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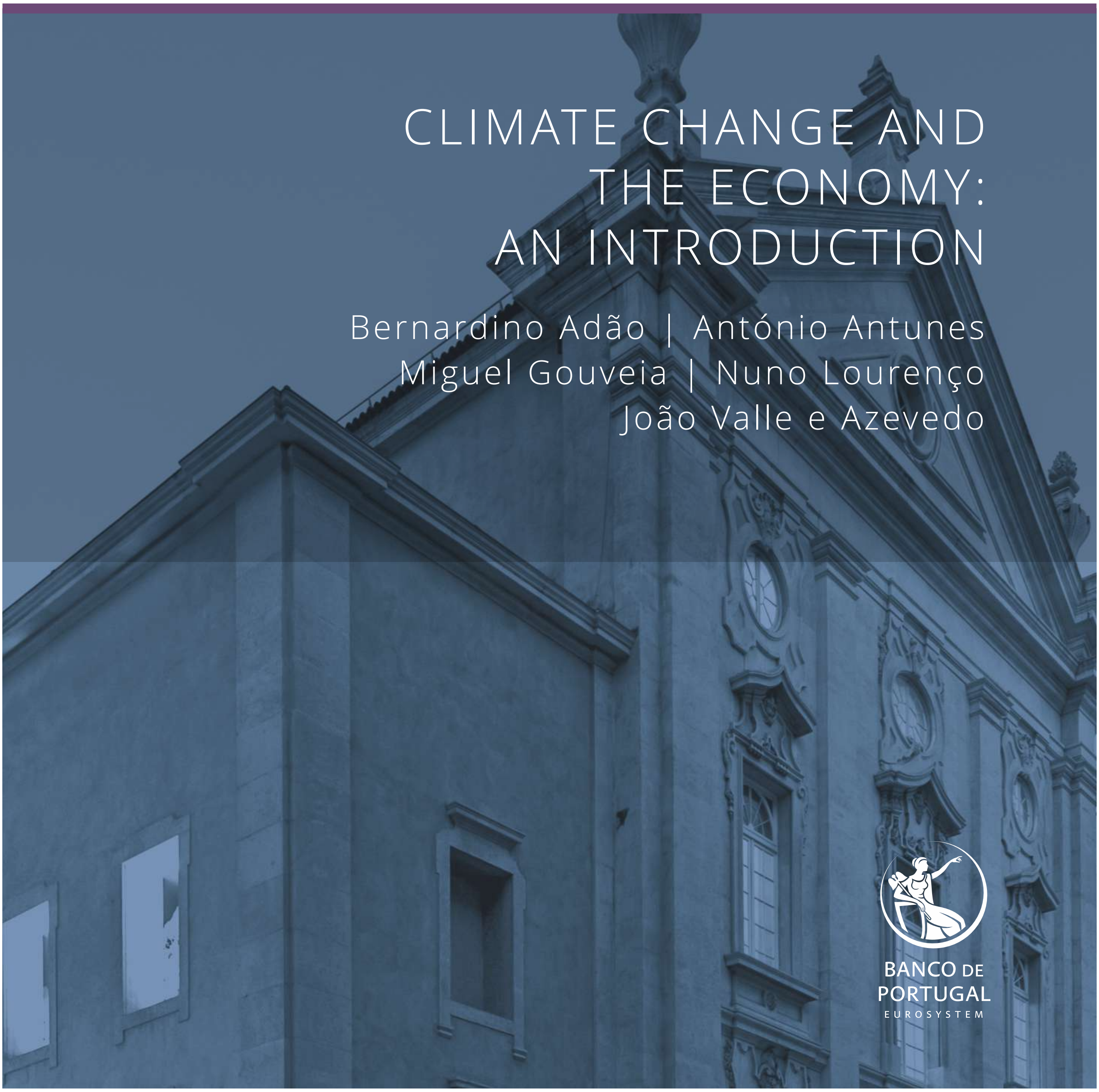

CLIMATE CHANGE AND THE ECONOMY: AN INTRODUCTION

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The analyses, opinions and findings of these papers represent the views of the authors, they are not necessarily those of the Banco de Portugal or the Eurosystem

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Climate change and the economy: an introduction

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Abstract
This work presents in an accessible way the functioning of the natural climate system and the mechanisms through which global warming occurs. The warming of the Earth's surface and the evolution of precipitation throughout the 20th century are documented, including for the Portuguese case. The channels of transmission of climate change to the economy are also analysed. The likely impact on the level of global GDP is negative, with a range of estimates very sensitive to the occurrence of phenomena that are difficult to predict. It also discusses economic policy proposals addressing the problem of fossil carbon emissions. Significant carbon taxation will likely have to coexist with the existing carbon emission permit system. The role of central banks in mitigating the effects of excessive CO_2 emissions is analysed, highlighting regulatory reporting with a focus on environmental issues and the assumption of concerns related to sustainability and corporate responsibility. Finally, model-based estimates of economic costs associated to climate change are presented. In this example, we conclude that the adoption of an optimal global policy would save Portugal about 0.5°C of warming.

JEL: E21, E60, F40

Keywords: climate change, economics, carbon taxes.

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Contents

1. Overview

This work is the authors' first attempt at an integrated analysis of climate change from the point of view of a central bank. At its genesis was an internal report drawn up from the autumn of 2019. The topics covered can be grouped into three areas: changes in the natural climate system; the economic aspects of climate change and economic policy measures to mitigate its effects; and prospective analysis of an optimal mitigation policy. This work formed the basis of a Special Issue published in the October 2021 Economic Bulletin, but it contains a more detailed and, in some dimensions, more idiosyncratic analysis.

The use of general access data, the consultation of the applicable scientific literature and the construction of methodologies directed to the topic under analysis were adopted. When possible and relevant, an incursion into the Portuguese case was made. The intention is to provide a comprehensive view of a complex issue that is likely to keep several future generations of academics and policymakers busy. Due to the exploratory nature of this work and the consequent inevitability of errors and omissions, the authors believe they can benefit from the reader's indulgence.

