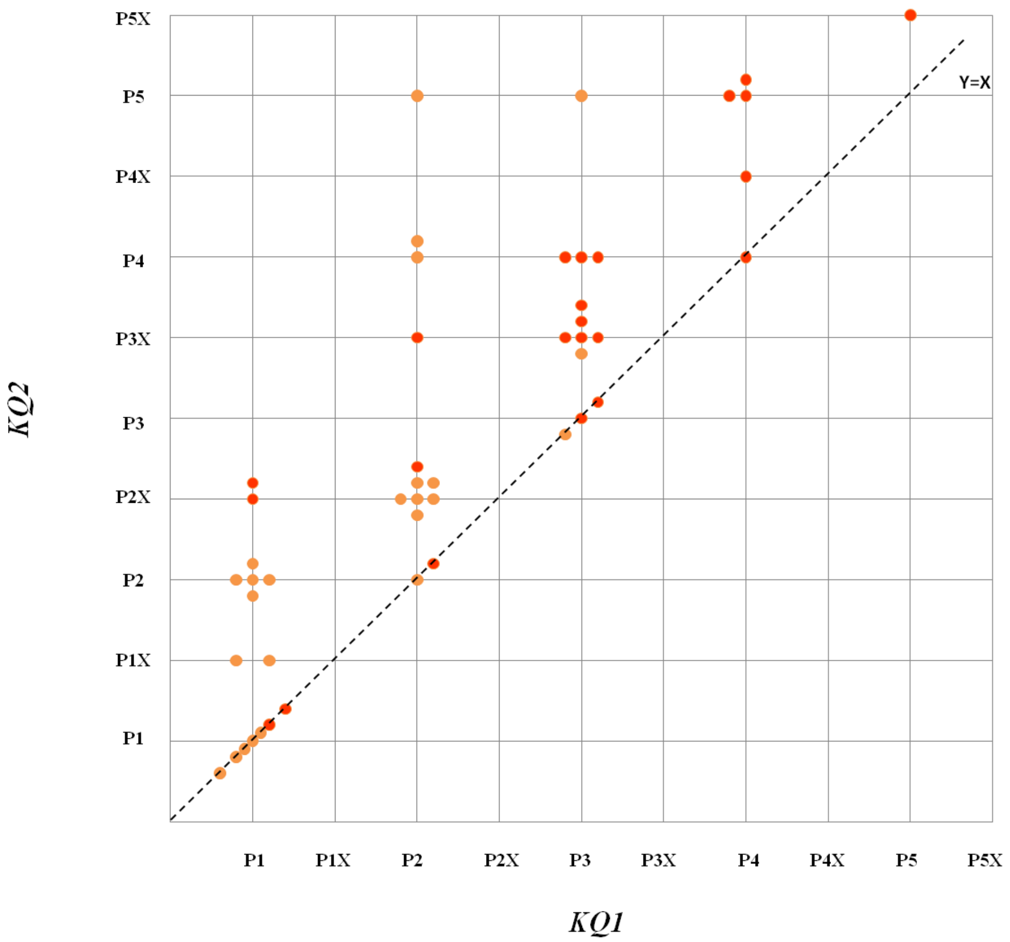


Figure 6.4. Correlation between KQ1 and KQ2

On the X axis are listed knowledge patterns in Q1, and on the Y axis knowledge patterns in Q2. Each point represents one student and his/her answers in Q1 and Q2.

The points that lay on the bisecting line represent students who have not changed knowledge pattern between Q1 and Q2. In the figure the two samples are differentiated; the light orange dots represent the students of the classroom, whilst the dark orange dots represent the students of PLS.

What emerges from the graph above is that there are in general no students who worsen their level of knowledge - it is apparent by the fact that no sample places itself below the bisecting line. However, there are students whose knowledge level remains quite low, i.e. those belonging to P1 in Q1: among the 16 students that belong to P1 in Q1, seven remain in P1 in Q2, two reach P1X and five reach P2 (thus remaining in low levels). Only 2 students starting from P1 reach a medium level - P2X, while no one reaches higher knowledge patterns.

Another point to be observed is that, while there is a general tendency to improve knowledge, such improvement is stronger in those who start from medium or high patterns, and lower for those who start from P1. Only students who are at least in P2 in Q1 are able to reach higher levels in Q2 (up to P5), thus making a more significant progress.

6.4.2. Behaviour

The graph below lists, in the X axis, the behavioural patterns, starting from pattern O (no answer) to pattern H (adoption of three or more environmentally significant behaviour regarding the topics addressed during the course):

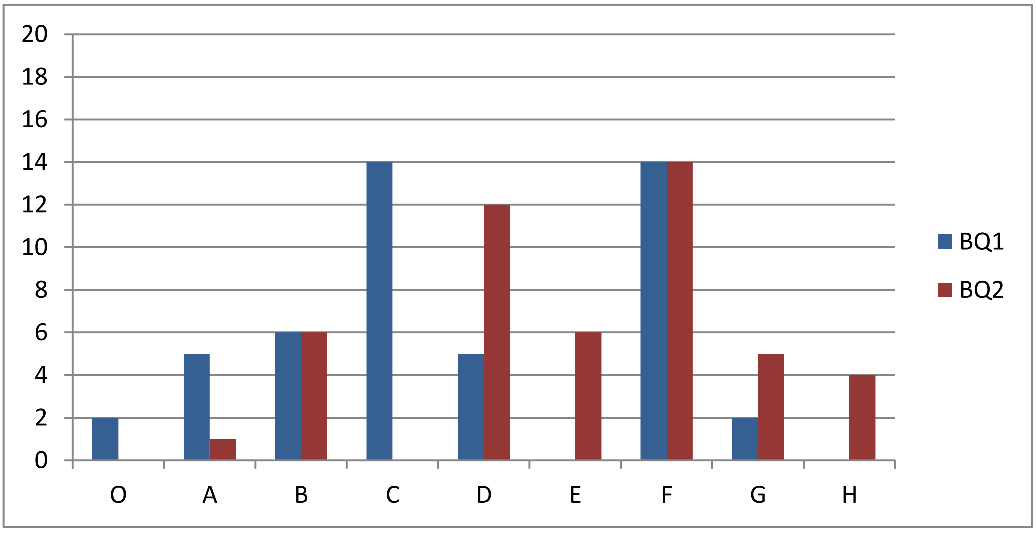


Figure 6.5. Distribution BQ1-BQ2 (Classroom + PLS)

Unlike knowledge patterns, here there is no necessary improvement from one pattern to the other patterns. As already stressed, O, A, B can be considered as being at the same level, representing merely different motivations given by student for *not* engaging in environmentally responsible behaviour. Pattern C indicates those students who respond to be willing to do something, but they do not know what to do. This pattern is populated only in Q1, and not existing in Q2, suggesting that many students felt they lacked information about behaviour that somehow they thought to have received during the course. Pattern D does not refer properly to a good answer, as it indicates a very general willingness to change behaviour not followed by any specific detail on actions to be performed, and is likely to be the response students thought it was “right one” to give. Patterns E, F, G and H are instead progressive, and a shift towards them in Q2 can be seen as an improvement, regardless from the answer given in Q1.

Also regarding behaviour, the difference between the two samples is quite apparent. The following figure shows the responses given by the non-volunteers:

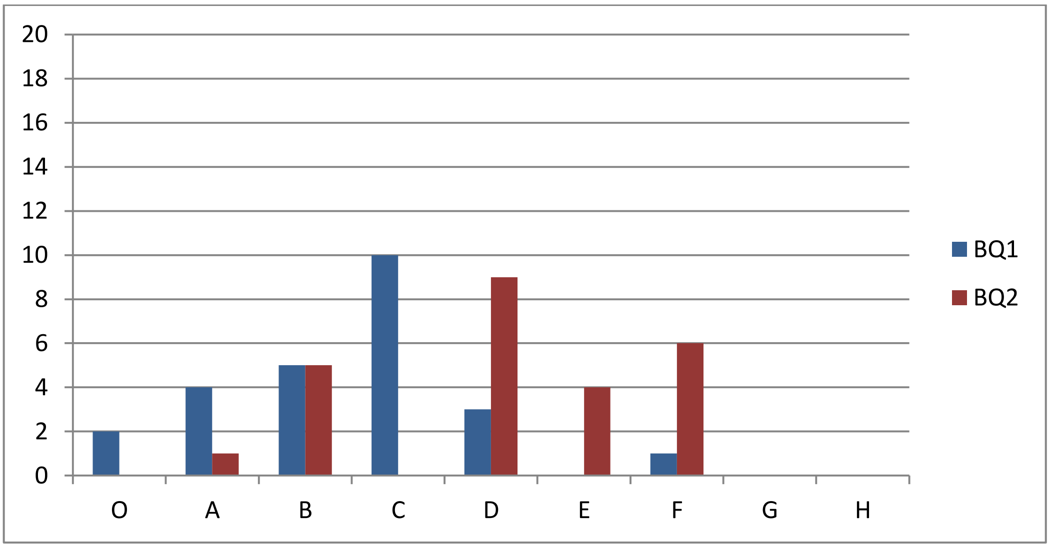


Figure 6.6. Distribution BQ1-BQ2 (Classroom)

Few students in Q1 were tackling action on CC, and only one was able to indicate some practical behaviours he/she was adopting. In Q2 there is a general improvement, as responses O, A and B decrease, while E and F significantly increase, going from 1 response in Q1, to 10 responses in Q2. The increase of D responses cannot be considered instead a real improvement.

The following graph shows responses given by the group of volunteers:

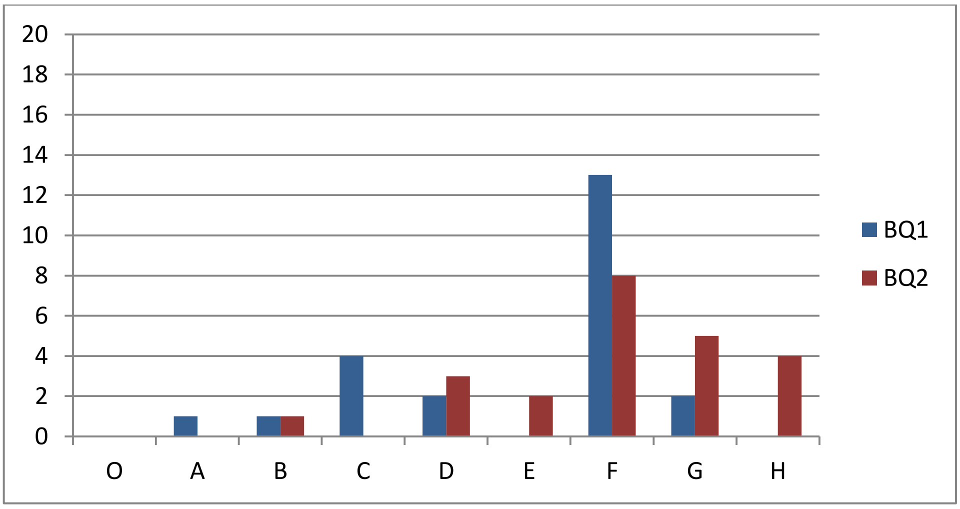


Figure 6.7. Distribution BQ1-BQ2 (PLS)

The different attitude and general involvement with environmental issues of this group of students is quite apparent from this graph. Patterns O to B are poorly represented in Q1 and even less in Q2. Most students show in Q2 not only the willingness to change behaviour, but can also list some relevant actions they will take, and patterns E to H are the most populated in Q2, with 19 answers out of 23. Only one student in Q2 is still unwilling to take action on CC, while 3 indicate a general willingness to do it without further details (pattern D).

The following graph represents the correlation between behavioural patterns in Q1 and those in Q2 of both samples:

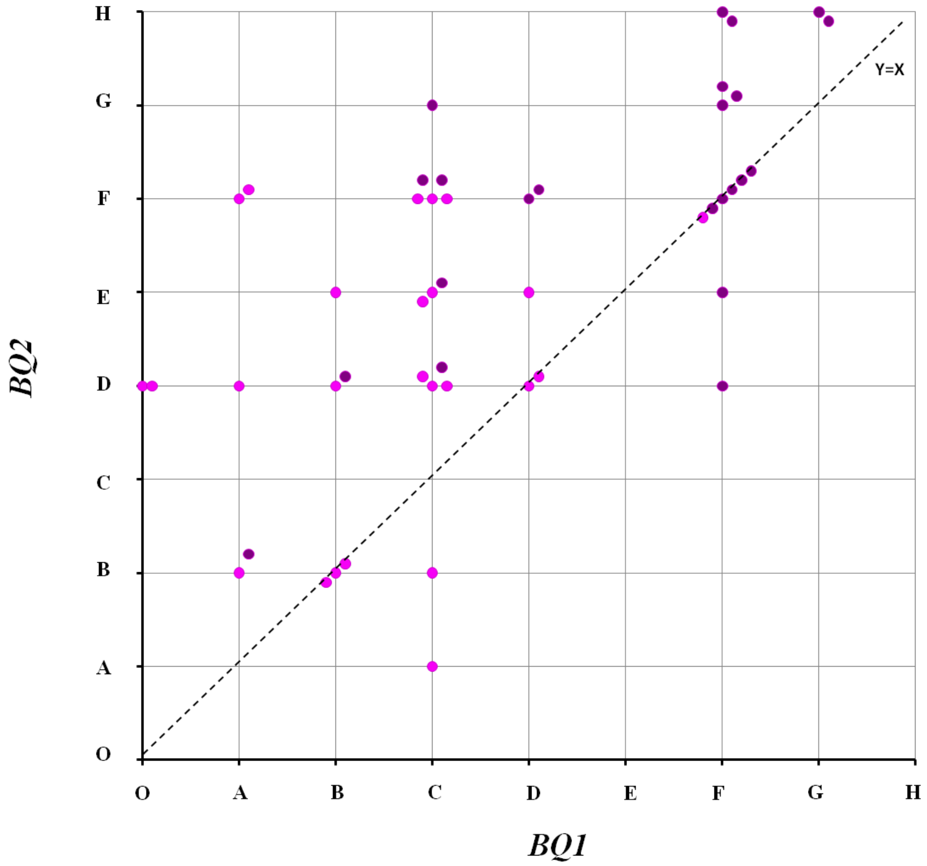


Figure 6.8(a). Correlation between BQ1 and BQ2 (differentiation of the two samples)

On the X axis are listed behavioural patterns in Q1, and on the Y axis behavioural patterns in Q2. Each point represents one student and his/her answers in Q1 and Q2.
In figure 6.8(a) the two samples are differentiated; the light violet dots represent the students of the classroom, whilst the dark violet dots represent the students of PLS.
In figure 6.8(b) the same situation is represented but without the differentiation of the two samples. In such a figure the attention is posed on the whole general picture.

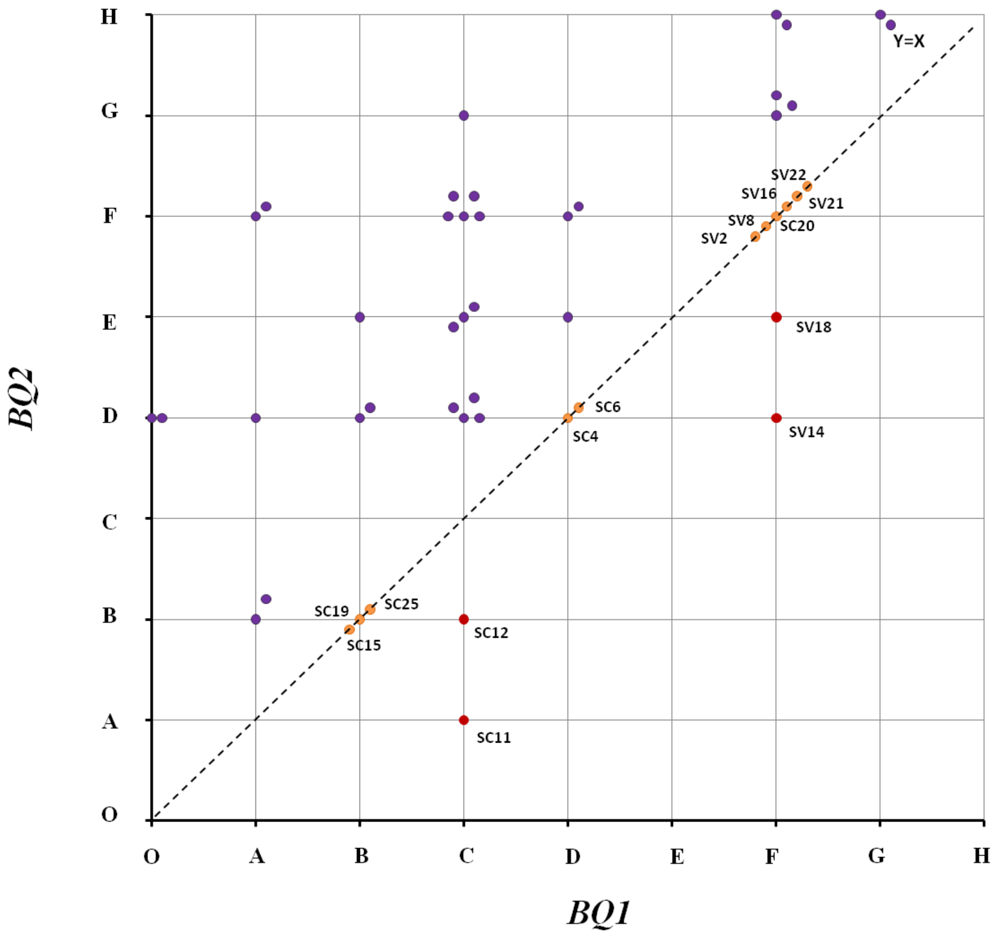


Figure 6.8(b). Correlation between BQ1 and BQ2

The points that lay on the bisecting line represent students who have not changed behavioural pattern between Q1 and Q2. As said before, we cannot consider as an improvement any shift towards patterns A or B (from patterns O or A) in Q2. And hardly is it a real improvement a shift towards pattern D in Q2 (although there might be exceptions).

22 out of 48 students definitely improve their behavioural pattern in Q2 (placing themselves in patterns E, F, G or H in Q2), while 9 migrate to pattern D, which can only partially be seen as good result. 11 students have not changed behavioural pattern, while 4 students have apparently worsened their responses in Q2 (those below the bisecting line). Yet, it might not be appropriate to consider a “worsening” any shift from C, B, A to a lower pattern in Q2, as patterns O, A and B are not progressive. Therefore, as concerns the points that are below the bisecting line, SC11 and SC12 do not really worsen their behaviour – they just provide a different motivation for not taking action in Q1 and Q2. As concerns instead SV14 and SV18, they were both in pattern F in Q1, but shift respectively to patterns D and E, and therefore can be said to have worsened their behavioural pattern.

6.4.3. Correlation between knowledge and behaviour

The graph below shows the correlation between knowledge and behaviour of all samples in both questionnaries: the green dots represent such correlation in Q1, and the red dots represent it in Q2.

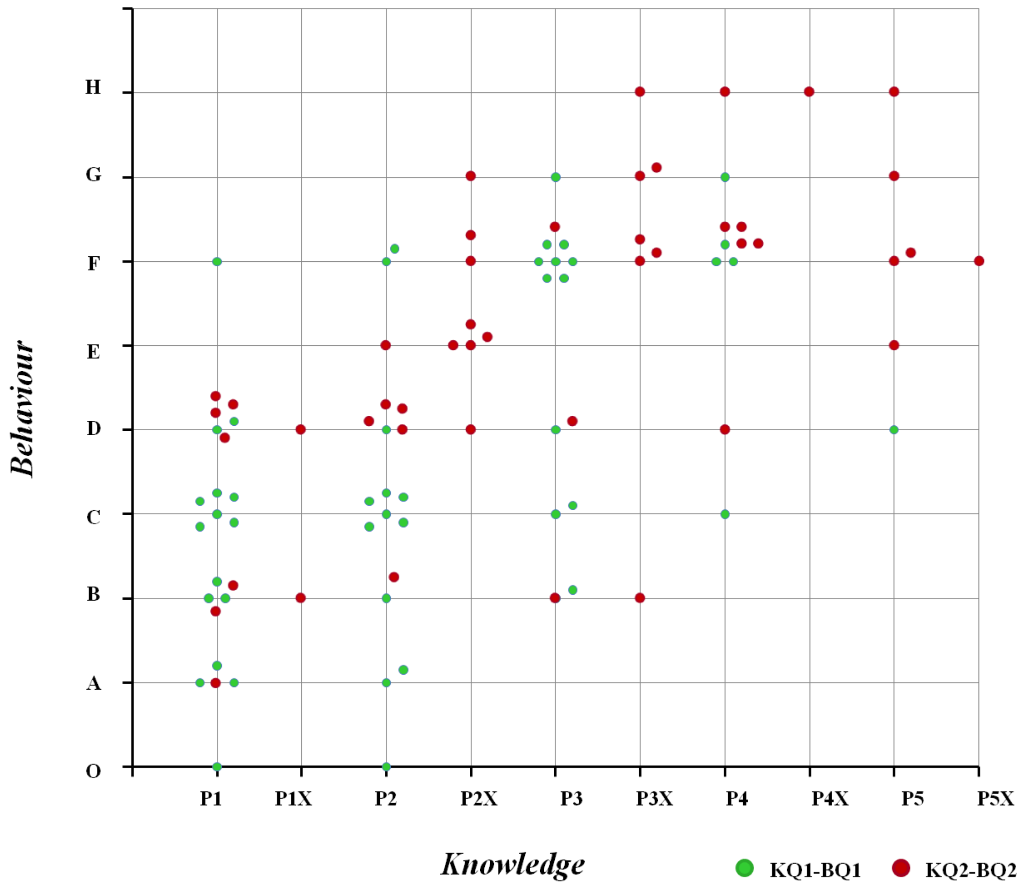


Figure 6.9. Correlation between KQ1-BQ1 and KQ2-BQ2

What emerges from this graph is that the green dots aerea concetrated in the bottom-left area of the graph. With respect to these, the red dots are located in the upper-right area of the graph. Such patterns indicate a general improvement along both the knowledge and the behaviour dimensions.

The graph below considers only the red dots (Q2) and it aims to show the correlation between knowledge and behaviour patterns reache at the end.

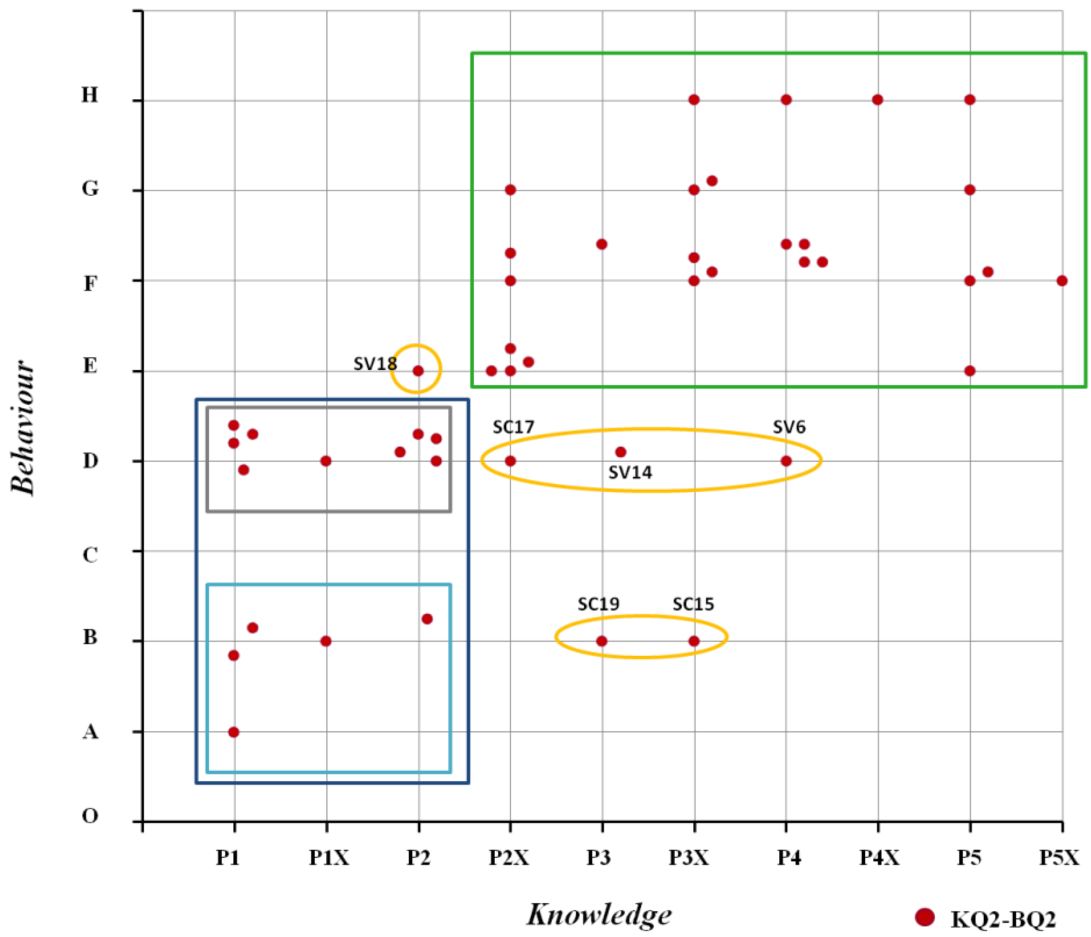


Figure 6.10. Zoom in on knowledge-behaviour correlation in the post-questionnaire (KQ2-BQ2)

The graph shows the existence of a correlation between knowledge and behaviour.

Poor knowledge levels (P1, P1X and P2) correlate with low behavioural patterns. Those who are still in such knowledge-patterns in Q2 can at best reach behavioural pattern D, which is generally not considered a good behavioural pattern, and is in most cases associated with low knowledge levels.

Willingness to take action coordinated with the capacity to indicate one or more coherent actions to be taken on CC (patterns from E to H) in Q1 generally presuppose the knowledge pattern P3, with just two exceptions: SV10, with knowledge pattern P1 in Q1, and SV18, with knowledge pattern P2 in Q2.

In Q2, instead, high behavioural patterns presuppose the minimum degree of knowledge of P2X. P2X is on a one hand a quite low knowledge pattern, as students are not able to write correct answers to open questions, showing still quite confused ideas. Yet, they improve in assessing CC causes as they are listed in question 2. They, in sum, still lack knowledge about how the GHE works, but have changed their mind about what causes CC. And this, somehow, is what allows them to understand how to "interact" with the CC issue, and to choose to take action on it. Those who lack even this minimum knowledge about CC causes (P1, P1X, P2) are not able to indicate any practical behaviour to take, and at best respond with a general answer about changing behaviour (such as “I will pollute less”), falling in pattern D, and otherwise declare not to be willing to change behaviour (pattern A or B).

P2X is, in other words, the lowest knowledge level in Q2 that allows a behavioural change. There is just one exception to this inference, represented again by SV18. This student was also mentioned in the discussion about behaviour, as is one of the two students (2 on 48) that can be said to have worsened his or her behavioural pattern from Q1 to Q2. His/her knowledge level was P2 in Q1, and is still P2 in Q2. There is therefore no improvement on the knowledge side (knowledge was low and remains low).

This leads to the second main observation: willingness to change behaviour regarding CC (displayed by a behavioural pattern E, F, G or H in Q2) is commonly associated with an improvement in knowledge level, at least for what concerns the assessment of importance to CC causes. The only pattern for which this rule does not apply is P1X: this knowledge pattern implies a broad lack of understanding not only of climate dynamics, but also about the distinction between the concept of “cause” and that of “consequence”. Students in this knowledge pattern cannot write logically coherent responses. Starting from such premises, even a moderate improvement in re-assessing the importance of CC causes (listed in question 2 in Q2) is not enough (especially considering that their previous responses in Q1 were completely wrong, and that their improvement even in this limited part of the questionnaire is also small). Where knowledge level is so low (despite being an improvement if related to students’ knowledge in Q1), no behavioural reaction is possible.

26 out of 29 students whose responses in Q2 belong to patterns E to H have in fact improved in knowledge. Among the three who do not, two were already placed in high knowledge patterns in Q1, belonging one to P3 and one to P4 in both Q1 and Q2. And one is SV18: but since his/her knowledge level is low in Q1 and remains low in Q2, it is not surprising that he/she does not improve in behaviour as well – but actually worsens his/her response. What can be generally inferred is that high behavioural patterns presuppose a generally high knowledge pattern, with 19 out of 27 students in behavioural patterns E to H coming from at least P3, and 18 out of 27 from P3X. The opposite, instead, cannot be so easily inferred: among the 31 students with a knowledge level above P2X in Q2, 5 were in either D or B in Q2. While changing behaviour and adopting correct pro-environmental behaviours presupposes a certain level of knowledge, having a certain level of knowledge does not imply that students will adopt pro-environmental behaviours: other motivations may lead them to choose business as usual, and they might not be willing to take actions that they perceive as a lowering of living standards.

CHAPTER 7

Analysis of the epistemological dimension

The aim of this part is to show the results of the data analysis carried out on the epistemological dimension and to see *if* the epistemological knowledge played any role in generating also a conceptual and behavioural response in the students.
In this research, we indeed started from the conjecture that behind many conceptual difficulties and emotional barriers lie particular epistemological obstacles related to a naïve and stereotypical view of science. These include, in particular, the belief that science still has the role and power to provide a unique, unquestionable, and certain explanation of events and processes. Such a naïve idea clashes strongly with the intrinsic complexity of climate science.
This part sets out to investigate *if* and *how* the improvement of epistemological knowledge can influence behavioural habits and foster students' engagement in climate change.
In order to explore such an issue and to answer to our RQ_3 and RQ_4 (*RQ_3: How do secondary school students react to the proposed materials? Are the materials effective in achieving the main goal of the research?RQ_4: Which analytic methods can be used to investigate the multiple dimensions of a teaching/learning classroom experience?*), we carried out two different kind of analysis based on two different corpus of data, both collected from the teaching experience developed in the classroom (Exp. D). The two sections in which the analysis have been shown are titled:

- *(7.1) Exploring Students' Epistemological Knowledge of Models and Modelling in Science*
- *(7.2) How does epistemological knowledge on modelling influence students' engagement in the issue of Climate Change?*

The first section (7.1) concerns the analysis of the data gathered through specific questionnaires on the idea of models and the relationship among model-experiment-reality. Such analysis aims to investigate students' reactions to the epistemological dimension of the materials, and to explore *if* and *how* the material enabled them to develop students' epistemological knowledge about models and modelling.
The second section (7.2) concerns the analysis of the data gathered through five interviews carried out at the end of the experience. Such analysis aims to investigate the role of the epistemological dimension in keeping together the different dimensions of the path, i.e. what kind of role is played by the epistemological dimension in fostering conceptual knowledge and affecting behavioural habits.

As it is already said for the societal dimension, although the work is empirically-oriented, it still aims to achieve goals that reach beyond the specific area, CC, to which the empirical study refers: i) to provide a contribution to the methodological problem of designing analytic tools in order to investigate if and how students' epistemological discourse on models and modelling evolve in real classes and ii) to provide new arguments for enriching the debate in science education about the role of models and modelling in learning and the perspective of complexity.

7.1. Exploring Students' Epistemological Knowledge of Models and Modelling in Science

Consistently with the specific goal of this analysis, the empirical study carried out and presented in this section guesses to answer the following sub-research questions RQa and RQb:

RQa) How did students' epistemological knowledge on modelling evolve during the implementation of a teaching experience on climate change?
RQb) What kind of analytic tools can be designed to investigate whether and how students improve their epistemological knowledge during classroom activities?

In order to answer our two questions, we focused the analysis on students' answers to open-ended questions included in the three questionnaires (Q_1, Q_m, Q_2). The questions considered are reported in Table 7.1. Furthermore, the five individual interviews provided data about how students experienced, in general, the epistemological perspective of complexity. These data are not taken into account in answering the two sub-research questions directly but are considered when discussing the results and their implications for future research.

Table 7.1. Data Sources and questions on the epistemological dimension

Data sources	Questions
Q_1	*What is your idea of model in physics? If you think about physical models, what kind of examples come to mind?*
Q_m	– *Thinking back to the first questionnaire, how would you answer today? What has changed in your idea of a model? How has this idea evolved? Make your ideas explicit. If necessary, you can also give some examples.* – *In the light of your reviewed ideas and reflections, we ask you to formulate and describe the model-experiment-reality relationship.*
Q_2	*During these lessons, some support concepts have been used as guides. In particular, great emphasis has been placed on the model - reality – experiment relationship. Could you describe what you now think about this relationship?*

Students' answers to the questions were analysed through a bottom-up iterative process, aimed at discovering ways to reveal if and how student discourses evolved during the activities.
A global overview of the whole corpus of data showed that two main shifts in students' knowledge occurred: a first shift in their "idea of model" in the step from Q_1 to Q_m and a second shift in the "model-experiment-reality" relationship in the step from Q_m to Q_2. As we will show, the first shift was still rough and macroscopic. It appears to be the start-up of a process that becomes increasingly refined throughout the course and, hence, an ever more subtle feature for observation and interpretation. Given this evidence, the whole picture of the two shifts is relevant in answering RQa, but only the second shift was a real challenge from an analytic point of view, requiring the creation of original analytic tools in order to capture and interpret the findings. These tools represent our answer to RQb.
Two kinds of analysis were carried out in order to understand the findings in the second shift: a textual linguistic analysis and an argumentative analysis.
Textual linguistic analyses in science education are relatively new. They refer to the use of specific linguistic software and algorithms (Bolasco, 2005; Lebart et al., 1998) able to point out emergent threads in students' lexicon.