Section 2 presents in an accessible way the functioning of the natural climate system and the mechanisms through which global warming occurs. It also shows why the concentration of CO_2 and other greenhouse gases in the atmosphere is one of the causes of global warming. The section also proposes new quantifications of the effects of climate change, throughout the 20th century and until 2020, in terms of temperature and precipitation, in the entire terrestrial surface but also in the Portuguese mainland. A warming of the Earth's surface is documented in line with values found in the recent scientific literature on the topic, of around 1°C from the beginning of the 20th century to the present. From the second half of the 20th century, the annual increase in the Earth's temperature accelerated, amounting to around 0.017°C. In the Portuguese case, the values are smaller, with an increase since 1900 of about 0.6°C and, from 1950 onwards, an annual increase of 0.0077°C. With regard to precipitation, the global results are not as strong as in the case of temperature, with increases in some regions and reductions in others. In Portugal, the variation in precipitation throughout the 20th century and until 2020 does not differ statistically from zero; measuring this variation only from 1950 onwards, a statistically significant but low value is obtained, although there are some pockets of rainfall reduction. The section also shows that climate change manifests itself with great spatial differentiation. In Portugal, this is reflected in significant variations in the cooling and heating needs of buildings, spatially differentiated and with significant changes after 1950. For example, throughout the interior and the south of the country, there was an increase in the cooling needs of buildings in the summer. With regard to winter heating, there was a reduction in its need, especially in the north of the country.

Section 3 summarises the transmission channels of climate change to the economy, explaining the likely effects of, for example, increases in temperature and extreme events. One of the most robust conclusions of this review is that the likely impact on the level of global GDP is negative, that is, climate change will in fact have costs relative to a trajectory that ignores its existence, and are situated, for moderate scenarios in terms of temperature increment, in a range likely centred on 1.5% of GDP. However, these estimates can easily be exceeded if difficult to predict phenomena occur. Another aspect addressed in the section is the time discount used in evaluating climate projects or policies. This question is especially important because the energy transition will take place for decades. Using a simple methodology, we propose a discount factor applicable to the Portuguese case between 1% and 4% per year, depending on the assumptions about the behaviour of agents and structural factors of the economy. These values can be adjusted depending on the application and availability of new data.

The section offers a discussion of suitable economic policy proposals for the problem of fossil carbon emissions. From it emerges the conclusion that significant carbon taxation will likely have to coexist with the system of carbon emission permits currently in place, taking into account issues of uncertainty, agents' incentives, and political economy. There is also an analysis of the role of central banks in mitigating the effects of excessive CO_2 emissions. This role should be accessory and not central, since the panoply of monetary policy instruments at the disposal of central banks is generally not effective in reducing CO_2 emissions. In certain cases, the implementation of measures that are inadequate for the intended purpose can lead to unexpected or undesirable results. This does not mean that there are not several dimensions in which the role of central banks is useful, as is the case with regulatory reporting with a focus on environmental issues, and the assumption of their obligations in terms of sustainability and corporate responsibility.

Finally, Section 4 presents an estimate of the costs and climate effects of an optimal policy applied to mitigate the effects of carbon emissions using an *integrated assessment model* (IAM), with results extrapolated to Portugal. This admittedly approximate example gives the reader a quantification of the optimal policies on carbon emissions and adoption of renewable energy technology. It is worth mentioning some of the conclusions of the exercise. Taxation of carbon emissions from burning fossil fuels is the most effective policy for reducing emissions and for the energy transition, while policies aimed at encouraging the adoption of renewable energy production technologies have only a supporting role. Furthermore, the values obtained suggest that the rates applied globally to fossil emissions should be increased by about 50% compared to the current situation. Depending on whether the optimal policies are adopted or not, the results also suggest significant differences in global temperature: in the optimal solution, the planet's temperature warms 0.8°C less than in the situation where nothing is changed given the current configuration of climate policies. The Portuguese case is more mitigated because the temperature in Portugal has a sensitivity to global terrestrial temperature of around 0.6, that is, for each degree Celsius of variation in global temperature, the average temperature in Portugal varies around 0.6°C. Adopting the optimal policy would save Portugal around 0.5°C of increase in temperature. Although these temperature increases imply a loss in GDP, well-being increases around 1.3% globally and 0.5% in Portugal relative to the business-as-usual policy, in terms of equivalent consumption. These numbers, prospective and based on simplifying assumptions and uncertain parameters as they are, have to be interpreted as illustrations; one suggestion is to look at them as mere quantifications of the problem.

2. Geophysical aspects of climate change

This section aims to provide the reader with a first contact with the more technical language associated with climate change, and starts from the observation that it is difficult to find a common grammar for the various specialists who are dedicated to this issue. The level of scientific detail will therefore be just enough so that the essential arguments of physicists, climatologists and biologists, among others, are not lost when economists begin to look at them and formulate their hypotheses and models. An attempt will be made to give a first idea about the functioning of the natural climate system and the reason why it is affected by the concentration of the so-called greenhouse gases, which will be designated by the acronym GHG, of which water vapour and carbon dioxide (CO_2) are the best known. The section also includes a brief analysis of publicly available climatological data covering a long period of time, with a special focus on the Portuguese case; this is perhaps the part that most resembles the methodologies used in economics.

Since this is an analysis carried out by economists, data and analyses based on climatological models will be taken as inputs of the quantitative economic approach. However, it will be necessary to model the effect of economic activity on carbon emissions; this link will be discussed in Sections 3 and 4.

2.1. The functioning of the natural climate system

The natural climate system is incredibly complex. Describing it accurately is an impossible task; the only thing a scientist can do is to understand its mechanisms by modelling and quantifying them, while trying to understand the magnitude of his error and the degree of insufficiency of his analysis. The terrestrial climate results from a multitude of natural phenomena that interact with each other and have as interveners not only the atmosphere and the Earth's crust but also the oceans, the cryosphere (that is, the icy or ice-containing part of the terrestrial and maritime surface), the biosphere, the Earth's interior, the Sun and the Moon. One could also list other important elements – cosmic radiation, for example – but the idea is clear that modelling them all is impracticable and possibly unnecessary.