The argumentative analysis, which is a type of analysis aimed at testing the quality of argumentation, is much more common in the field of science education. Such type of analysis is carried out in contexts where students are encouraged to construct scientific explanations and/or argumentations, which are indeed essential practices of scientific growth (Berland & Reiser, 2008) and a core element of the scientific enterprise (Evagorou & Dillon, 2011). Although constructing scientific explanations is a complex practice, testing the quality of argumentation is believed to be functional for giving important feedback on types of reasoning by students and for viewing the development of their epistemological knowledge (Osborne, Erduran, & Simon, 2004). The method that we will use in our investigation concerns a bottom-up phenomenological search for emergent patterns of argumentation in students' reasoning which can provide insight into their epistemological knowledge.

Operatively, the dual analysis allowed us to identify some *operative markers* which could reveal *if* and *how* students enriched and refined their epistemological knowledge. The markers concern: *i)* the use of vocabulary, i.e. the number, quality and semantic fields of epistemological words used by the students in writing and talking about modelling physical phenomena; *ii)* the patterns of argumentation used by students in talking about the Model-Experiment-Reality relationship. The application of markers to data collected at different points of the classroom activities will allow us to track the evolution of the quality of students' epistemological knowledge.

7.1.1. Data analysis and results

First Shift: Start-up Evolution in Students' Idea of Model

In the pre-questionnaire (Q_1), students appear very confused about the idea of models. In general, only few students (6 out of 26) attempted to answer the question about models and these students borrowed the words from everyday life and common sense. Language and awareness about modelling were not part of their physics background. A synthetic view of the answers is reported in Figure 7.1.

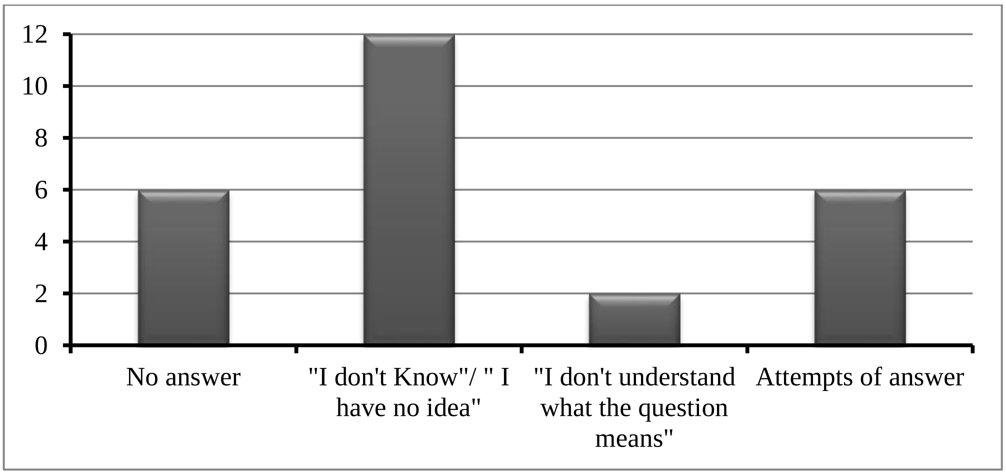


Figure 7.1. Students' ideas of model in Q_1

Meanwhile, 20 out of 26 students[5] skipped the question or expressed their difficulties through sentences like: *"I have no idea what a model is*", or *"I cannot answer this question because I don't understand what it [the question] means"*.
The 6 students who attempted to answer searched for an example from their common knowledge or provided a tentative definition borrowed from everyday life. Examples included: "*A model is, for example, the atomic model"* and *"For me, a model in physics is a scale model representing something, like in the case of DNA".*
Such a result was not surprising since in the Italian physics teaching tradition no special emphasis is given to the models, and a previous pilot-study reported exactly the same reactions. In individual interviews, the students of the pilot-study stated that they had never discussed modelling during their physics curriculum (Tasquier, 2013).
After just three lessons, students' answers to the epistemological questions were very different. Their answers to Q_m were as follows:

- Nobody answered: *"I have no idea".*
- All 25[6] students provided long answers, at least 5-6 lines for each of the three questions;
- Most of them felt the need to stress something like: *"Before I had no idea, now I'm reflecting on it and I've clarified something".*

A more detailed phenomenological analysis highlighted two categories of answers, respectively aimed at describing what a *model is* and what a *model* is *for*.
Within the category *model is*, we identified the following types of answers:

· Model is a *description*. This includes answers where importance is given to the descriptive features and role of a model (an example answer is: *"A model is a description of a real phenomenon from a mathematical point of view"*);
· Model is a *simplification*. This includes answers in which only the simplification and sterilization of a real-world phenomena is stressed (e.g. *"A model is the simplification of a process that we are studying"*);
· Model is a *reproduction*. This includes answers which refer to a procedure of copying "something original" or a real-world phenomenon, including scale reproduction or construction of prototypes (e.g. *"A model is a microscopic [SIC!] reproduction of what happens in the macroscopic [SIC!] world"*);
· Model is an *experiment*. This includes answers in which the basic idea is the complete overlap of meaning between model and experiment (e.g. *"A model is an experiment used to test something"*);
· Model is a *representation*. This includes answers in which models are associated to an abstract idea/concept of reality and/or a symbolic exhibition of reality (e.g. *"A model is a conceptual representation of something able to explain that something"*);
· Model is a *construction*. This includes answers in which the idea of model concerns not only a mere reproduction of something in reality but also a creation/construction of something abstract that is needed to interpret the reality (e.g. *"Model is a construction needed to explain a physical phenomenon"*);
· Model is a *global way of looking at*. This includes answers which express a systemic/global approach and in which models are seen as the lenses needed for looking at the real-world phenomena (e.g. *"A model is a global way of looking at a complex phenomenon which is made up of several elements"*).

Within the category *model for*, we identified the following types of answers:

- Model is *for explaining*, e.g. *“A model is created for explaining a physical phenomenon”*;
- Model is *for understanding*, e.g. *“A model, both physical and mathematical, is a gimmick, more or less complex, for designing and understanding natural phenomena”*;
- Model is *for testing*, e.g. *“Model is a prototype for testing a phenomenon”*;
- Model is *for predicting*, e.g. *“By means of a model you are able to predict something about the real-world”*.

Figures 7.2, 7.3 and 7.4 show the distribution of students’ answers.

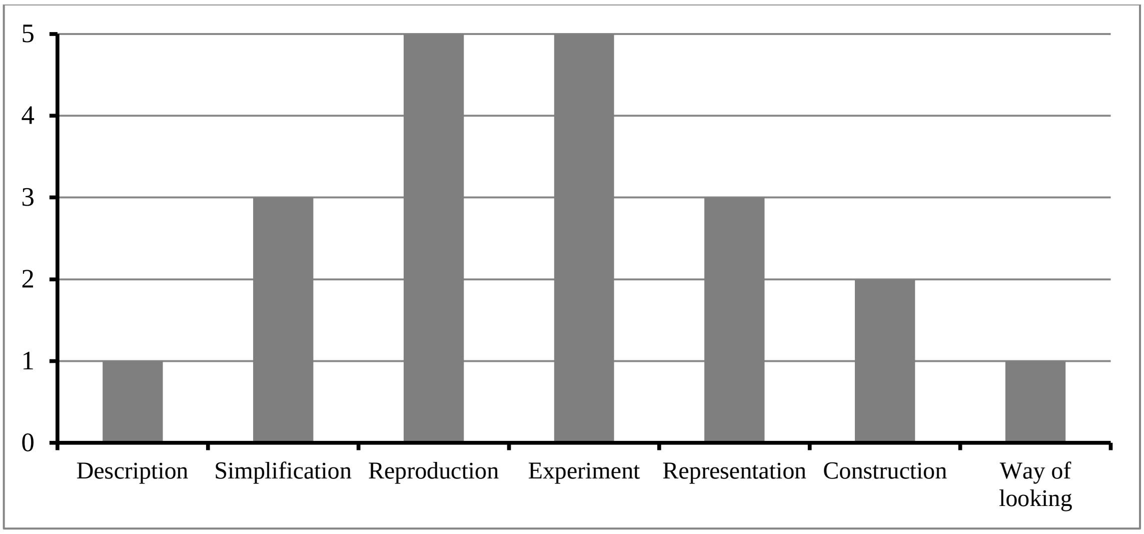


Figure 7.2. Distribution of students’ answers which tackle the definition “Model is”

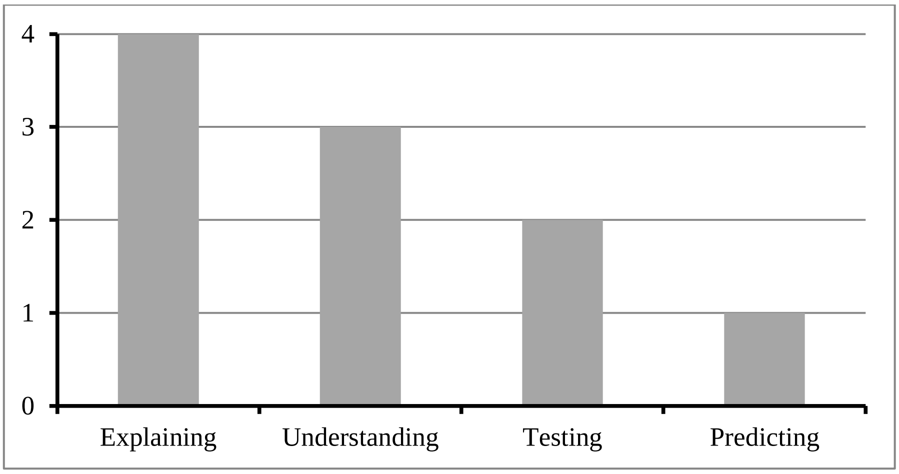


Figure 7.3. Distribution of students’ answers which tackle the definition “Model is for”

		Model is for			
		Explaining	*Understanding*	*Testing*	*Predicting*
Model is	*Description*				
	Simplification				X
	Reproduction		X	X	
	Experiment	X		X	
	Representation				
	Construction	X	X		
	Way of looking				

Figure 7.4. Distribution of answers which address both “Model is” and “Model is for”

The main conclusions that can be drawn from the data in figure 7.2 are that: *i)* mid-way through the teaching/learning path, the students feel free to express their ideas about what *a model is,* and the answers are distributed over a plurality of ideas; *ii)* most of the students focus their argument on model as a *reproduction* of reality and model as an *experiment*.
As we argued in the theoretical framework, such ideas of models are very attractive for the students and difficult to problematize. They can represent a point where epistemological discourse becomes stuck and turns instead into stereotyped hyper-realistic views.
This is what happened in the pilot-study (Tasquier, 2013) where, at the end of the project, students still revealed the tendency to identify models and experiments. In the light of such a result we revised the *fil rouge* to pay more attention to the epistemological language during the lab-lessons and the lesson on complexity. We hence hoped that the greater emphasis placed on these aspects in the first three lessons could reveal its potential in the second part of the project, where students were guided to reflect explicitly on the epistemological paradigm of complexity.
Of the 10 students who provided arguments about the function of models (see figure 7.3), 3 of them focused their answers only on what a *model is for,* without any attempt to provide a definition. The other 7 students (see figure 7.4) used the argument *model is for* to complete and refine their answers. In these cases we see a slight indication that, unlike the case of the pilot-study, the students here were to some extent becoming better prepared to give increasingly refined epistemological views.

Second Shift: Evolution in Students’ Epistemological Reasoning

As we had anticipated, during the second part of the lab-course something more relevant happened. A second, deeper and more refined, shift emerged when comparing students’ answers to the same question posed in Q_m and Q_2 about the Model-Experiment-Reality relationship. In order to analyse such a shift, both a linguistic and an argumentative analysis were carried out.

Linguistic analysis
The first evidence gathered from the students’ answers emerged from the different vocabulary used in Q_m and Q_2. In order to capture such a difference and produce a way to measure the difference, we carried out a guided textual analysis through the use of a specific linguistic software (Lebart et al.,

1998). The aims of the analysis were to understand if there really was a change in the quality of students' vocabulary throughout the project (from Q_m to Q_2) and, in particular, if this change represented an enrichment in students' epistemological discourse. Operationally, the analysis was articulated in various phases. First, the software was applied to students' answers in order to produce an alphabetic list of all the words (substantives, verbs, adjectives, adverbs, articles, connectors, pronouns, etc.) used by the students and to count the frequency of each word. Then, we deleted function words, i.e. those without inherent meaning but functional to the construction of the sentences, like connectors, pronouns, adverbs (e.g. *the, if, that, perhaps, something*). After that, we made a further selection in which we deleted the words whose meaning emerge only at a syntactical level and not at a mere lexical level (e.g. *to be, to have, can, thanks to, said, analysed, possible, aspects, factors*, etc.).

This operative process gave us a list of words that are meaningful from a lexical point of view, as used by students in their answers, and as a result of their relative frequency. The next phase involved grouping the words according to similarity of meaning and identifying semantic fields[7]. The semantic fields indentified are:

A. *experimental* field – including words which refer to typical laboratorial and experimental language like *observations, proofs, results*.
B. *utilitarian* field – including words which express an intrinsic finality, in the sense of a utilitarian purpose, like *to serve, to use, useful*.
C. *reproduction* field – including words which refer to procedures of copying/duplicating an original thing, including scale reproduction (smaller or bigger than the original). This field includes words like *reproduction, scale, reduction*.
D. *truth* field – including words which refer to the quality of being in strict accordance with facts or reality such as *truth, real, verified*.
E. *similarity* field – including words which express the distance from reality, referring to something that has the appearance of being real or true and/or shows likeness to real-world phenomena; examples are *close to, verisimilar, to mirror*.
F. *simplifying* field – including words which refer to a simplification or complication of the reality, like *simplify, complex, easy*.
G. *modelling* field – including words which mainly refer to the meaning, sense and role of modelling in understanding physical phenomena, which highlight the presence of ideas, conjectures, hypotheses in the act of investigating physical phenomena and which are particularly suitable for expressing the idea of modelling as a creative act; examples include *to create, to explain, to interpreter, to hypothesize*.
H. *mathematical* field – including words which refer to the typical language used in maths, like *to demonstrate, calculus, to infer*.
I. *representation* field – from the Latin "repraesentare", which means to make it present, to set in view, show, exhibit, display; this field includes words which portray reality by means of signs or symbols that can be either concrete entities or abstract; it includes words like *represent, representation*.

A tenth category J "*context-dependent epistemological words"* has been added to the previous semantic fields so as to include words that might carry potentially relevant epistemological meaning, but whose specific meaning is too context-dependent to be recognised at a mere lexical level. This category includes words like *process, mechanism, consequences*.

The process of selecting and aggregating the words of both questionnaires into semantic fields was carried out by a team of three researchers who triangulated their analyses (GT, OL and MG[8]). The first two selection phases raised no problems since the criteria for deleting the meaningless words were very simple to share and apply. Some controversial issues arose, instead, during the processes of grouping the words and identifying the semantic fields. The more controversial issues regarded words that we grouped within the "grey category", i.e. words like *search, phenomenon, process, mechanism,* and *consequences,* which students could use either within an everyday language domain or within an epistemological discourse. These words were analysed one by one in order to reconstruct their linguistic domain, deleting only those which had no epistemological sense. The graphs below show the results.