At first glance it is not obvious that the release of greenhouse gases into the atmosphere interferes with the climate to the point where the issue becomes important. To get an idea of the quantities involved, the atmosphere has a volume of around 26 billion cubic kilometres, considering the strip that runs from the Earth's surface to the top of the stratosphere, at about an altitude of 50 kilometres. By comparison, the annual CO_2 emissions from burning fossil fuels resulting from human activities, estimated for 2018 to be about 37 gigatonnes of CO_2 (Friedlingstein *et al.* 2019),[1] would occupy approximately 20 thousand cubic kilometres at ambient temperature and pressure, that is, a volume 1.3 million times smaller, at the same time that part of these emissions are absorbed by the oceans and other terrestrial systems.[2] However, the cumulative effect of these emissions over many decades may be relevant if there are not enough mechanisms in place. powerful for its elimination from the atmosphere. In fact, the concentration of CO_2 in the atmosphere is currently 414 parts per million (ppm) (Global Monitoring Laboratory 2020), that is, about 0.041% of the gaseous content of the atmosphere. Although this value represents a significant increase from its level in the mid-19th century, when it was 280 ppm, how can such a residual fraction of the atmosphere have such a large impact on the natural climate system? To answer this question it is necessary to understand three phenomena:

- The thermodynamics of bodies;
- The energy balance of the system formed by the Earth and the surrounding space;
- The impact of GHG on energy transfers between the Earth's surface, the atmosphere and outer space.

2.1.1. Thermodynamics made simple. One of the best known phenomena in the natural world is that all bodies exchange energy among themselves and that this tends to flow from warmer bodies to cooler ones in the absence of heat sources or sinks. This is why, while reading this text, the reader may have noticed that the coffee left in the cup on the desk was at room temperature, when before it was almost at the boiling point. The energy accumulated in the coffee in the form of heat warmed everything around it: first the cup and the air in contact with it; then the top of the desk and the air in contact with the cup; finally, everything else that was a little further away, and so on. The transfer of energy – from the coffee to everything around it – cooled the coffee and warmed the objects and environment around it. The change in the total energy contained in the coffee (also known as

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1. The units used in the literature on carbon emissions are the gigatonne of carbon dioxide ($GtCO_2$), the gigatonne of carbon (GtC) and the part per million (ppm). A GtC corresponds to 3.664 $GtCO_2$, and a ppm corresponds to 7.782 $GtCO_2$. Emissions of other GHG, such as methane, are converted into carbon equivalents according to their contribution to the greenhouse effect per unit emitted.

2. Friedlingstein *et al.* (2019) estimate fossil carbon emissions in 2018 at about 10 gigatonnes. The molecular weight of CO_2 is 44 grams per mole, while the molecular weight of carbon is 12 grams per mole, which implies that each gigatonne of carbon emitted corresponds to about 3.7 gigatonnes of CO_2. Knowing that a cubic meter of CO_2 weighs 1.84 kg at normal atmospheric pressure and a temperature of 25°C, converting the fossil emissions of CO_2 into volume gives the figure indicated. Note that in the upper layers of the atmosphere the temperature and pressure are much lower so the volume of CO_2 in these layers must be adjusted.

enthalpy) was negative. That means a negative change in the enthalpy of a body cools it, and a positive change heats it. The reverse process of heating coffee above room temperature requires a heat source.

How does this transfer of energy in the form of radiation take place? The answer is complex, but the following can be said: a body radiates more energy the hotter it is, depending on its shape and the materials it is composed of. In the case of coffee, energy is transferred mainly in the form of heat. There are, however, other forms of energy radiation, most prominently electromagnetic energy. All bodies with a temperature above absolute zero (about -273°C) radiate electromagnetic energy at various frequencies. On the other hand, bodies also tend to reflect the electromagnetic radiation that falls on them. A blackbody reflects less visible electromagnetic energy than a whiter body. In the case of coffee, its dark colour means that the light that impinges on it is not reflected in visible frequency, instead being absorbed and heating it; however, this effect is much smaller than the heat transfer described above.

In short: in the absence of heat sources or sinks, bodies exchange energy so that the hotter ones get colder, and the colder ones get hotter. The energy radiated by bodies can be in the form of heat or electromagnetic waves, among others. Bodies reflect part of the energy that falls on them and absorb the rest. These are the necessary notions to understand the second phenomenon.

2.1.2. Energy balance of planet Earth. One can think of the Earth, its atmosphere and the outer space that surrounds it as a thermodynamic system that exchanges energy between the different components. Outer space contains a particular body, the Sun, which is of fundamental importance. It is an enormously powerful energy source that floods the Earth and its atmosphere with electromagnetic radiation, with the consequent transfer of heat. The Sun's heat is a consequence of nuclear fusion reactions that constantly take place in its core, and in turn produce electromagnetic radiation in all directions. A part of this energy, in the form of visible light, ultraviolet radiation and infrared radiation, among others, reaches the Earth and its atmosphere, which will, as seen above, reflect part of this energy and absorb the rest. Figure 1 shows the magnitude of the Sun's radiation for the various wavelengths (or spectral radiance), normalised by its maximum value. Note that longer wavelengths of radiation correspond to lower frequencies. As one can see, the Sun's radiation is maximal at wavelengths visible to the human eye, and a significant part of the total energy that impinges on Earth (calculated by the gray area under the curve corresponding to the Sun) is visible light.

Of the absorbed energy, a part will heat the atmosphere, composed of clouds (water droplets), various gases (including GHG, oxygen and nitrogen) and aerosols, which are particles of different origins (pollution and volcanic eruptions, for example) in suspension in the atmosphere, and another part will heat the globe.