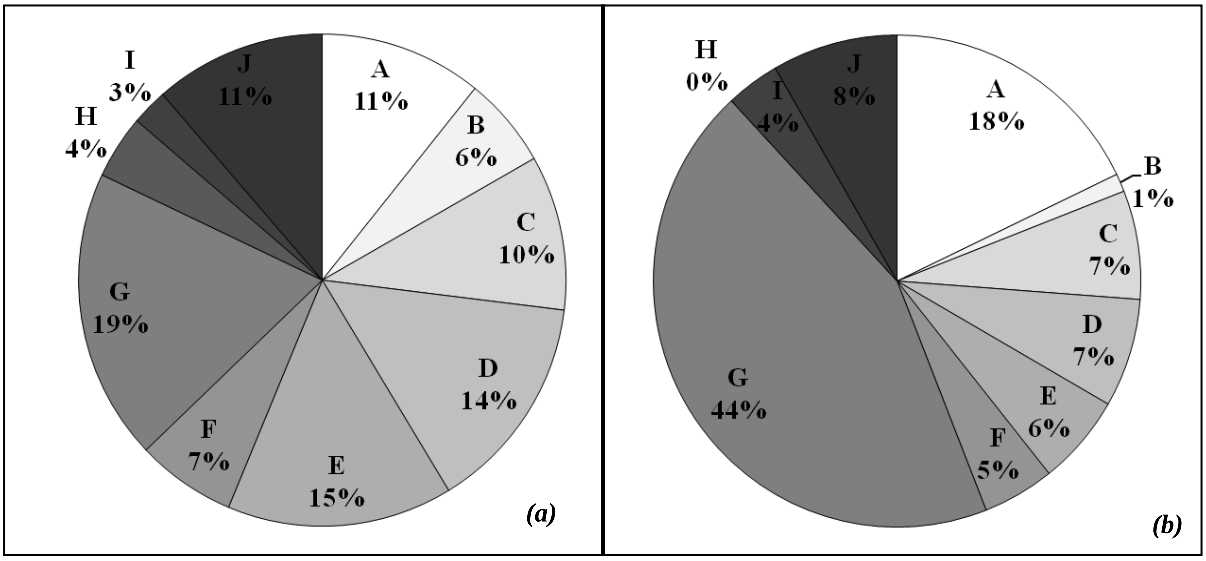
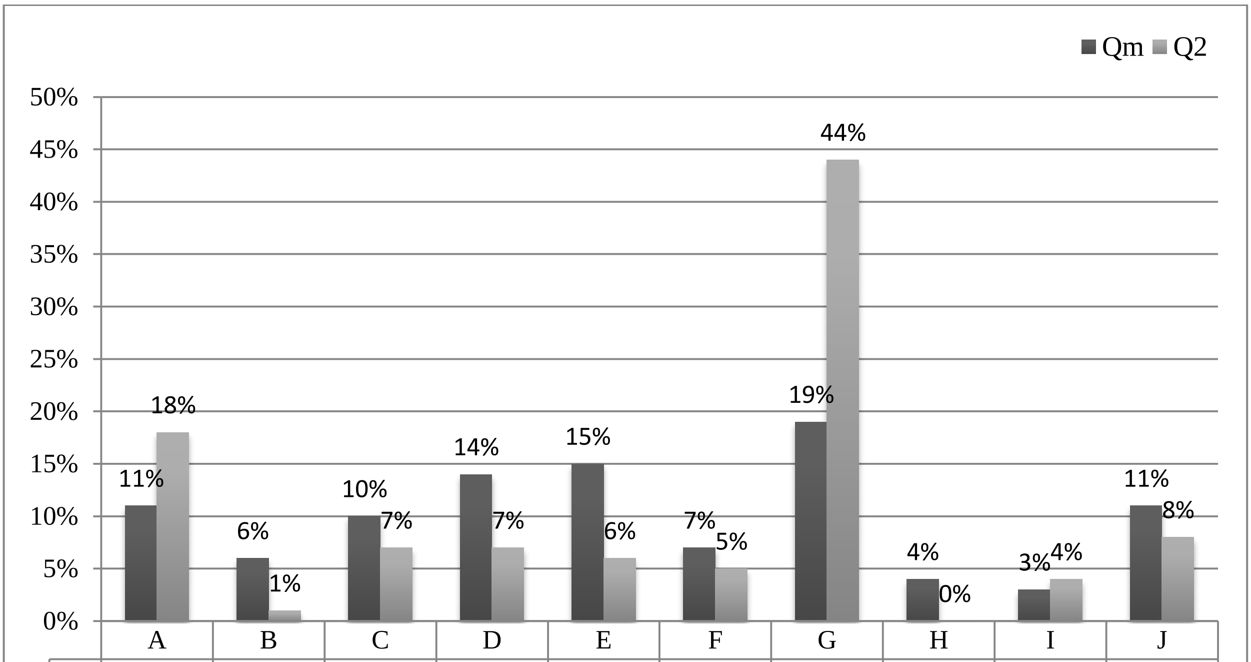


Figure 7.5. (a) Distribution of semantic fields in Qm; (b) Distribution of semantic fields in Q2

Figure 7.6 compares the distribution percentages of each field between the two questionnaires.



	A	B	C	D	E	F	G	H	I	J
Qm	11%	6%	10%	14%	15%	7%	19%	4%	3%	11%
Q2	18%	1%	7%	7%	6%	5%	44%	0%	4%	8%

Figure 7.6. Comparison of semantic fields Qm-Q_2

The graphs highlight several changes in the distribution. There is an increase in the *experimental* field but a decrease in the *utilitarian* field - this change indicates that the *experimental* semantic field remains a comfortable register for students but the almost total disappearance of a utilitarian purpose reveals a change in the way they use this language. The almost total disappearance of utilitarian nuances in the language (alongside the increase of the modelling field) demonstrates that the practical and instrumental use of experimental words has given way to a more focused use on the identity and autonomy of the experiment.

The three fields D, E and F registered a significant decrease, from 36% to 18%. This result can be interpreted as a signal that the students' language became less oriented to searching for truth or even closeness to reality. In that sense, we see a refinement in students' language that seemed to move progressively away from the naïf hyper-realism reported in the literature. This result is also supported by the decrease of the *reproduction* field (field C) and by the clear increase of the *modelling* field from 19% (Q_m) to 44% (Q_2).

Also, the decrease of the *context dependent* field can be read as a sign of improvement: students seem to be able to use a more precise epistemological language. As apparently minor results, the *mathematical* field H disappeared in Q_2 and there was a relatively insignificant change in the use of *representation* words. This initial evidence seems to reflect the fact that, even though mathematical models were widely used and discussed in lessons 2-3-4, the language used by the teachers was in general more physics- than mathematics-related. Verbs like "to show", "to obtain", " to measure", and " to test" were preferred by the teachers to verbs like "to demonstrate", " to deduce", "to calculate" and so on. In contrast, the low recurrence of the word "representation" in student usage appears puzzling, since "to represent" was probably one of the words most frequently used by the teachers. This data will be reconsidered in the next analysis since it may constitute a subtle signal that students did not yet feel confident enough with epistemology to use such a demanding word.

Argumentative analysis

As stated earlier, the same data were also analysed from an argumentative point of view which, as we will see, provided new insights for interpreting the trends observed in the linguistic analysis. In order to carry out this analysis, a selection of students' answers was used to construct a coding scheme for patterns of argumentation that we iteratively refined by testing the codes against all the students' answers. This process resulted in the identification of four argumentative patterns which express different ways of situating models, experiments and reality in their mutual relationship. The patterns are reported in Figure 7.7.

"Pattern 0" represents the identity between Model, Experiment and Reality. Students' answers are ascribed a relationship of identification if they use expressions like "the experiment *is/mirrors/reproduces* a model".

"Pattern 1" is characterized by the identity between experiment and reality. In this relation a model is viewed as being at another level. A typical answer for this pattern is: "A model is an idea to be tested against experiments/reality". The three different arrows represent three directions of this relationship inside this pattern ("first comes the model, and then its testing"; "model is derived from reality/experiments"; there is no privileged direction). The dashed arrow represents a particular case, here referred to as the "sceptical". This group includes students who believe that models can never explain or interpret reality as it is. Their answers refer to a hyper-simplified, artificial world.

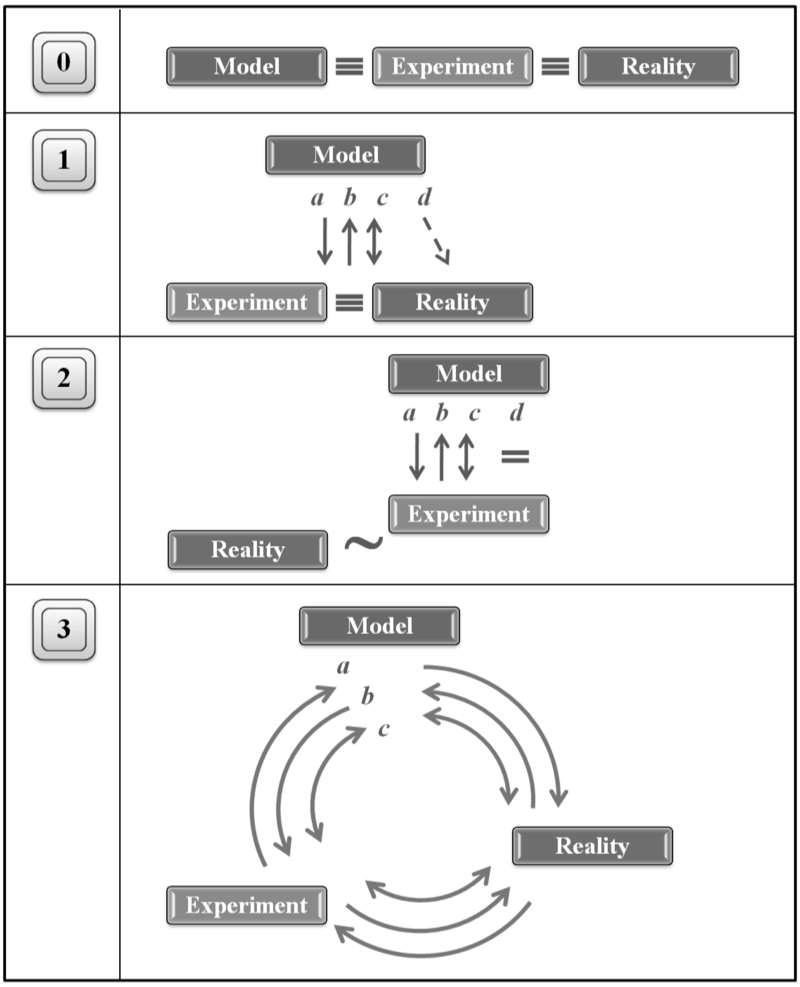


Figure 7.7. Patterns of reasoning in students' argumentation about the Model-Experiment-Reality relationship

"Pattern 2" is characterized by a relation of verisimilitude between experiment and reality ("experiments consider only some aspects of reality"). Again, the model is posed at another level. The three different arrows represent the previous three directions of this relationship inside this pattern. Moreover, inside this pattern there is a particular relation where students identify model and experiment.
"Pattern 3" is characterized by an iterative relationship among model, experiment and reality. Each term of the relationship is posed on a different level and there is a dynamic (and circular) mechanism among the three. The three different arrows represent three directions of this relationship inside this pattern, specifically, the "a" arrows represents a top-down dynamic (the circular process is initiated by an idea, a model), the "b" represents a bottom-up dynamic (the circular process is initiated by experiments) and the "c" represent a mixed dynamic (sometimes confused). An example of Pattern 3 answers is: *"We create a model by looking at the real situation; then according to the obtained results, we conduct experiments"*.
Figure 7.8 shows the changes in students' answers.

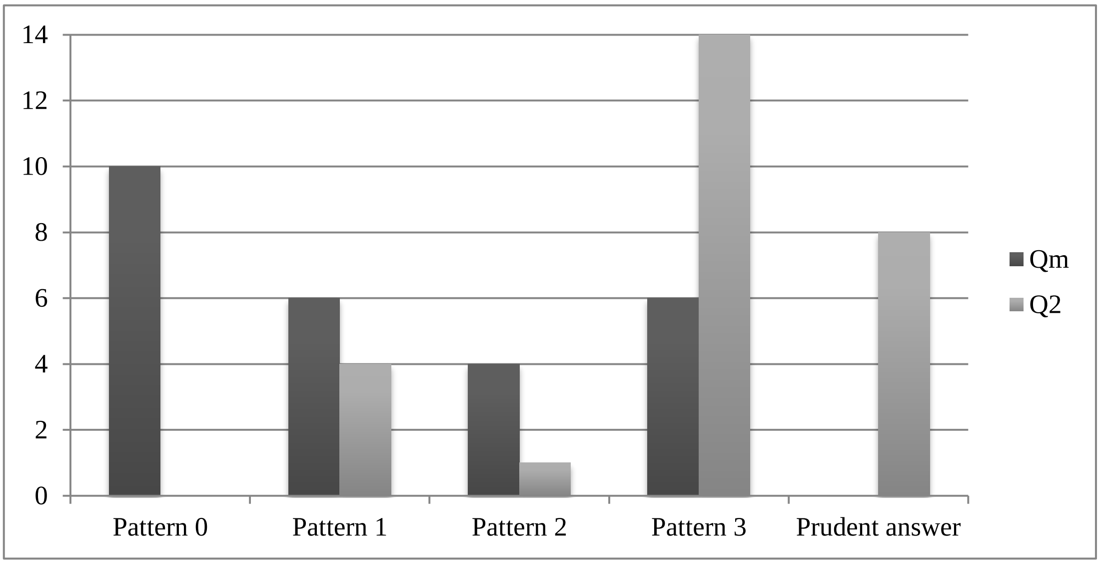


Figure 7.8. Students' patterns of argumentation from Q_m to Q_2

From the graph, the evolution of students' argumentation is very evident. The first finding is that "Pattern 0" completely disappeared in Q_2; the second finding is that "Pattern 3" increased in a logical way. It is also significant that in Q_2 a considerable number of students provided a "prudent answer", e.g..: "the relationship is complicated and I still need to think about it". We considered such answers to be evidence that several students are still within a process of epistemological maturation. In this sense, these answers can be related to the other result obtained in the textual analysis (see figure 6), i.e. the low recurrence of demanding epistemological words like *representation*.

7.1.2 Discussion of the Results

The analysis showed that the special emphasis placed in the teaching materials on the epistemological *fil rouge* of "models and the game of modelling" led the students to acquire and refine their epistemological language.

In answering RQa, we can argue that the overall process of analysis highlighted a two-stage process in the development of students' knowledge: i) a start-up stage that resulted in an *enrichment* of students' ideas about "what a model is" and "what a model is for", and ii) a *refinement* stage that resulted in a substantial improvement both in students' vocabulary and in their argumentation.

In order to complete our answer to RQa and to answer RQb, further details on how we chose to investigate the second shift are helpful. The analytic tools we developed enabled us to identify and measure the epistemological refinement that we perceived in students' discourse, as well as to recognize a residual form of lack of confidence in talking about modelling.

By means of the textual analysis, we were able to track a substantial improvement in the quality and relevancy of epistemological vocabulary used by the students. The low recurrence of the word *representation* was recognized as evidence of residual lack of confidence.

By means of the argumentative analysis, we were able to track that students overcame their static idea of the relationship between model-experiment-reality and progressed to recognizing the role of modelling as a bridge between knowledge, real-world and experiment. The presence of what we classified as prudent answers shows that the development of epistemological knowledge is a complicated process, especially if a student arrives, as in our case, from a very different tradition of reasoning.

Since the two analytic tools are independent and focused on complementary levels, lexical and argumentative, the comparability and consistency of what they point out provide our results with reliability and confirmability (Denzin & Lincoln, 2000).

In answering RQb, we add two further methodological comments. Firstly, both the tools have been developed in order to relate the results as closely as possible to actual data so as to give the reader not only a picture of what happened in class, but also an idea of the authentic "students' voices". Secondly, the tools function to maximum potential when the aim is to measure a slight change, a refinement, between two close and comparable states of students' knowledge. The same tools would be ineffective if applied to an analysis of the first switch-on shift.

7.1.3 Conclusion and Final Remarks

This study originated from the conjecture that CC represents not only a societal and disciplinary but also an epistemological challenge. Scientific debates imply sophisticated epistemological argumentations which refer, more or less implicitly, to a refined way of looking at modelling in climate science.

In this sense, the study was intended to provide a contribution to a science education research issue that has so far been poorly explored: students' reactions to the epistemological issues raised by the study of CC. By comparing the results we achieved and the content of the teaching path, we can see that the two stages of student development – enrichment and refinement –correspond respectively to the completion of the lab-activities (lessons 1-3) and to the two lessons on the epistemological perspective of complexity and the political and economic scenarios of global changes (lessons 4-5). Such a correspondence leads us to infer that the delicate process of isolating a phenomenon to be investigated in the laboratory, as well as the multiple perspectives (thermal, electromagnetic, optical) from which the GHE has been investigated, played a fundamental role in expanding students' imagination about the meaning and the role of models in science.

On the other hand, we can infer that the epistemological reflection on complexity and the application of physical models to social phenomena played a crucial role in helping students to problematize the relation between reality, knowledge and experiments by overcoming the known tendency of mixing and overlapping these issues.

One open issue that arises from the study concerns the residual lack of confidence that we observed in some students. *What is its nature? Can the teaching material be improved and such distrust investigated in more detail?*

Another open issue, more relevant for research purposes and addressed in the next section, concerns the impact of the observed epistemological improvement on other dimensions of learning.