The ratio between the energy reflected by a body and the total energy that falls on it is called *albedo* and can be measured in natural units or as a percentage. The albedo varies with the frequency of radiation in question. Recent measurements

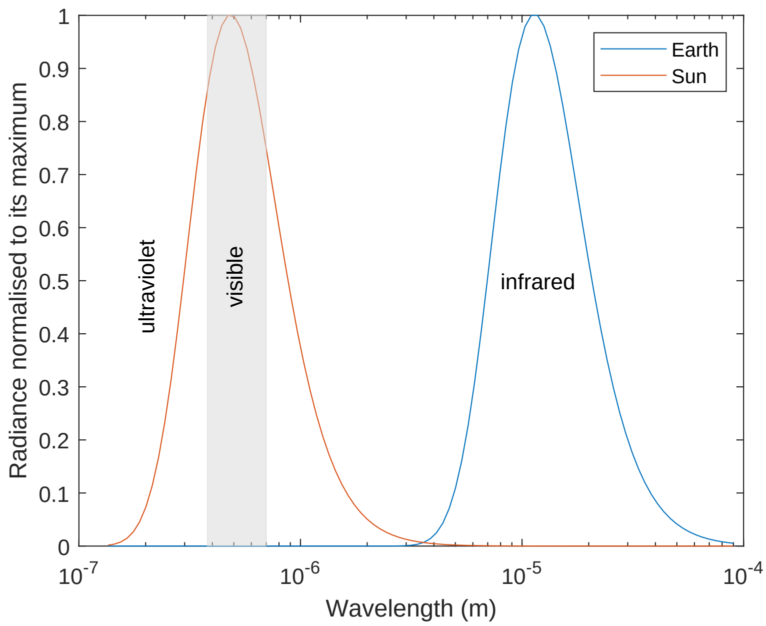

Figure 1: Spectral radiance of the Sun and Earth.

Source: authors' calculations.
Note: Planck's spectral radiance expressed in $\mathrm{watt\,m^{-3}\,str^{-1}}$ normalised to its maximum value.

suggest that the terrestrial albedo in the range of frequencies emitted by the Sun is close to 30%. This is an important notion in thermodynamics: an albedo close to 100% means that the object reflects almost all the light that falls on it. A dark object tends to absorb the light that falls on it, as we saw in the coffee example, and therefore it should have a low albedo.

If the solar energy that falls on the Earth is not compensated in some way, the Earth will heat up to become uninhabitable. On the contrary, we know that the Earth's temperature, despite having undergone very significant fluctuations over time, did not show a permanent upward trend. The explanation for the apparent impossibility is the electromagnetic radiation that all bodies emit mentioned above, sometimes referred to as "Planck's radiation". In other words, the Earth emits electromagnetic radiation because it has an average temperature on its surface higher (actually, much higher) than absolute zero, the same happening with the Earth's atmosphere. This radiation is mainly emitted at wavelengths above the visible range for humans and compensates the energy that reaches the system formed by the Earth and its atmosphere in order to maintain the temperature approximately constant. Figure 1 shows the intensity of this terrestrial radiation at various wavelengths. It is observed that the values are largest at wavelengths much higher than those of solar radiation and that there is practically no spectral overlap in the radiation of the two bodies. Note that, in the figure, the Earth's spectral radiance is normalised to its maximum value, which is about 7.2 million times smaller than that of the Sun.

The relatively stable atmospheric temperature that makes life as we know it possible on Earth is the balance between the energy that arrives from the Sun and that which the Earth-atmosphere system emits into space.

Table 1 presents a simplified summary of the energy exchanges between the Earth's surface, its atmosphere and space. The first line shows the flow of energy emitted by space – essentially the Sun – impacting the system formed by planet Earth and its atmosphere. It is a flow of energy per unit of time and per unit of exposure surface. This energy spans a wide frequency spectrum but is greatest in visible light, which is why it is often called *insolation*. Based on the Sun's temperature and its average distance from the Earth, it is possible to calculate its average value over a year, which is 341.3 watt/m^2. This is a useful reference and all values in Table 1 are expressed as a percentage of this value, even if they are not directly comparable to it.

<table>
<tr><th></th><th></th><th colspan="3">Energy destination</th><th>Total emitted</th></tr>
<tr><th>Source of energy</th><th>Type</th><th>Space</th><th>Atmosphere</th><th>Surface</th><th></th></tr>
<tr><td>Space</td><td>solar radiation</td><td>29.9</td><td>22.9</td><td>47.3</td><td>100.0</td></tr>
<tr><td>Atmosphere, GHG and other gases</td><td>long wave rad.</td><td>54.7</td><td></td><td rowspan="2">97.7</td><td rowspan="2">161.1</td></tr>
<tr><td>Atmosphere, clouds</td><td>long wave rad.</td><td>8.7</td><td></td></tr>
<tr><td>Surface</td><td>long wave rad.</td><td>6.4</td><td>109.7</td><td></td><td rowspan="3">144.7</td></tr>
<tr><td>Surface</td><td>evapotranspiration</td><td></td><td>23.5</td><td></td></tr>
<tr><td>Surface</td><td>thermal rad.</td><td></td><td>5,1</td><td></td></tr>
<tr><td>Total received</td><td></td><td>99.7</td><td>161.1</td><td>145.0</td><td></td></tr>
</table>

Table 1. Energy budget between the surface of the globe, the atmosphere and space. Values in percentage of the average solar radiation incident on the Earth-atmosphere system.

Sources: Trenberth and Fasullo (2012) and authors' calculations.
Notes: The average value of incident solar radiation on the Earth-atmosphere system is 341.3 watt/m^2. The partials may not add up the totals due to differences in rounding.

As can be seen in the table, about 29.9% of the solar radiation is reflected by the clouds and by the Earth's surface (3/4 and 1/4 of the total, respectively); this is the terrestrial albedo. The remaining 70.1% of the insolation is absorbed by the atmosphere (22.9%) and by the terrestrial globe (47.3%).

The atmosphere is an autonomous component of the Earth's climate system. The gases that compose it radiate energy, just like any other body, especially at wavelengths higher than those of visible light. Part of this radiation is lost in space: an amount of energy equivalent to 8.7% of the insolation value is emitted by water droplets in the atmosphere's clouds and 54.7% by GHG and other atmospheric gases. The remaining atmospheric radiation falls on the Earth's surface, in a value equivalent to 97.7% of the insolation value.

As for the Earth's surface, most of the emitted energy (116.1% of the insolation value) corresponds to the electromagnetic radiation inherent in any body and occurs at wavelengths higher than those of visible light. This radiation is absorbed by the atmosphere, with a small part (about 6.4% of the insolation value) escaping directly into space, the so-called "atmospheric window".

In addition to the electromagnetic radiation already seen, part of the energy exchange between the Earth and its atmosphere takes place through a phenomenon known as *evapotranspiration*. When a water surface is heated by the Sun or other heat sources, some of the water evaporates. In the case of plants, the loss of water due to sunlight is due to transpiration. These phenomena tend to warm the atmosphere and cool the surface. This heat exchange is worth about 23.5% of the insolation value. It should also be noted that volcanic activity, fires and other forms of heat transfer produce a warming of the atmosphere whose balance is 5.1% of the insolation value.

The relevance of atmospheric gases in the Earth's climate system is clearly evident in their gross energy emission, 161.1% of the insolation value, when compared to that of the Earth's surface, 144.7%.

However, there seems to be an imbalance in the table: the insolation (100% in the upper right corner) seems to be greater than the energy directed to outer space, which can be calculated by adding the values in the first column (99.7% of insolation value). This difference is not the result of rounding and, according to Trenberth and Fasullo (2012), its precise value is 0.9 watt/m^2, or 0.26% of the insolation value. This magnitude may be affected by some measurement errors, but it is a first indication of a possible imbalance leading to global warming.

2.1.3. The GHG in energy transfers between the Earth's surface, atmosphere, and outer space. As can be seen in Table 1 only a part of the energy emitted by the Earth's surface is released into space. This fact is of vital importance; the following describes why.

The energy emitted by the system formed by the Earth and its atmosphere occurs mainly in long wavelengths and can be modelled as a *blackbody*. A blackbody is an abstraction used in thermodynamics for a body that absorbs all the energy incident on it and, if in thermal equilibrium, radiates isotropically, that is, uniformly in all directions, and with spectral distribution determined by the body's temperature.

The total energy emitted by a blackbody at the temperature T (expressed in degrees Kelvin) is given by the expression [3]

$$R = \sigma T^4 \qquad \text{(watt/m}^2\text{)}$$

where σ is the Stefan-Boltzmann constant, with value 5.67×10^{-8} watt/(m^2 K^4). That is, the energy radiated by a blackbody varies with the fourth power of its temperature.[4] In Table 1 we have that the energy emitted by the Earth and its atmosphere that effectively reaches outer space is equal to the total energy radiated by this system minus the energy that is reflected to space from the Sun, which gives approximately 69.9% of the insolation value, that is, $R_e = 238.5$ watt/m^2. Applying the above formula, it is as if the Earth and its atmosphere behaved like a blackbody seen from space at a temperature of $T_e = 255°$K. This value, which roughly corresponds to -18°C, is considerably less than any estimate we have for the Earth's surface temperature. This estimate suggests that there is a significant amount of long-wave energy radiated by the Earth's surface that is trapped in the atmosphere, which constitutes evidence of the "greenhouse effect".

Table 1 shows that long-wave electromagnetic energy[5] emitted by the Earth is 116.1% of the insolation value, which corresponds to $R_s = 396$ watt/m^2. This value is very different from the radiation emitted by the Earth-atmosphere system to outer space. *Transmittivity* is the fraction of the energy emitted by the Earth that is not retained in the atmosphere. Denoting it by τ, it is easy to see that its mean value is $\tau = \frac{R_e}{R_s} = 0.6$. In other words, the greenhouse effect contributes to the retention of approximately 40% of the energy radiated by the planet due to GHG effects.

Another way of looking at the question is to compare T_e, the temperature of the Earth-atmosphere system as seen from space, and the temperature at the Earth's surface, T_s. This is easy to obtain using the above formula and making the simplifying assumptions above: $T_s \approx 289°$K, that is, about 16°C.

Both in terms of energy balance and in terms of temperature, there is a large difference between what happens on the Earth's surface and what is observed from outer space, and this effect originates, at least in part, in the atmosphere. It follows that any change in the composition of atmospheric gases, in particular in terms of GHG and their distribution, can have first-order effects. For this to happen, it is necessary to relate the concentration of these GHG and the potential for energy retention in the atmosphere.

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3. The temperature must be expressed in degrees Kelvin because in this scale the value zero corresponds to the absolute zero referred to above as the temperature such that bodies do not emit any energy; thus, 0°K corresponds to -273°C.

4. The previous expression is obtained from the spectral radiance shown in Figure 1, non-normalised, by integration in the wavelength and in the solid angle to the center measured in steradians.

5. Energy exchanges between Earth and atmosphere in the form of evapotranspiration and heat transfer are not relevant to the exchanges between the Earth and space.

The Earth will be in energy balance if the short-wave radiation incident on it – essentially in the form of sunlight – is equal to the long-wave radiation emitted by it. Let us designate by $T_{\bar{s}}$ the temperature at the surface corresponding to the energy balance. If R_S is the insolation, α the terrestrial albedo and τ the Earth's transmittivity,

$$(1-\alpha)R_S = \tau\sigma T_{\bar{s}}^4 \tag{1}$$

will have to hold. In other words, the temperature at the Earth's surface will have to be such that the solar energy incident on it, discounting the reflection effect, is equal to the energy radiated to outer space by the Earth, discounting the atmosphere's retention effect. Working these calculations out and assuming that the transmittivity does not change, we get $T_{\bar{s}} \approx 290$°K. What is the meaning of this value slightly higher than T_s? It is that the temperature of the Earth's surface will increase until reaching the situation in which the energy balance is restored. For these simple calculations, the value of this increase, relative to the situation shown in Table 1, would be around 1°K, but this value is underestimated for reasons explained below. The rate at which the adjustment takes place depends on many factors, but rudimentary calculations suggest a slow adjustment at the human scale, albeit fast at the geological scale (see Section 5 of Lesson 2 of Rose 2021).