7.2. How does epistemological knowledge on modelling influence students' engagement in the issue of Climate Change?

The empirical study carried out and presented in this section aims to answer the following sub-research question (RQc):

RQc) Did the improvement of epistemological knowledge influence students' behavioural and social attitudes and their personal involvement in climate change issue? If so, how?

In order to answer such a question, we focused on the five interviews collected at the end of the teaching experience. The five students were chosen in order to respect the variety of the class. Student 6 (S6) was the "*shy*" member of the class but he actively took part in the lab activities; student 13 (S13) was the *"excellent"* student of the class, much appreciated by the teacher; student 16 (S16) was a *"sceptic"* and not interested in the CC issue; student 25 (S25) was the *"outsider"* of the class and not particularly interested in the CC issue; finally, student 26 (S26) was the *"silent"* member of the class, but very heedful throughout the whole process. Table 7.2 provides a summary of the sample, aims of the interview and the protocol outline.

Table 7.2. Summary of interview features

Number of students	Five (4M, 1 F)[30]
Features of the sample	Heterogeneous group (the shy, excellent, sceptical, outsider and silent class members)
When?	One week after the end of the teaching experiment
Aims	– To check conceptual understanding – To investigate students' idea of modelling in physics – To gain feedback on how students experienced the lesson on complexity
Protocol outline	– ***First part:*** students' ideas about modelling in Physics – ***Second part:*** students' ideas about the specific models addressed in the Climate Change path – ***Third part:*** students' ideas about complex models

The graph of figure 7.9 sums up the changes of the five students along the epistemological and the behavioural dimensions as achieved in the analysis presented in chapter 6 and in the previous section (7.1).

[30] In order to guarantee anonymity, we will refer to all the students by using *he* or *him*, neutrally and regardless of actual gender.

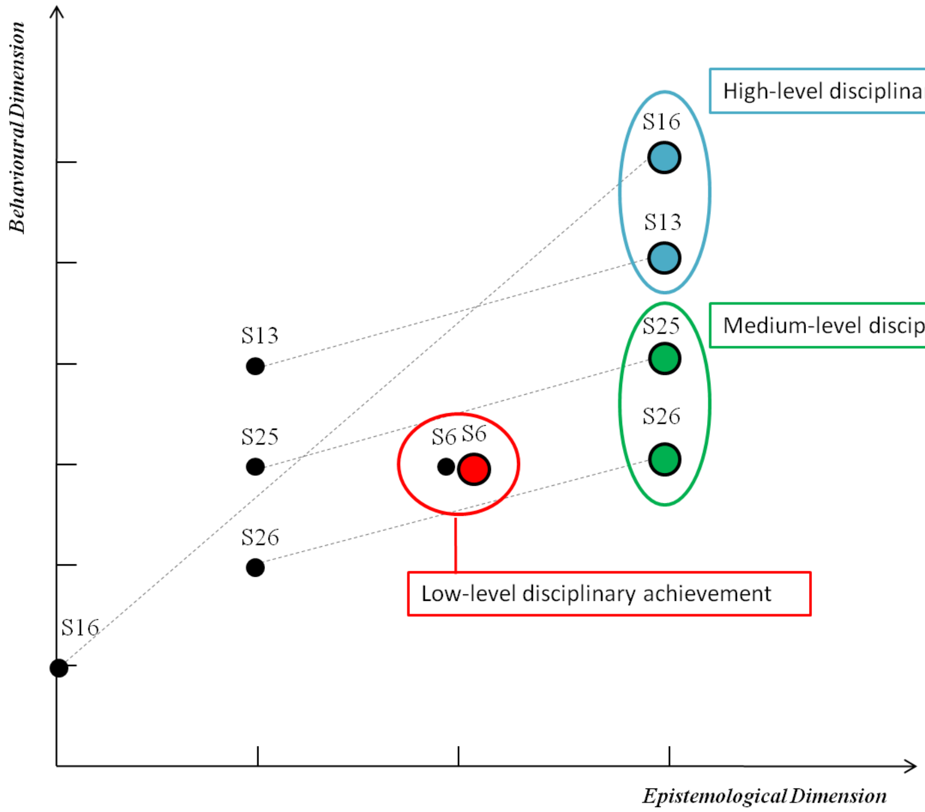


Figure 7.9. Students' changes along the dimensions

In the graph, the epistemological scale is on the x-axis. On this scale, the lowest level is represented by a total lack of an epistemological language that leads students, for example, to identify a model with an experiment. The highest level is represented by a mastery of epistemological arguments, which leads students to describe the relationship between models, experiment and reality as an iterative back and forth relationship. The behavioural scale on the y-axis represents different patterns of behaviour. On this scale, the lowest level is represented by a lack of willingness to take action on CC or change one's own lifestyle and habits in order to prevent CC. The highest level is represented by the willingness to take action or to change habits, together with a detailed explanation consistent with the content of the course. The black dots represent the position of the students at the beginning of the course and the coloured dots represent the position of the students at the end of the whole course; the different colours of the dots, in the final state, show the different level of disciplinary achievements. The graph shows that only S6 (*the shy*) did not change significantly in the epistemological and behavioural dimensions. Furthermore, he encountered strong difficulties with the disciplinary dimension. Indeed, he was able to provide short answers to very specific questions with the help of the teacher, but he had difficulties in autonomously managing the basic physics concepts treated during the course. For instance, even at the end of the course, he was confused about the difference between emission and reflectance, and made mistakes when tackling the physical properties discussed in the course for interpreting the greenhouse effect. The other four students made visible changes along both dimensions of the graph and also achieved good results in the disciplinary dimension. In particular:

- S13 (*the excellent*) reached an excellent level of knowledge in the written task He was the best in the class, even though he still had problems transferring what he learned in contexts differing from what was usually required by his teacher. He improved his epistemological knowledge on the Model-Experiment-Reality relationship. Regarding the behavioural dimension, the small improvement can also be attributed to the fact that he was already interested in the topic of CC.
- S16 (*the sceptic*) achieved a high-level of disciplinary knowledge. Even though he did not achieve the best mark in the written task, like S13 he demonstrated a real ability to use the concepts of physics learned during the course for interpreting the greenhouse effect and its relationship with global warming. S16 was the student who demonstrated the biggest improvement in the epistemological and behavioural dimensions, despite the fact that the topics of CC and, more in general, physics were initially very far removed from his personal interests.
- S25 (*the outsider*) reached a medium-level of physics knowledge. He understood the most important concepts in physics but he had some difficulties in managing the concept of emissivity. He showed a big improvement in the epistemological dimension and finally came to grasp the sense of the discourse about models and modelling. He had a medium-high improvement in the behavioural dimension, despite the fact that at the beginning the topic of CC was very far removed from his field of interests.
- S26 (*the silent student*) reached a medium-level of physics knowledge. He understood the most important concepts in physics but he needed to talk about physics properties, like transparency, by relating them to the specific experiments carried out during the course. He showed significant improvement in the epistemological dimension and, regarding the behavioural dimension, he progressively changed his reasons why, in his opinion, few things could be done to prevent CC. In this sense, he showed a significant improvement also along the societal/behavioural dimension.

In the light of such a map, the RQs become: *Is it possible to find correlations among the reactions of these students along the three dimensions? What general inference can be drawn from these cases?* The analysis of the interviews has been carried out to answer these questions.

7.2.1. Data analysis and results

Operationally, we decided to to answer the RQs by analyzing students' interviews so as to design "profiles" of the students (Levrini et al., 2014a). During the interviews, we observed significant differences among them. Some students were particularly involved and used articulated arguments, whilst other students had to be systematically encouraged by the interviewer. These different types of interaction revealed, in our opinion, two different kinds of reaction: some students felt embarrassed whilst others felt at ease and developed their arguments without any "pressure" from the interviewer. Such an impression has been captured in the following temporal maps (Levin et al., 2013) that show the different pace and type of interaction between each student and the interviewer (Fantini et al., 2014). The participants and the silence are represented along the y-axis and each participant's talking time is represented along the x-axis (the time unit is two seconds).

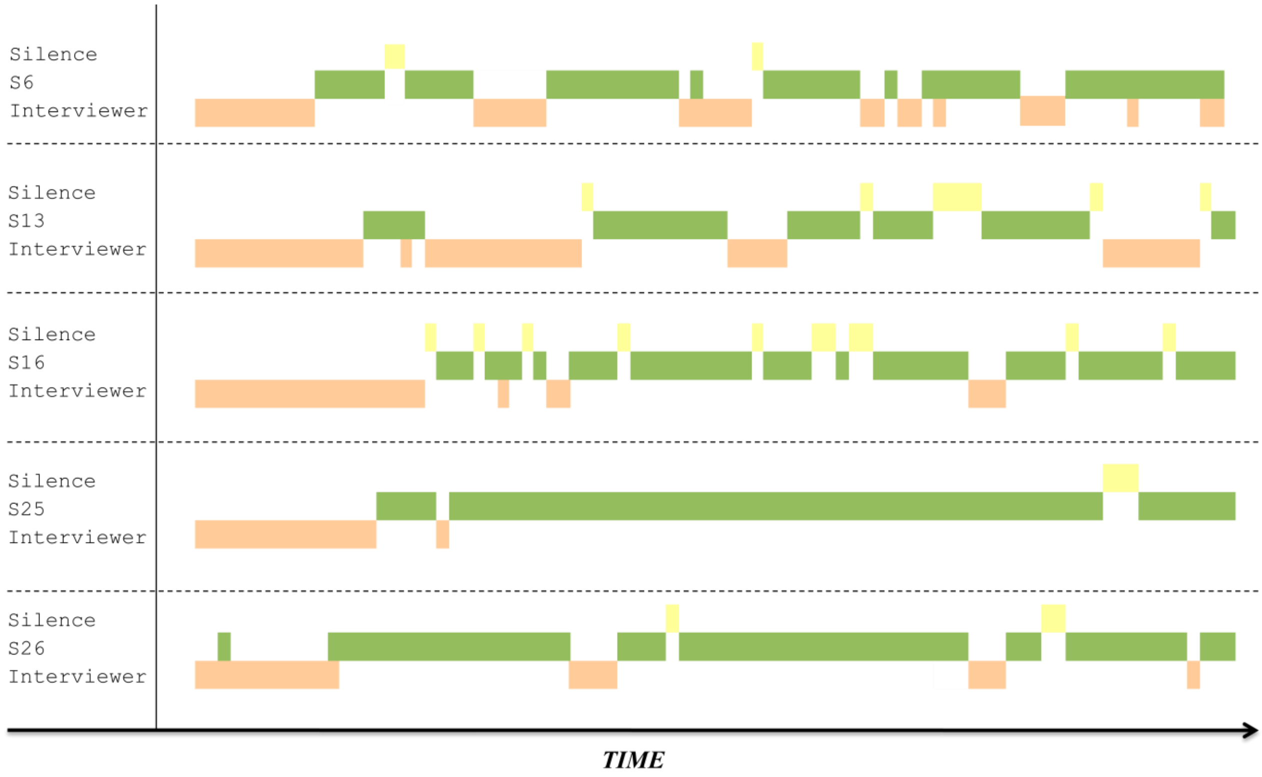


Figure 7.10. Excerpts of temporal maps from students' interviews (time unit: 2 seconds)

In order to make the maps comparable, they have been created using the same part of each interview, i.e. the first part. The pace of the discussion between the interviewer and student confirmed the impression that 3 students (S16, S25, S26) felt more at ease during the interview than the other two (S6, S13). Indeed, the first two maps show more frequent, interventions by the interviewer than in the others, even though the topic of discussion was the same.
Moreover, students' argumentations and their choice of words were significantly different. In particular, S16, S25 and 26 took the interview as an opportunity to express a main message about their experience in the course and, in the third part of the interview, each of them centred the argument on different key-words and terms related to the perspective of complexity. Our impression was that their use of specific words in the interview was representative of how they experienced the path on CC and how the epistemological dimension touched both their scholastic attitude (as students) and behavioural attitude (as young citizens).

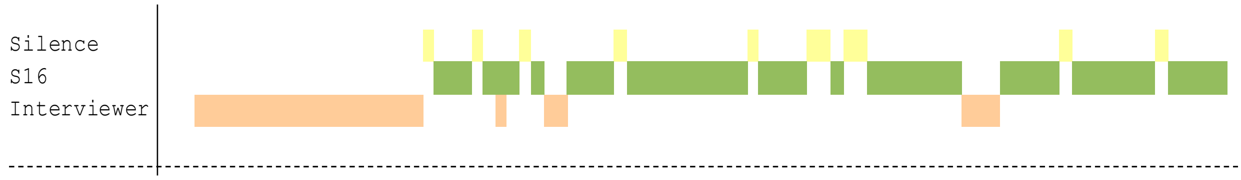
In the light of such considerations, we designed the profiles of S16, S25 and S26 as follows:

(i) we took into account the *temporal map* of the single student in order to identify for each of them a specific pattern of interaction between the students and the interviewer;
(ii) we identified the *main message* expressed by the student about his personal experience in the course;
(iii)we identified *words or expressions* that each student repeated several times during the interview to express and articulate their main message.

As will be shown, comparison of the three profiles allows us to produce a draft argument to answer the RQs.

The draft argument will be tested and refined against the cases of S6 and S13, which appear significantly different from the previous three cases. Besides the different pace of the interviews, in the transcripts of S6 and S13 it was neither possible to identify the emergence of a main central idea, nor to identify words or expressions related to the complexity that had captured their attention. The profiles of students S6 and S13 were built so as to further explore the credibility of our argument and to outline its limit of validity (Anfara et al., 2002). In this sense, S6 and S13 acted as contrastive cases.

S16: "The sceptic"
(i) *Temporal map*. During the interview, S16 appeared at ease from the outset. Although there were several moments of silence, there were only few and short interventions by the interviewer. Particularly, the moments of silence seem to be important moments of reflection, functional to the discourse. In this sense, the map shows that S16 was constructing his discourse and the interviewer allowed him time to do this.

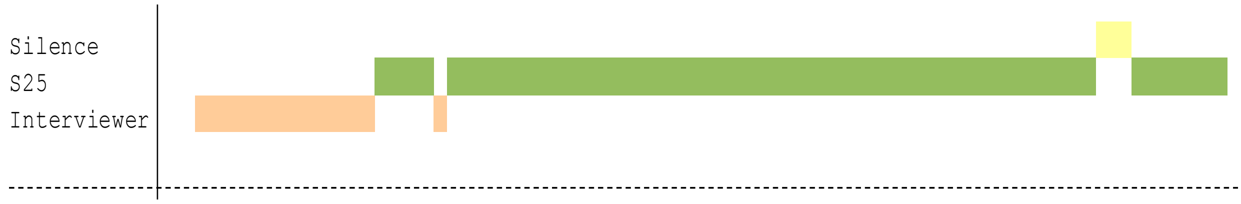


(ii) *Main message*. From the very beginning of the interview, S16 told us that before the course he had been sceptical about the issue of CC and the scientific reliability of information provided by the media. He expressed the need to have correct and solid information in order to avoid being manipulated by the media. The alarmism that, in his opinion, characterizes the way in which this subject is often treated, does not represent a guarantee of the real existence of global warming. His position later evolved as a result of the whole course and particularly thanks to the introduction of the perspective of complexity and of the features of modelling of complex systems. In particular, the model of Schelling was an element that led him to activate the societal dimension, which was initially absent: "*Let's say that before I knew little on the subject, because at the beginning this was not a topic of interest for me. But as these meetings went on, providing more information, I arrived at the understanding that these are instead important topics that must be followed and they are in fact interesting. [...] Before that course, I thought it was all just huge alarmism and nothing else*".

(iii) *Key words*. In the interview, S16's discourse was strongly characterized by the repetition of words like *to determine exactly, regularity, to know exactly*. These are words that he systematically used in every part of the interview and that seem to express his need to know exactly what happens. In the following excerpts, for instance, S16 explains how the Lorenz attractor has revolutionized his idea of "the determination of the behaviour of a body": "*[in classical physics] I can determine where it will be at a certain point after a certain period of time, whilst here [in the Lorenz's butterfly] I cannot do that. Here it is impossible, I know where such a point moves but I cannot know exactly where it is now. Whereas before the course I was convinced that there was only classic physics, in this case the whole situation has reversed ... and I was a little bit disoriented but fascinated*". Consistent with his view, the word of complexity around which he developed his reasoning was *unpredictability*. Indeed, when the interviewer asked S16 about the words and concepts that he found more interesting or that changed his perspective, S16 claimed: *"Surely 'unpredictability'; let's say that all the other words of complexity, I think, serve to explain this word ... let's say that the most important word is 'unpredictable' because with this word I explain what it means to study phenomena on a global scale"*. In order to give credibility to the issue of CC, S16 expressed a need to elevate unpredictability to the rank of a scientific concept and to attach a more refined meaning to the provisional power of science and the kind of data and models on which science founds its previsions: *"I realized that, for example, the melting of glaciers and a rise of just one degree of the average temperature, can lead to important consequences. I understood that these things need to be evaluated on a very dilated scale of time. Whereas I was initially convinced that the data variation from year to year was enough to understand these things [changes in the climate], instead I understood that we must have data based on years and years of experience"*.