The problem of determining what happens to the Earth's temperature depends on how the quantities shown in equation (1) are affected by the action of GHG and the changes induced by them. In other words, knowing the effect of GHG on the terrestrial albedo and the Earth's transmittivity, we will be able to calculate the equilibrium temperature at the surface of the planet. Unfortunately, these effects are difficult to estimate, and much more complex models than those we have just seen are needed. A likely effect is that transmittivity may decrease as the concentration of GHG increases, because GHG have energy absorption modes at the frequencies at which the Earth emits it. The smaller this parameter, the greater the atmosphere's capacity to absorb electromagnetic energy, increasing the greenhouse effect.

Beyond these, there are effects triggered by disturbances of the balance that must be taken into account, generically called positive or negative feedback. An example of positive feedback is increasing the amount of water vapour (a GHG) in the atmosphere: higher temperatures increase the atmosphere's ability to retain it. This would tend to increase the greenhouse effect and therefore it would be a positive feedback.

A possible negative feedback pathway will be in albedo. As the surface temperature increases, evapotranspiration also increases and it is believed that this will increase cloud cover. This would imply a lighter planet when viewed from space and therefore a higher albedo, which would tend to counteract global warming, although the net effect of cloud cover is not clear (see IPCC 2021). On the other hand, the reduction in the polar ice caps resulting from the increase in temperature would mechanically decrease the planet's albedo. The net effect of these albedo feedback mechanisms is likely to go in the positive direction (for an advanced discussion of this topic, see lessons 13 and 20 of Rose 2021).

Despite these qualifications, the simple characterisation of an energy balance is surprisingly rich. For example, we can assume that the greater the difference between $T_{\bar{s}}$ and T_s, the greater the speed of temperature adjustment. This change will allow us to characterise not only the equilibrium temperature (as we have already seen), but also the speed of convergence for it. Another improvement of the model will be to use a description of each layer of the atmosphere: so to speak, each region of the atmosphere would be characterised by albedo, transmittivity and temperature, depending on its composition in terms of GHG. A third level would be the incorporation of fluid dynamics models to describe meteorological phenomena. Then, explicit modelling of droplets in clouds would add a level of detail to the model. These sophisticated models are commonly known as global circulation models, or GCM, for *Global Circulation Models*. More recently, the integration of elements related to the biosphere itself, that is, the set of living beings, gave rise to the so-called ESM (from *Earth System Models*). In any case, the simplest model already allows us to see where the energy imbalances that lead to global warming come from.

2.2. The GHG as a dominant cause of climate change

A final important point has to do with the concentration of GHG in the atmosphere. The emission of some of these gases, including CO_2, made anywhere in the planet will affect their concentration in the *whole* atmosphere and not just in the regions close to the emission source. This fact makes the problem special from an economic point of view, meaning that we are facing an externality: the GHG emitter subjects all other economic agents to their effects without incurring the total costs of its own activity. It turns out that, with the exception of water vapour, GHG are almost residual components of the atmosphere. Table 2 shows that the most determining factor for the current energy imbalance, CO_2, constitutes only about 0.04% of the atmosphere. Other GHG such as ozone, nitrogen dioxide and methane are also a very small part of the atmosphere. The most abundant and, in many ways, the most important GHG is water vapour, that is, the gaseous phase of water dissolved in the atmosphere. The reason why it is not considered an important primary cause of global warming is that, for a given atmospheric temperature, an excess of water vapor quickly tends to produce precipitation, reducing its concentration.

GHG cause a greenhouse effect because their energy absorption modes occur at the wavelengths at which the Earth emits energy, acting as a transmission barrier to outer space. At wavelengths where the Sun emits energy, the GHG typically do not absorb it, with the exception of ozone, which absorbs ultraviolet rays and thus protects humans from their cancer-causing effects. Generally speaking there are three wavelength ranges in which the atmosphere is transparent to radiation: the visible zone (wavelength 0.3–0.9 μm), the so-called "atmospheric window" (wavelength 8–13 μm) and the microwave band (wavelength from 1 mm).

Gas	Chemical formula	Quant. in the atmosphere	Absorption wavelength
Nitrogen	N_2	78%	
Oxygen	O_2	21%	ultraviolet
Argon	Ar	$< 1\%$	
GHG			
Water vapour	H_2O	0.5%	infrared
Carbon dioxide	CO_2	400 ppm	infrared
Methane	CH_4	1.7 ppm	infrared
Ozone	O_3	0.5 ppm	ultraviolet, infrared
Nitrogen dioxide	NO_2	0.31ppm	infrared

Table 2. Atmospheric gases.

Source: Adapted from Marshall and Plumb (2008).

It is important to note that the presence of GHG in the atmosphere, although small, is relevant to its electromagnetic energy absorption characteristics. Water vapour, for example, generally constitutes a relatively small part of the atmosphere but determines a large part of its absorption zones for electromagnetic waves above the visible region. Below this, in the ultraviolet region, another residual gas, ozone, makes the atmosphere essentially opaque to electromagnetic radiation. In other words, small concentrations of some gases have very significant effects on the transmittivity of the atmosphere at certain wavelengths and therefore their concentration has an effect on the planet's overall energy balance.

The concentration of CO_2 has been rising consistently since the mid-19th century, going from 285 ppm in 1850 to 410 ppm in 2019 (Global Monitoring Laboratory 2020). The rate of increase between 2009 and 2018 was around 2.3 ppm/year (Friedlingstein *et al.* 2019). A large part of this increase is due to human action, with emphasis on the burning of fossil fuels to obtain energy, which transfers to the atmosphere the carbon accumulated in them by the action of plants over millions of years. The current process is very abrupt in that it returns the carbon sequestered over long periods in a few decades. Unfortunately, this carbon takes a long time to eventually dissolve in the oceans or be sequestered again by plant action and other processes. It is estimated that about half of human-induced carbon emissions since 1850 still remain in the atmosphere. This is why the problem does not resolve itself within a reasonable timescale. The following section presents some contours of this climate change.