S25: "The outsider"

(i) *Temporal map*. During the interview, S25 appeared very at ease. In the excerpt below there was only a moment of silence and only within S25's discourse, to indicate a moment of reflection. Hence, it seems that he was ready to articulate his discourse.



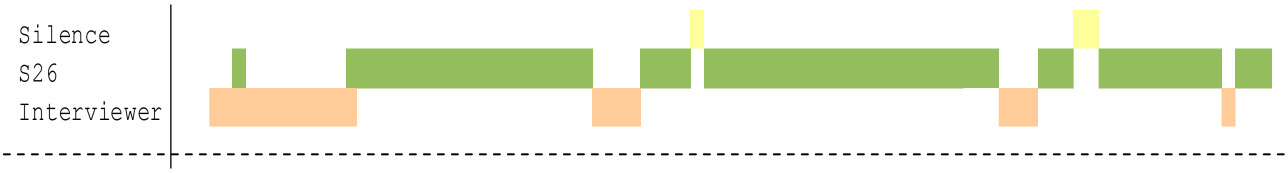
(ii) *Main message*. During the interview, the main message which emerged is that, despite the difficulty of the subject and of physics in general, the game of modelling and the progressive complexification of models offered S25 a key to address the topic. Particularly, the lesson on complexity was a fundamental moment in his learning path because it represented an intellectual challenge that he decided to take up. Furthermore, the perspective of complexity allowed him to analyze a scientific issue from multiple points of view, and to form a global and coherent picture. At the end of the interview, S25 revealed that he was a musician and that he loved art and math, whilst he was not particularly interested in science: "*The lesson on complexity was particularly interesting, i.e., more than anything else, it was like a challenge, so I said 'okay, let's try to figure it out'. Then it was nice to find out how to go from a laboratory model of a virtual model, imagine how they might go, if everything goes as we imagine things; how things could go in space, or in a place connected to us. That is to say, it is nice to know and to be able to predict some things"*.

(iii) *Key words*. S25 did not select only one word of complexity around which he organized his discourse. He was fascinated by all the words of complexity and their evocative power. During the lesson, he was guided by the charm that those words evoked and he tried to collect all the stimuli that the new perspective of complexity transmitted to him. The fascination for the aesthetical dimension that stimulated his interest dominated his whole interview. In commenting on the course, he focused on a picture of the Dutch graphic artist M.C. Escher, which was used as a cover page for the lesson on complexity. S25 gave the picture a special significance in explaining the idea of global and local view, the difference between macro and micro, and the concepts of regularity/irregularity and order/disorder.

He revealed that at the beginning of the project, he was bored by the idea of dealing with CC. The *fil rouge* on modelling and the lesson on complexity were the two elements that captured his attention and that initially attracted him to the issue. The aesthetical dimension and, in particular, the new and more fascinating perspective on science introduced by the lesson on complexity represented a way to engage such a student. Particularly, in the perspective of complexity he found an opportunity to study science in a game between freedom and constraints in which creativity can also play a role, just like for a painter or musician.

S26: "The silent"

(i) *Temporal map*. During the interview S26 appeared at ease. He was able to take responsibility for his answers. He managed the discourse by himself with pauses when necessary, even though he sometimes needed some minor assistance from the interviewer.



(ii) *Main message*. S26 immediately explained that he needed to address every issue in a practical and concrete way: *"The laboratory experiments were clear and explicit. However, in my opinion, it is easier to learn by doing things rather than just by listening. [...] Indeed, I better understood the issue of models when I made models by myself, by seeing and creating them, and also thanks to the tutorial that was given to us during the experimental lessons"*. His need to learn by doing was not only related to the lab-activities but also to the implementation of computer-designed models. S26 was also really attracted by the computational aspects of modelling, indeed he was interested in the way Lorenz concretely elaborated his theory.

(iii) *Key words*. Throughout the whole interview there was the recurrence of the words "complicated" and "complex"
which at the beginning of the interview were used alternately in a confused way. In our opinion, his sentences revealed a more or less conscious need to find a way to distinguish what is complicated, and then reducible to something simpler, as opposed to what is complex, then non-reducible. In coherence with his linguistic style, he chose "irreducibility" as the most evocative word of complexity, around which he organized his thoughts: "*Well, irreducibility is the word that I better understood [...] irreducibility in the sense that there are things that cannot be reduced to only one parameter, as we saw in the example of the iteration of Lorenz ... when he inserted his values into the computer and then cut some significant digits, then he had a different situation from what he expected ... there is a limit to the simplification"*.

S26 overcame the idea that "irreducibility" was a limitation or something which was possible to solve thanks, for instance, to advanced technology, or something that was possible for him to unravel. Instead, "irreducibility" became an implicit feature of the nature of certain phenomena. Thanks to this development in his thinking, he matured in his awareness both of this topic specifically and also more generally about science. However, this process is still underway at the time of the interview The conflicting use of the words "complicated" and "complex" is proof of this. This conflict was positively managed, indeed the interview helped S26 to progressively recognize the distinction between the two words and to change his way of looking at the relationship between the individual and the solution. Such a distinction has an important role in defining the shift of perspective from the classical models to complex models: from an initially very pragmatic approach to the awareness needed in a more complex and non-reductionist approach in searching for solutions.

Discussion of the first set of profiles

Through the comparison of the three profiles, we can infer examples of *functions* played by the epistemological dimension in triggering an attitudinal change toward CC.

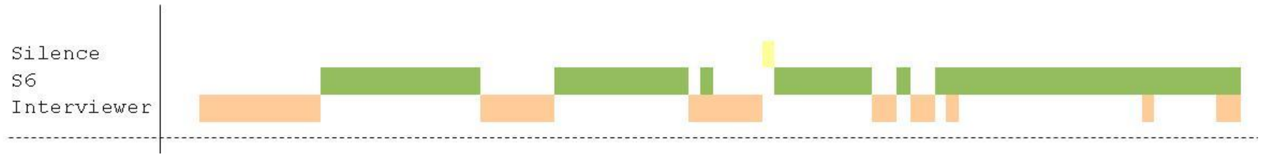
For S16, the epistemological dimension served to nurture his intellectual interest by providing a sort of "scientific reliability" to any discourse about CC. In particular, the elevation of unpredictability to the rank of a scientific concept allowed him to overcome his initial scepticism and to find room for a personal social involvement. As for S25, the charm of the epistemological dimension functioned as an attractor capably of nurturing his aesthetic pleasure. Indeed, the challenging character of said dimension touched his artistic personality and triggered the activation of a social involvement. For S26 at least, the epistemological dimension acted as a key i) to overcoming the personal barriers created by his pragmatism which prevented him becoming involved in something too complicated; and ii) for tackling scenarios with new possible and reliable, even though more complex, methods of thinking.

To sum up, the draft answer to our RQs is as follows: the epistemological dimension and, in particular, the perspective of complexity was, in some cases, productive in triggering a change in students' attitude towards CC. The examples show a spectrum of three different specific functions that it played: to provide scientific reliability, to infuse intellectual charm to the discourse, to extend the field of possible actions. These functions are, of course, idiosyncratic and we suppose that many other functions could be found if we enlarged our empirical basis. Nevertheless, our three cases alone allow us to conclude that significant correlations can be found between the epistemological and behavioural dimensions and that the teaching path was able to create, for some students, a virtuous dynamics among them.

The two cases that we will consider now provide further contributions to understanding why that happened with these students and why it failed with others.

S6: "The shy"

The interview was dominated by very short answers from the student and by many pauses with the frequent use of expressions like "*ehm*". S6 systematically needed the interviewer's help in articulating his thoughts.

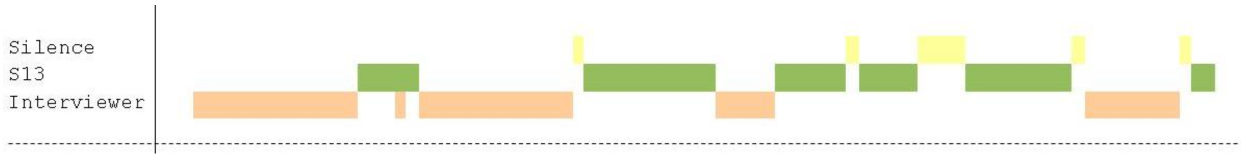


From the beginning, this student stated that his attention was focused on things he found "easy", such as the experiments. For him the lesson on the perspective on complexity represented an intellectual obstacle that he did not even try to address.

His interview discourse was fragmented and not articulated enough to enable us to evaluate to what extent his thinking was globally consistent from the points of view of disciplinary content and epistemological message. Indeed, he listed the words of complexity, simply saying that he did not understand them and that he did not relate the first part of the course to modelling with the perspective of complexity: *"What caused me difficulty was the circular relationship and then the non-linear causality ... ehm ... I cannot connect it to the idea of complexity"*. Within his discourse it is not possible to identify the presence of a core idea around which he organizes his thoughts. The poorness of the discourse leads us to conclude that S6 found the path too difficult. This student reacted with occasional short answers that do not reveal any attempt to find a personal method to understand the content. This is demonstrated by the recurrence of the expression "*I did not understand*". He ended the interview by saying that he was happy to have tackled this "modern environmental problem" because he trusted his teacher but that the difficulties he met with the content prevented him from following the epistemological and societal *fil rouge*.

S13: "The excellent"

From the very beginning, the embarrassment of S13 is evident. From the map and the short and fragmented answers he provided, we can see that he did not feel at ease. S13 systematically needed the help of the interviewer in articulating his discourse.



Looking at the other data collected from this student, it emerged that he reached top levels in each dimension (see figure 1). He understood the scientific discourse (the concepts of absorbance, transmittance, reflectance and the greenhouse mechanism). He managed the discourse on models well (up to the lessons of the laboratory) and he also changed some aspects of his behaviour. Despite such results, he showed many difficulties during the interview and the tone revealed a sort of "cold acceptance". Why did this happen? One reasonable explanation for his blanket of embarrassment is provided by the student himself at the beginning of the interview, when he stated very clearly that he did not understand the link between the epistemological perspective of complexity and the rest of the course: "*More than anything else I do not understand the relationship that exists among: the models, what we did in the laboratory and the complexity"*. His failure to link the different parts of the course seems to show that he accepted the path in all its parts but did not feel the need to form a personal view. Unlike the first group of students, it is not possible to find key-words or a central message in his interview.

The words he offered during the interview are not enough to provide a unique interpretation of the reasons for his reactions. The hypothesis that we find most convincing is that he approached the course in a scholastic way, in the sense that he expected to be spoon-fed the connections by the teacher as opposed to forming a personal view of the content and taking responsibility himself for acquiring the knowledge (Cornelius & Herrenkohl, 2004).

During the interview we perceived that he felt discomfort at being removed from an ordinary teacher-student situation and, thus, without the traditional rules of a common oral task (Brousseau, 1986; Yackel & Cobb, 1996). S13 limited his personal involvement in the epistemological and emotional dimensions probably because he wanted to keep under control his insecurity towards the apparently novel scholastic context. Still, as is evident from the beginning, he did not accept entirely the existence of an epistemological dimension, particularly the existence of an intrinsic complexity in the nature of science. Even though he grasped the scientific meaning passed on by the course, the inner epistemological debate about CC hindered him in tackling a new emotional challenge.

Discussion of the two contrastive cases

Comparing the two contrastive cases with the previous results allows us to refine our draft argument and our answer to the RQs. In particular, the comparison leads us to identify some boundary conditions that are needed to trigger a personal and conscious involvement in CC issue. From the analysis of S6's profile, it emerges that the first condition is the importance of meaningful learning of scientific content. In our course, the epistemological and behavioural dimensions are deeply rooted in the discipline and, without a significant learning of the basic concepts of physics, the other dimensions become meaningless. From the analysis of S13's profile, a second condition emerges, regarding the freedom of a social role that the student has to play (related to the expectations of his teacher and classmates). Indeed, S13 was the "excellent" member of the class and it seemed as though he had to defend this role for his self-efficacy (Bandura, 1994). His social interest toward the topic seems to be still effectively dependent on his teacher (Cornelius & Herrenkohl, 2004). On the contrary, in the first three profiles, we saw that they felt free to express their personality without behavioural constraints, they were free also to be initially sceptic and to follow a personal path of learning and view-forming.

7.2.2. Conclusion and final remarks

The analysis presented in this chapter is the last stage of a wider investigation into the reaction of secondary school students to our multi-dimensional path on CC. The path aimed to foster behavioural and personal involvement through a refined epistemological reflection on modelling and on the perspective of complexity. In order to investigate possible links between the epistemological competences and the behavioural attitude toward CC, five students were selected and analyzed. The analysis highlighted different types of emotional reaction to the epistemological dimension: the general acceptance was coloured with enthusiastic intellectual satisfaction by some students, with "cold" acceptance, or with a prudent and responsible curiosity by others. The various types of reaction seem to have interesting links with students' emotional and social attitude toward CC. Three cases concern students who had an initial distrust or resistance toward CC issues and found personal new reasons for engagement in the epistemological perspective of complexity. Two of them found, in the epistemological dimension, a stimulating opportunity to nurture their intellectual or artistic talent. One (more pragmatic) found new arguments to see and evaluate possible directions of action. The other two students acted as contrastive cases and allowed us to see some boundary conditions needed to trigger personal involvement. These conditions regard the need to master disciplinary knowledge in order to recognize the value of the epistemological and social dimensions and the importance of feeling free from the teacher's expectations before being able to explore and find one's own position with respect to such complex issues. In the light of these results, we can assert that, under certain conditions, specific epistemological know-how can positively impact not only productive disciplinary engagement, but also a more personal and authentic involvement in CC. However, the analysis of the two contrastive cases raises two open issues. The first one concerns the domain of validity and the problematic issue of searching for the boundary conditions that foster and support authentic behavioural responses. The second concerns the role, well-known in literature, of the external expectations (from a teacher or other people) in fostering or hindering proper, authentic and genuine involvement.

CONCLUSIONS

The research project described in this thesis aimed to study *if*, *how* and *why* the scientific contents related to CC could be reconstructed so as to integrate the many dimensions involved in the issue. Specifically, the project set out to create and test innovative materials and activities for secondary school students, designed to foster: i) effective and meaningful understanding of the concepts involved in CC; ii) a growing *personal involvement* in environmental issues; iii) epistemological reflections aimed at problematizing the traditional and outdated image of science which is still widespread among citizens.

In the design and analysis of the materials, we conjectured that behind many conceptual difficulties and psychological barriers lie particular epistemological obstacles related to a naïve and stereotypical view of science.

This conjecture was explored by organizing the work according to four research questions:

> *RQ_1: What operational criteria can be identified for reconstructing physics so as to integrate the many dimensions considered in the main goal?*
> *RQ_2: (a) Which models of greenhouse effect and GW are effective for implementing the criteria identified? (b) What experimental activities can be designed in order to promote an inquiry-based approach to the study of environmental issues, and to help students understand the models and their multi-dimensionality?*
> *RQ_3: How do secondary school students react to the proposed materials? Are the materials effective in achieving the main goal of the research?*
> *RQ_4: Which analytic methods can be used to investigate the multiple dimensions of a teaching/learning classroom experience?*

To answer RQ_1 and RQ_2, the analysis of the research literature (chapter 1) led us to identify three operational criteria that acted as design principles in developing the conceptual path described in chapter 2. The most innovative feature of the criteria was their explicit reference to the main psychological and behavioural barriers that prevent citizens from feeling involved in the issue of CC (chapter 1, section 1.2.2).

In order to address the first type of barrier (*Not individual but collective*), the applied criterion was to make the role of the individual explicit in the modelling of global warming, by discussing how individual actions influence parameter *a (coefficient of absorption in atmosphere)* of the atmosphere and how individual choices turn into social behaviour in Schelling's model on social segregation. For the second type of barrier (*Too big or too small*) the applied criterion was to make explicit in the modelling of global warming: i) what is shared and what is still uncertain within the scientific community; ii) examples of causal connections (typical of complex systems) between man-nature-technology and examples of feedback to show that minor causes can have major effects and *vice-versa*. In particular, the model used to interpret GW showed the vital role of parameter *a* in showing examples of causal links and feedback mechanisms (e.g., if the absorbance of the atmosphere increases under certain conditions, then the temperature of the Earth's surface rises; if the temperature rises, the glaciers melt; if the glaciers melt, the absorbance of the atmosphere increases). Finally, for the third barrier (*Too far*) the applied criterion was to place the examples already dealt with on a time scale, typical of an evolutionary approach to complex systems, in order to reflect on possible future scenarios.