2.3. The global evolution of temperature and precipitation

This section documents the evolution of terrestrial temperature and precipitation throughout the 20th century. These two measurements are frequently used by climatologists to characterise each type of climate, especially if they are observed monthly or daily. Other relevant measurements are the monthly minimum and maximum temperatures. This section documents some stylised facts about climate change for the land surface as a whole and for mainland Portugal.

2.3.1. Publicly available weather data. There are numerous publicly available climate databases. One example is the *Global Historical Climatology Network-Monthly* (GHCN-M), an effort to collect older data from various climate archives around the world. For a detailed characterisation of these data, see for example Lawrimore *et al.* (2011) and Fick and Hijmans (2017). These papers have the advantage of providing information about additional climate measures and regional differences. The data used in this work are provided by the University of Delaware, USA, and produced by Matsuura and Willmott (2018b,a). They include temperature and precipitation and cover the entire terrestrial surface of the planet with a resolution of half a degree of longitude by half a degree of latitude, with monthly frequency from 1900 to 2017. This resolution defines points that are distant from each other, in the latitude of Portugal, about 55.6 km north-south and 43.4 km east-west. The climatological data available in Matsuura and Willmott (2018b,a) imply that the Portuguese mainland has 40 points, and will be annualised for the purpose of this analysis.

These data are complemented by the daily E-OBS database (Haylock *et al.* 2008; Cornes *et al.* 2018). This is a database with finer geographic resolution and daily frequency for period 1950–2020, updated regularly. Like the previous one, it concerns the Earth's surface and covers the whole of Europe. In mainland Portugal there are 936 points.[6] This database has a high level of conformity with that of the University of Delaware as far as mainland Portugal is concerned, for the years when both are available.

With daily data it is possible to calculate energy consumption measures such as the annual need for heating and cooling of buildings inside the Portuguese territory. These data will be used for a spatial characterisation on the Portuguese mainland of the evolution of some climate measures.[7]

6. Another database, the Iberia01 (Herrera *et al.* 2019), has daily values for the 1971–2015 period with a resolution comparable to that of the E-OBS. The coverage of the Iberian Peninsula also appears to have fewer temporal and spatial errors than E-OBS, but its smaller temporal coverage has led us to using E-OBS.

7. Climate data in territorial grids are typically interpolations of meteorological station data adjusted for altitude and other factors. For this reason, they are affected by considerable margins of error in each individual observation, the greater the further the grid point is from the nearest meteorological station and especially in the case of precipitation. In any case, this does not mean that the results obtained cannot be accepted with confidence. Nickl *et al.* (2010), Fick and Hijmans (2017), Cornes *et al.* (2018) and Herrera *et al.* (2019) provide detailed discussions of this issue.

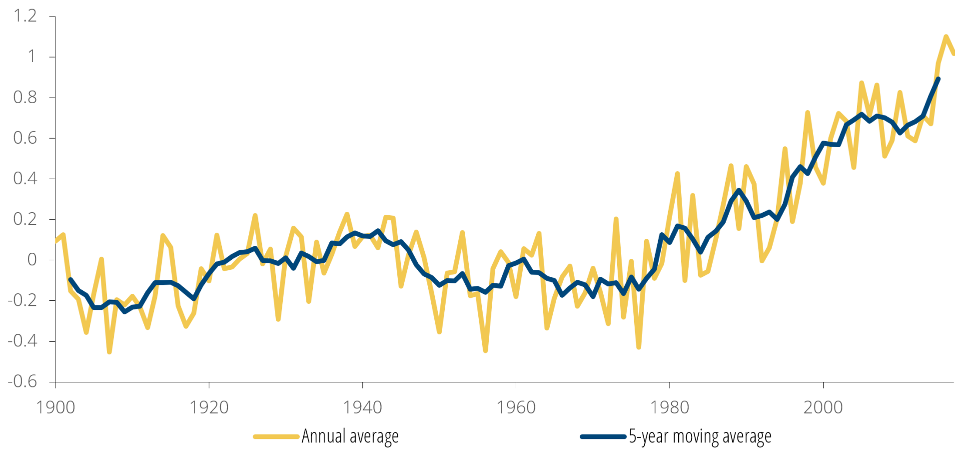


Figure 2: Anomaly of the mean annual temperature on the Earth's surface for the period 1900–2017 relative to the 20th century average, in °C.

Sources: Matsuura and Willmott (2018a) and authors' calculations.
Notes: Annual average temperature is defined as the year-round average of the monthly average temperature. Values are weighted by the respective geographic cell area, and expressed as the difference from the 1900–1999 period mean.

2.3.2. Changes in temperature and precipitation on the terrestrial surface. Figure 2 shows the evolution of temperature on the Earth's surface over the period 1900–2017, expressed as the anomaly relative to the 20th century mean.[8] During this period of more than a century, the terrestrial world temperature increased by about 1°C. This increase is concentrated in the second half of the last century, especially from the 1970s onwards. During the period 1950–2017 the rate of warming of the Earth's surface, estimated using a linear regression, was 0.017°C per year. The reasons for this increase are obviously subject to discussion, but there is a causal mechanism, described above, that may have contributed to this evolution. According to IPCC (2021), this increase will have been in the range 0.8–1.3°C by the late 2010s, and it is "extremely likely" that GHG emissions associated with human activity are the dominant cause of the temperature increase observed in Figure 2.

Figure 3 provides a spatial view of this temperature increase. It is very evident that almost the majority of the Earth's surface warmed during the 68 years of this analysis. This increase is statistically significant for 82% of the land surface (at a significance level of 5%), and contrasts with 2.8% of the land area with a drop in average temperature.

8. See in Appendix A a brief characterisation of the variables under study in the terrestrial Earth's surface and in the Portuguese mainland from the second half of the 20th century on.