In spite of its simplicity, the model of GW developed along the whole path appeared to have epistemological, cultural and learning potential (chapter 2):

- The model is based on an energy balance reasoning (as opposed to the more widespread and misleading idea of trapping), as recommended by the more advanced studies in physics and physics education;
- The model provides an opportunity for re-analyzing basic concepts from a new perspective which breaks down barriers between disciplinary areas (optics, thermodynamics, electromagnetism);
- The model can be progressively constructed through a back-and-forth dynamic process between theoretical hypothesis and exploration of the phenomenology, according to an inquiry-based approach;
- The model implements the selected operational criteria in order to overcome the behavioural barriers identified;
- The model allows an epistemological *fil rouge* about models and modelling to be emphasised.

In answering RQ_3, we analyzed each dimension individually, comparing the preliminary results obtained from the pilot-study (chapter 4) and considering what the recursive process of refinement of the materials and analysis of the dimensions has yielded.

As far as the disciplinary dimension is concerned, the analysis of the pilot-study revealed the permanence in the students of conceptual difficulties which are well-documented in the research literature (chapter 1, section 1.2.1).

The conceptual path provided a chance to resolve the problem of confusing different environmental phenomena. Indeed, the path led students to recognize: i) the distinction between global warming and general pollution and, moreover, ii) the distinction between global warming and the ozone layer depletion (Niebert & Gropengießer, 2013).

What remains unresolved are two specific physics issues: i) the difficulty in managing the concept of emission and ii) the confusion between heat and radiation.

For the first point we have different results from the pilot-study and the classroom experience. Whilst in the pilot-study students were confused by the difference between emission and reflection, this sort of confusion disappeared in the teaching experience. The students of the classroom context demonstrated that they well understood the properties of absorbance, reflectance and transmittance, and they did not overlap the process of reflection with the process of emission. This is only a partially successful result because students continued to show difficulties in considering the emission of energy of a body which has a temperature and to consider this behaviour in terms of energy balance.

The second point remained a difficulty both in the pilot-study and in the classroom experience. Students still found it difficult to distinguish between heat and radiation, although this was a point which was strongly stressed throughout the project.

These two problems are those in which there is the greatest discrepancy between common sense and scientific thinking. As a result, we believe that these points should be taken into account and developed in future work, not only within an atypical experience, but also in taking a revised approach to the way in which they are addressed within the standard *curricula* and school textbooks.

The previous points imply further investigation but, as our other studies on thermodynamics show, they must be addressed immediately when the basic concepts of thermodynamics and electromagnetism are introduced. Otherwise, the path on CC has too many foci of attention and risks overwhelming students.

As far as the societal dimension is concerned, there was a positive resonance between the results obtained in the analysis of the pilot-study and the other experiences: here, all the experiences showed that students had positive behavioural responses. The analysis of the mutual interaction between knowledge and behavioural response (chapter 6) strengthens this result. Indeed, while in the pilot-study our hypothesis was that the activation of a societal dimension was mainly due to the fact that the students were only volunteers and already interested in the topic of climate change, the analysis showed that the conceptual path also had a very positive influence on students who were not volunteers. In particular, the detailed analysis of the classroom experience showed that although the condition of voluntariness intrinsically represents a triggering factor, it is not in fact the only one. The evolution of a certain type of knowledge and awareness and, mainly, the introduction of the epistemological perspective of complexity appeared potentially able to provide students with the cultural tools necessary to rationally navigate through the jungle of ideological/media wars about environmental issues. Indeed, the kind of epistemological knowledge developed throughout the whole path provided in our opinion a significant contribution towards: i) avoiding that the climate change issue be perceived by students as generally uncertain; ii) understanding which scientific dynamics within climate change still present a certain level of uncertainty.
This form of awareness represents a crucial point for perceiving science as a reliable source of knowledge, and an important goal in the challenge of educating young people in scientific citizenship.

The epistemological dimension was increasingly emphasised in the experiences, and represents a particularly original feature of this research work (chapter 7).
In the pilot-study, we discovered a remarkable lack of knowledge about models and modelling and we could see to what extent this represented a limitation. However, in that specific case the students' strong pre-existing societal involvement in the issue allowed them to trust the proposal and try to participate in the discourse on models. But, their existing engagement in the topic was not enough to allow them to enter the perspective of complexity and these students could not recognize the importance of the core epistemological lesson.
The enhancement of an epistemological *fil rouge* (chapter 2, section 2.2), the design of specific investigative tools regarding this dimension (chapter 3) and the development of new methodological tools of analysis (chapter 7) enabled us to investigate the importance of such a dimension from several viewpoints and to explore its relationships with the other dimensions.
The first epistemological analysis (section 7.1) provided a contribution to a science education research issue that has so far been poorly explored: how students react to the epistemological issues raised by the study of climate change. By comparing the results we achieved and the content of the teaching path, we can see that the two stages of student development – enrichment and refinement – correspond respectively to the completion of the lab-activities (lessons 1-3) and to the two lessons on the epistemological perspective of complexity and the political and economic scenarios of global changes (lessons 4-5). Such a correspondence leads us to infer that the delicate process of isolating a phenomenon to be investigated in the laboratory, as well as the multiple perspectives (thermal,

electromagnetic, optical) from which the GHE was investigated, played a fundamental role in expanding students' reasoning about the meaning and the role of models in science.
On the other hand, we can infer that the epistemological reflection on complexity and the application of physical models to social phenomena played a crucial role in helping students problematize the relation between reality, knowledge and experiments by overcoming the known tendency to mix and overlap these issues.
The second epistemological analysis (section 7.1) reached the core of our conjecture and investigated possible links between the epistemological competences and behavioural attitude toward climate change. For this purpose, five focal students were selected and analyzed. The analysis highlighted different types of emotional reaction to the epistemological dimension: the general acceptance was coloured with enthusiastic intellectual satisfaction by some students, with "cold" acceptance, or with a prudent and responsible curiosity by others. The various types of reaction were argued to have interesting links with students' emotional and social attitude toward climate change. Three cases concern students who had an initial distrust or resistance toward climate change issues and found new personal reasons for engagement in the epistemological perspective of complexity. Two of them found a stimulating opportunity in the epistemological dimension to nurture their intellectual or artistic talent. One (more pragmatic) found new arguments to see and evaluate possible directions of action. The other two students acted as contrastive cases and allowed us to see some boundary conditions needed to trigger personal involvement. These conditions regard the need to master disciplinary knowledge in order to recognize the value of the epistemological and social dimensions, and the importance of feeling free from the teacher's expectations before being able to explore and find one's own position with respect to such complex issues.

Finally in answering RQ_4, new and original analytic tools were developed to carry out fine-grained analyses able to take into account the many aspects that characterize this research. From a methodological point of view, we had to cope with two types of problems raised by the ambitious goals we intended to pursue: i) how to assess the multi-faceted impact of a teaching experience that was designed to transform students' relationship with climate change along different dimensions and ii) how to adapt the research needs to the constraints and habits of school realities.

In order to address the first type of problem, we organised the data collection and data analysis so as to focus initially on the single dimensions and later on the correlations among them. This strategy implied the development of analytic tools able to bootstrap from the data results related to each dimension but also analytic techniques that could make the results of each dimension comparable to each other. Such an issue was addressed by searching for patterns along almost all the dimensions - epistemological, knowledge, behavioural. The patterns were highlighted through qualitative bottom-up methods that foresaw the involvement of different researchers for triangulation, an appropriate process of data reduction and long back-and-forth processes of refinement and testing of the results' reliability and accountability. We believe that the analytic methods we developed can be inspirational for several other studies and provide a new contribution to the methodological debate in science education.

As for the problem of coordinating research and school needs, the difficulties encountered were considered as "part of the game" but some of them had problematic implications for the whole project. In particular, the negotiation between the research purposes and the constraints of a normal classroom setting led the study to be affected by some methodological problems.

First of all, the climate change issue, even though it has been recently included in the curricula, remains an additional topic to be chosen only if desired by science teachers. Hence, it was not easy to find the opportunity to undertake experiences in a real classroom context. The context we found was not used to collaborations with research groups in science education and it was not easy to negotiate, for example, some issues related to data collection, which were deeply affected by the demands of the teacher and school. In particular, the data collected for the disciplinary dimension are seriously weaker than we had hoped but the principle goal of the written task was to assess the students' knowledge and it was mainly designed by the teacher in response to school requirements. The main implication of such a process of negotiation is that the constraints of the school did not allow us to give students the concept inventory on GHE as stated in the research literature. Such a lack in the data obliged us to make a methodological effort to try and use the data of the written task for our research purposes and to interpret the students' conceptual achievement from this data. In this regard, we analyzed the questions by grouping them according to the kind of problem that the research literature suggests investigating. This process allowed us to understand what problems the path helped resolve and which problems still remain open. Nevertheless, the analysis did not allow us to thoroughly investigate the nature of these unresolved problems.

However, we were aware from the beginning that the work, given its multidimensional and complex nature, was very challenging for a real standard classroom and that we could not overload students with too many data collection processes.

Because of these intrinsic difficulties, we are even more convinced that the analytical tools we developed provide a relevant contribution to the issue since they had to be applied in problematic natural settings and they proved able to capture and interpret the voice of the students by respecting the criteria of validity, quality and rigor (Anfara et al., 2002; Hammer & Berland, 2013).

I would like to conclude with a personal reflection. I believe that the epistemological dimension allows the construction of a particular *forma mentis* that helps students to think "*in* the science" and "*with* and *for* the society".

The development of epistemological capabilities (e.g. the ability to read and interpret graphs, to isolate phenomena or to look at phenomena from different perspectives, to be able to project scenarios, or to use the language of probability) helps to promote a scientific attitude in which uncertainty, evaluation of risk and comparison between different perspectives are not cause for bewilderment but issues to be analyzed with rationality and awareness.

On one hand, the research results in the field of social and behavioural sciences had shown that there is an articulated emotional attitude which manifests itself in feelings such as guilt, confusion or frustration (Norgaard, 2006; Weintrobe, 2012). On the other hand, psychological and sociological research demonstrated that in facing the complexity of the debates on environmental issues such as climate change, people developed a new fear of the global age, what Zygmunt Bauman (2006) called "liquid fear" - an indistinct and distrust fear generated by the sense of insecurity and perception of not holding control over events. The diffusion of this fear led to the emergence of irrational and regressive responses, like denial of the problems or excessive individualism (Pulcini, 2009).

That which is unknown, uncertain, complex or debated, generates fear which manifests in a sense of disorientation due to the impossibility of taking action (Weintrobe, 2012).

This attitude leads citizens to have expectations of science that it cannot cope with. The consequent disappointment of these expectations that citizens have in science and scientists leads to the spread of hardship, hopelessness and sadness in our society where people tend to delegate responsibility to the governing authorities (Giddens, 2009) and deny individual responsibility (Weintrobe, 2012).
I personally believe that a mature and responsible citizenship must be developed as a priority in its cultural dimension. In this sense, education, (particularly science education) plays a fundamental role in the development of a responsible citizenship (Horizon, 2020).
I hope my work, through the enhancement of an epistemological dimension and its correlation with both a disciplinary and societal dimension may provide a contribution to research into science education and support its role of promoting a responsible citizenship.

ANNEXES

Annex A: Pre-questionnaire (Q_1)

In this experience we will face an issue much debated today: the climate change. The theme will be faced with a cut that will highlight how the process of modelling the phenomenon should be gradually complexified in order to understand the specificity from a scientific and epistemological perspective, and also from a societal one.
With the questionnaire we would like to gather some information about your perception of the phenomenon, and about what you expect from this experience..

1. We often hear about climate change and/or global warming and, not infrequently, we discuss the reality of these phenomena. To what extent do you believe that these phenomena are real?

- □ Very much
- □ Enough
- □ Little
- □ Not at all
- □ I don't know

If you answered "Not at all", please justify your answer:
…………………………………………………………………………………………………

2. By referring to the items listed below, to what extent do you think they are causes of the climate change?

		Very much	**Enough**	**Little**	**Not at all**	**I don't know**
A	the accumulation in the atmosphere of GHE produced by individuals					
B	the accumulation in the atmosphere of GHE produced by the industries					
C	Livestock					
D	The ozone hole					
E	Deforestation					
F	Pollution					
G	Nuclear energy					
H	Other …					

Please, justify your answer:
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…………………………………………………………………………………………………
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3. What are the phenomena of which you've heard as consequences of the climate change? Which of these phenomena scares you the most?
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4. Is there anything that you have changed in your lifestyle thinking to climate change?

□ Yes □ No

4.a. If you answered *"yes"*, please explain in what sense:

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4.b. If you answered "*no*":

□ You really would like something but you do not anything because:

……………………………………………………...............……………………………………………

□ I'm not doing anything and I won't to do anything because:

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5. How much have you learned about climate change, from each of the following sources?

	Very much	**Enough**	**Little**	**Not at all**
Television				
Internet				
Books or scientific magazines				
Radio				
Movies				
School				
Family and friends				
Environmental associations				
Conferences and/or museums				
Seminars and/or events				

6. How much do you trust the following sources of information about the issue of climate change?

	Very much	**Enough**	**Little**	**Not at all**
Scientific programs on television				
Scientists				
Museums of science or natural history				
Family and friends				
Politicians				
Environmental associations				
University professors				
School teachers				
TV news				
TV reports on weather				

7. You've surely heard about global warming, what is your idea? Try to explain, with your words, the mechanism that is at the base of this phenomenon.

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8. Do you see a relationship between greenhouse effect, global warming and climate change? If yes, what kind of relationship?

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9. Do you think there is a relationship between the greenhouse effect and the ozone hole? And between the greenhouse effect and pollution? If you answered yes, what kind of relationship?

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10. Have you ever heard of greenhouse gases? In your opinion, what are they?

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11. What is your idea of model in physics? If you think about physical models, what kind of examples come to mind?

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12. What do you expect from this experience? What aspects / issues / problems would you like to be addressed?

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Annex B: Post-questionnaire (Q_2)

In light of the issues addressed during the experience, in which we have talked about the greenhouse effect, global warming and climate change, we ask you to think about whether you would change some answers to the first questionnaire.

1. Thinking about this experience, have you changed your ideas about the problem of climate change?

□ Before the course I had doubts, and I have clarified some
□ Before the course I had doubts, but I have clarified all
□ I had no doubt before and I do not even now
□ I had no doubts before, but now I have a little

Please, justify your answer:
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2. In light of what it was addressed during the course, have you changed your ideas with respect to the following items mentioned as possible causes of climate change?

		I thought that this factor had more importance	**I thought that this factor had less importance**	**My idea is not changed**
A	the accumulation in the atmosphere of GHE produced by individuals			
B	the accumulation in the atmosphere of GHE produced by the industries			
C	Livestock			
D	The ozone hole			
E	Deforestation			
F	Pollution			
G	Nuclear energy			
H	Other …			

Please, justify your answer:
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…………………………………………………………………………………………………

3. What are the main consequences of the climate change? Which of these scares you the most?
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4. Thinking at what it has been addressed during the course, is there anything that you will change in your lifestyle? □ Yes □ No

4.a. If you answered *"yes"*, please explain in what sense:
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4.b. If you answered "*no"*:
□ You would like to do something but you will not do anything because:
……………………………………………….............……………………………………………
□ I'm not doing anything and I won't to do anything because:
………………………………………………………………………………………………………

5. What idea did you develop with respect to the greenhouse effect? Try to explain, with your words, the mechanism that is at the base of this phenomenon..
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6. Do you see a relationship between greenhouse effect, global warming and climate change? If yes, what kind of relationship?
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7. Do you think there is a relationship between the greenhouse effect and the ozone hole? And between the greenhouse effect and pollution? If you answered yes, what kind of relationship?
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8. What are in your opinion the green house gasses? What physical properties they have and for what reason they are called GHE??
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9. What is your idea of model in physics? If you think about physical models, what kind of examples come to mind?
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10. During these lessons, great emphasis has been placed on the model - reality – experiment relationship. Could you describe what you now think about this relationship??
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11. There were aspects of novelty with respect your background (level of knowledge, level of awareness, level of concern, level of emotional management, ...)? If so, what?
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12. What aspects of the lessons you are getting more or less interesting? Which more or less difficult? What do you understand it better or worse? What did you find most useful or not?
Fill in the table and if you want to add other aspects that are not written in the table.

		Interesting	**Less interesting**	**Useful**	**Needless**	**Easy**	**Hard**	**Better understood**	**Worse understood**
Explanation of the greenhouse effect in terms of energy balance	**A**								
Concepts of absorbance - reflectance - transmittance	**B**								
Concept of emissivity	**C**								
Bond between the absorbance of the atmosphere and the temperature rise	**D**								
The models used to explain the greenhouse effect	**E**								
The experiments on radiation-matter interaction (cylinders)	**F**								
The experiments on the greenhouse effect (greenhouse box)	**G**								
The idea of feedback	**H**								
The transition from classical models to complex models	**I**								
Reflections on the idea of model in physics	**L**								
Reflections on the transition from the real to the virtual laboratory	**M**								
Reflections on the relationship among model-reality-experiment	**N**								
The political and economic scenarios	**O**								
The anthropogenic origin of the increase in the atmosphere of greenhouse gases	**P**								
Other …									

Comments: ....
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Annex C: Questionnaire on model and modelling (Q_m)

The word model is a keyword that guided our reasoning from the beginning. We have seen, in fact, how models and the game of modelling are a fundamental *fil rouge* to understand the physical description of the world.

Thinking back to the first questionnaire, how would you answer today? What has changed in your idea of a model? How has this idea evolved? Make your ideas explicit. If necessary, you can also give some examples.

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In the light of your reviewed ideas and reflections, we ask you to formulate and describe the model-experiment-reality relationship.

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Annex D: Written task

Question 1: **"***What is a Black body?"*
A1. A body which cancels all the radiation
A2. A body which absorbs all the radiation
A3. A body which emits all the radiation
A4. A body which absorbs all the radiation and emits

Question 2: *"The physical phenomena which cause the greenhouse effect depend ..."*
A1. both on the properties of the radiation and the properties of the gases that make up the atmosphere
A2. only on the properties of the incident electromagnetic radiation
A3. only on the properties of the gases that make up the atmosphere
A4. none of the above answers is correct (justify this choice)

Question 3: *"What is the absorbance?"*
A1. the amount of radiation absorbed by a body
A2. the percentage of the total radiation that is absorbed by a body
A3. a characteristic property of opaque bodies
A4. the opposite of transmittance

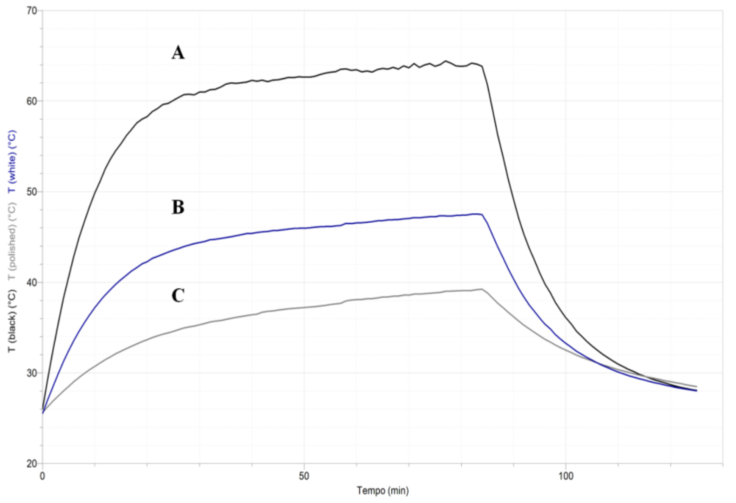
Question 4: *"The atmosphere is considered a:"*
A1. opaque body for the low-frequency radiation and a transparent body for the high-frequency radiation
A2. opaque body for the high-frequency radiation and a transparent body for the low-frequency radiation
A3. opaque body for both the low-frequency radiation that for those high frequency
A4. a transparent body both for the low frequency radiation that for those high frequency

Question 5: *"A body with transmittance = 0 is defined as:"*
A1. grey body
A2. opaque body
A3. translucid body
A4. transparent body

Question 6: *"Associate properly formulas and the law"*

A	$a_\lambda + r_\lambda + \tau_\lambda = 1$	1	Stefan-Boltzmann law	**A**	**2**
B	$E = \varepsilon \sigma T^4$	2	Balance law of the incoming radiation	**B**	**1**
C	$E_{in} - E_{out} = cm\Delta t$	3	Kirchhoff law	**C**	**4**
D	$a_\lambda = \varepsilon_\lambda$	4	General law of conservation energy	**D**	**3**

Question 7: *"The graph below represents the temperature versus time of three cylinders (the cylinders of the lab-activities) illuminated by the same bulb. Please, associated each profile with the appropriate cylinder."*



White cylinder	B
Aluminium cylinder	C
Black cylinder	A

Question 8: *"An opaque object A (e.g. a block of wood or stone) and a transparent object B, having the same thermal capacity and the same initial temperature equal to Ti, have been exposed to sunlight for the same time t. The temperature TA and TB of the two objects at the end of the exposure time will be:"*

A1.TA = TB

A2. TA > TB

A3. TA < TB

A4. You cannot determine the relation if you do not know the mass of each object

Question 9: "A block of plexiglass (plastic) is:"

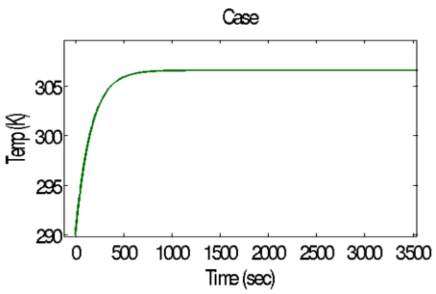
A1. transparent to any type of radiation

A2. transparent for visible radiation

A3. opaque to infrared radiation

A3. opaque to ultraviolet radiation

Question 10: *"This graph (Time-Temperature) represents an object which is heated by radiation energy. Why does the graph reach a temperature plateau?"*



A1. Because the object reaches the equilibrium temperature with the lamp

A2. Because the temperature of this specific object can't overcome this limit

A3. Because in that point the energy emitted is the same as the energy absorbed

A4. Because the lamp cannot provide more heat than that

Question 11: *"What is the effect of greenhouse gases in the atmosphere?"*

A1. They trap the heat absorbed from the earth producing an overheating

A2. They produce a decrease in the thickness of the upper atmosphere, increasing transparency for high-frequency radiation

A3. They cause an increase the absorbance of the atmosphere for the low-frequency radiation

A4. They cause an increase the transmittance of the atmosphere, increasing the amount of radiation that strikes the earth

Question 12: *"The feedback consists in:"*

A1. the action of a continuous and prolonged disturbance that produces more and more increasing effects on the system

A2. The combined action of several factors that produce more and more increasing perturbations in the system

A3. the fact that the effects produced by a perturbation of a system become cause of successive perturbation

A4. the fact that a phenomenon which reached its maximum development returns spontaneously to the starting situation

Question 13: *"Climatology is a field which studies:"*

A1. the physical properties of the atmosphere

A2. the evolution of atmospheric phenomena noting its evolution up to a maximum of ten days

A3. the behaviour of a system over the long term (greater than 10 years)

A4. the atmospheric phenomena that develop over distances varying from tens to thousands of kilometres

Annex E: Protocol of interview

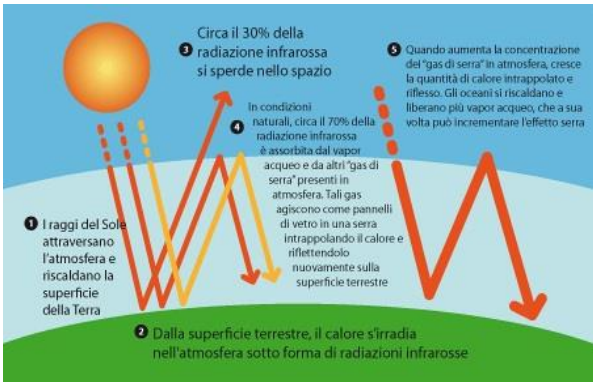
Thinking back to the conceptual path addressed during the experience, could you make a list of moments and/or contexts which were important for you in order to understand and/or change your point of view?

1st Part: Modelling in physics

In the questionnaire you wrote what is, in your opinion, a model in physics. Can you tell us more about your position? Can you think some examples that can illustrate the idea of the model you expressed?

2nd Part: Specific models addressed in the Climate Change path

These images on the greenhouse effect are taken by informative panels. We have chosen them because they are scientifically questionable and contain some imperfections. In the light of the concepts learned during our activities and the idea you got on the greenhouse effect, may you comment, analyze and/or criticize these images?



What difference do you see between these images and the explanation of the greenhouse effect in terms of energy balance?

3rd Part: Mathematical models and complexity

What was your reaction to the lesson dedicated to the complexity? What did you learn from this lesson?

The lesson is designed to highlight the transition from classical models to complex models. In particular:

- Looking at the picture of the Lorentz's butterfly, What do you remember? What do you think?
- Looking at the slide with the "words of complexity", What were the most significant and/or evocative words for you to grasp that there was a change of perspective in physics? What you did not understand? What about your doubts?

Finally, what did this experience mean for you?

Annex F1: Tutorial of the cylinders' experiment

The tutorial is articulated in three parts: *rethink, foresee, interpret*.

1st Part. *Rethink*

Dear students,
going back to the topics seen so far, we ask you to rethink the meaning that some words used in everyday speech assume when they are used in the language of physics: ***opaque, polished, transparent****.*
Try to give a "physical definition" of these words and make examples of real objects or situations which they may be linked.

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Exercise n.1.
An opaque object A (e.g. a block of wood or a stone) and a transparent object B (e.g. a block of glass), having the same thermal capacity and the same initial temperature equal to T_i , are exposed to sunlight for the time t. The temperatures T_A and T_B of the two objects at the end of the exposition time will be:

a. $T_A = T_B$
b. $T_A > T_B$
c. $T_A < T_B$
d. I don't know

Please, justify your answer.

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Exercise n.2.
Three objects are exposed to the sunlight for a long time. The three objects have the following features:
OBJECT 1 → black and opaque
OBJECT 2 → white and opaque
OBJECT 3 → transparent
In your opinion, does each object reach an equilibrium temperature?

Object	**Yes**	**No**	**I don't know**
black and opaque			
white and opaque			
Transparent			

Please, justify your answer.

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Exercise n.3.

An opaque object are exposed to sunlight for the time t (first situation). Then in a second situation the same object (with the same initial temperature) are exposed to a bulb for the same time t. Please say how will be the relationship between the equilibrium temperature of the object in the first situation (T_S) and in the second situation (T_L):

a. $T_S = T_L$

b. $T_S > T_L$

c. $T_S < T_L$

d. I don't know

Please, justify your answer.

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Exercise n.4.

Two objects, one white and opaque (A) and the other aluminium and polished (B), having the same thermal capacity and the same initial temperature equal to T_i , are exposed for the time t to two different situation:

Situation n. 1. *Exposition to the sunlight*
Situation n. 2. *Exposition to a bulb*

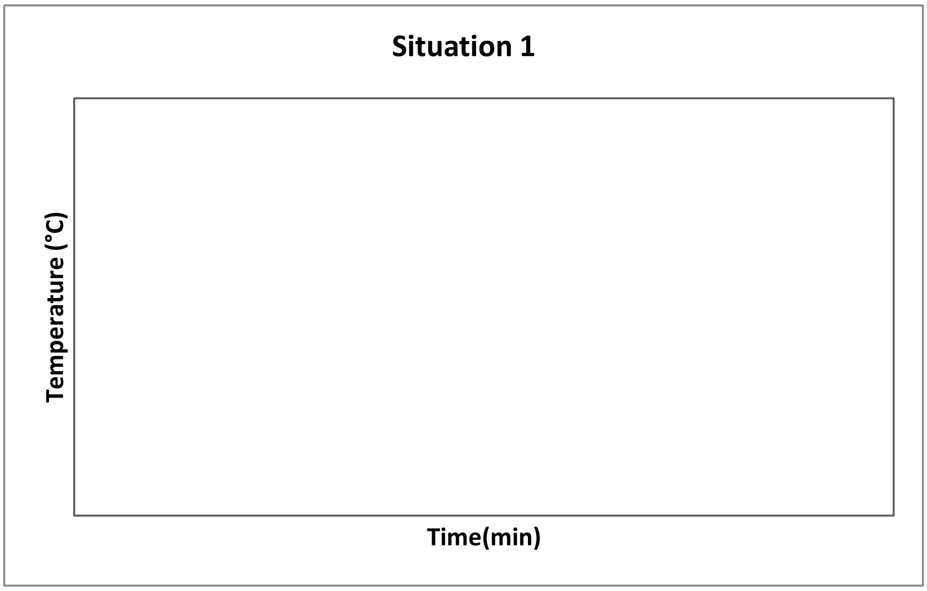
The temperature of T_A and T_B at the end of the exposition, will be:

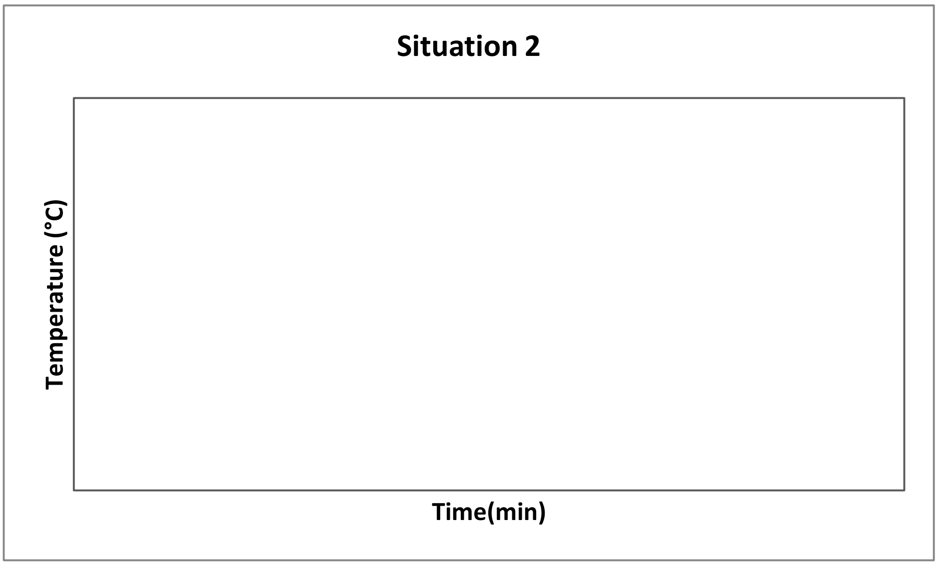
Situation n. 1. *Exposition to the sunlight*	**Situation n. 2.** *Exposition to a bulb*
a. $T_A = T_B$ b. $T_A > T_B$ c. $T_A < T_B$ d. I don't know	a. $T_A = T_B$ b. $T_A > T_B$ c. $T_A < T_B$ d. I don0t know

Please justify your answer and draw a graph time versus temperature of for the two objects in both the two situations.

Situation n.1:

Situation n.2:





<u>2° Part</u>. *To foresee*

Before the experiment is completed, try to draw the trend of temperature (T) versus time (t) for each of the cylinders you have. Please write your comments about what is important to stress in your opinion.

[Space to draw the graph]

Thinking back to the physics concepts introduced in the previous lesson, how would you explain the trend of the graph?

<u>3° Part</u>. *To interpret*

After thinking and tried to predict the behavior of objects, you can watch the graph that is forming on your experiment. We ask you to interpret the results and compare them with your predictions.

[Space to draw the graph]

What differentiates the graph obtained with respect to your forecast?

Thinking back to the concepts of physics seen during the lesson, how you would explain the trend of the graph obtained?

Annex F2: Tutorial of the greenhouse box experiment

The tutorial is articulated in three parts: *rethink, foresee, interpret*.

1st Part. *Rethink*

Dear students,
thinking back to the topics seen in the last lesson we ask you to draw (with the technique you prefer) "your model" of interaction between radiation-atmosphere-earth by varying the absorbance of the atmosphere ($0 \leq a \leq 1$). Assume the Earth as a black body and the atmosphere as a homogeneous and uniform body.
Please, give also an explanation of the model that you propose.

2nd Part. *Foresee & Interpret*

Before the experiment is completed, try to draw your hypothesis of the graph that you should observe in your opinion if you expose the box (WITHOUT the lid) to the light bulb.

Now try to draw your hypothesis of the graph that you should observe by exposing the box to the light bulb (WITH the lid).

Finally, try to draw your hypothesis of the graph that you observe exposing the box the light bulb (without cover first and then adding the cover at some point) and put out the things that are important.

Please explain your graphs.

The graphs obtained from the experiment are different from your predictions? If yes, in what sense?

Thinking of the physics concepts seen in the previous lessons, could you explain the graph obtained?

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