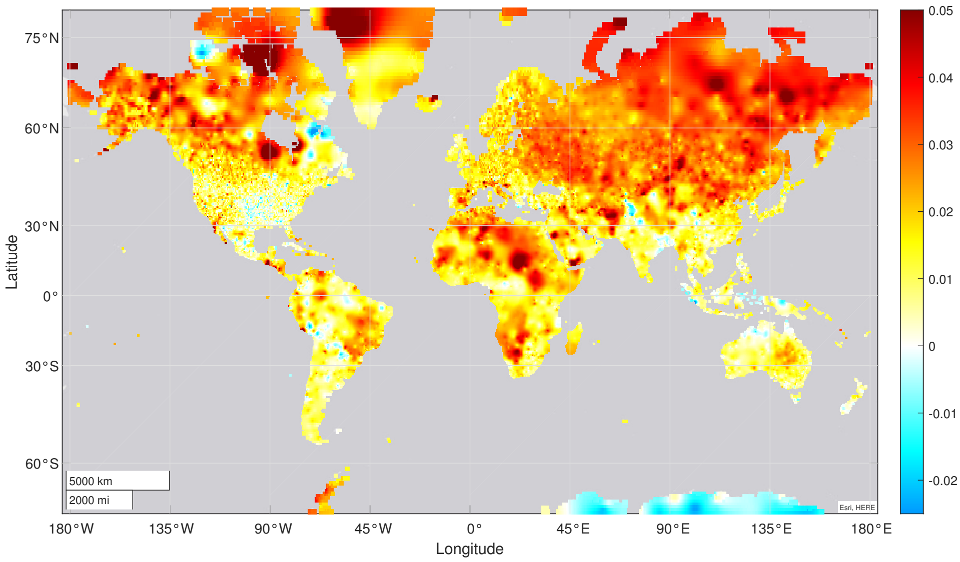


Figure 3: Average annual temperature variation on the Earth's surface for the period 1950–2017. Values in °C per year.

Sources: Matsuura and Willmott (2018a) and authors' calculations.
Notes: The values shown correspond to the slope for each geographic location of the regression lines of the mean annual temperature in the temporal variable (year). The regression is specified with location fixed effects, and with these interacted with the temporal variable. The annual average temperature is defined as the year-round average of the daily average temperature. Values higher than 0.05°C were truncated.

These results are consistent with the finding that warming is sufficiently strong and evenly distributed to be statistically significant over large regions. This fact suggests that the cause must be systemic, that is, it is not related to local factors such as increased urbanisation, increased population concentration or regional energy consumption; rather, it should be explained by the remarkable speed of homogenisation of some GHG in the lower layers of the atmosphere.

Regarding precipitation, the results are less pronounced, as global warming tends, in the aggregate, to contribute to an increase in rainfall (IPCC 2021, p. SPM-6). Figure 4 shows the mean global terrestrial precipitation in the period under study. An abrupt drop in rainfall is noted during the second half of the 1970s and the first half of the 1980s. Nickl *et al.* (2010) present a discussion of this fall in terrestrial rainfall, which was mainly centred on North America, the Indian subcontinent, and in South Asia. However, global terrestrial precipitation has been increasing since 1985 at an average rate of 0.87 mm per year, having recorded during the 2010s values comparable to those of the beginning of the last century.

Figure 5 provides a spatial view of precipitation in the period 1950–2017. Unlike temperature, precipitation has a very different behaviour across regions,

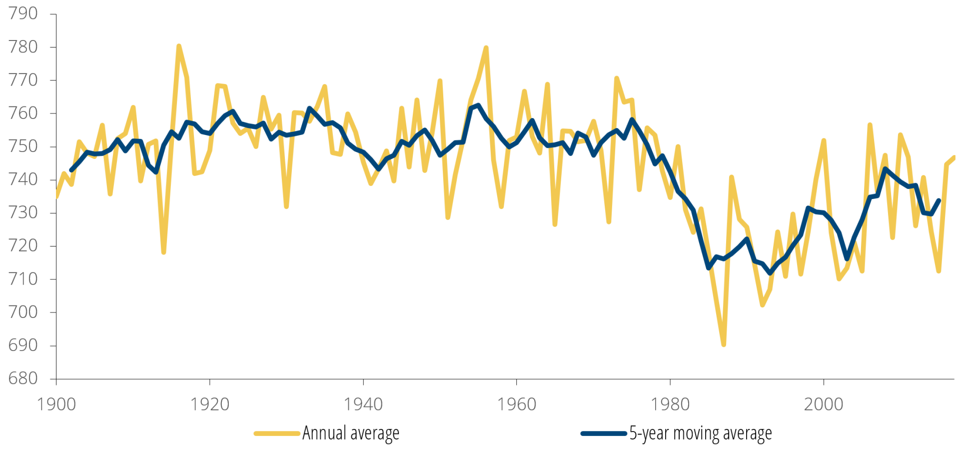


Figure 4: Average annual precipitation on the Earth's surface for the period 1900–2017, in mm.

Sources: Matsuura and Willmott (2018a) and authors' calculations.
Notes: Average annual precipitation is defined as the temporal average of the accumulated precipitation throughout the year.

with increases in some and falls in others. The African continent had a reduction in rainfall, as did parts of Southeast Asia, southern Europe and the Middle East. Increases have been seen in the temperate zones of Europe, North and South America, as well as in vast regions north of the Indian subcontinent. In about 13% of the Earth's surface there was a statistically significant increase in precipitation at a significance level of 5%, which contrasts with about 26% of the Earth's surface with a statistically significant reduction in precipitation. However, precipitation over the oceans is not accounted for here, so the calculation of the total figure is difficult. The IPCC (2021, page SPM-6) report indicates that global warming is likely to have caused a global increase in average annual precipitation.

The changes documented above have broad economic implications, both globally and locally. They also hide a high variability within different territories. The Portuguese case is explored in the next section.

2.3.3. The heterogeneous evolution of temperature and precipitation in Portugal. It is beyond the scope of this work to propose an extensive characterisation of the Portuguese climate. Interested readers may consult Fragoso (2008); de Lima *et al.* (2013); see also Appendix A. We will only characterise the evolution over time of two fundamental variables of any climate system: the average annual temperature and the total annual precipitation.

Using the data from the University of Delaware of the previous section on the grid points corresponding to the Portuguese mainland, the temperature evolution of Figure 6 is obtained. The results are more muted than for the entire terrestrial

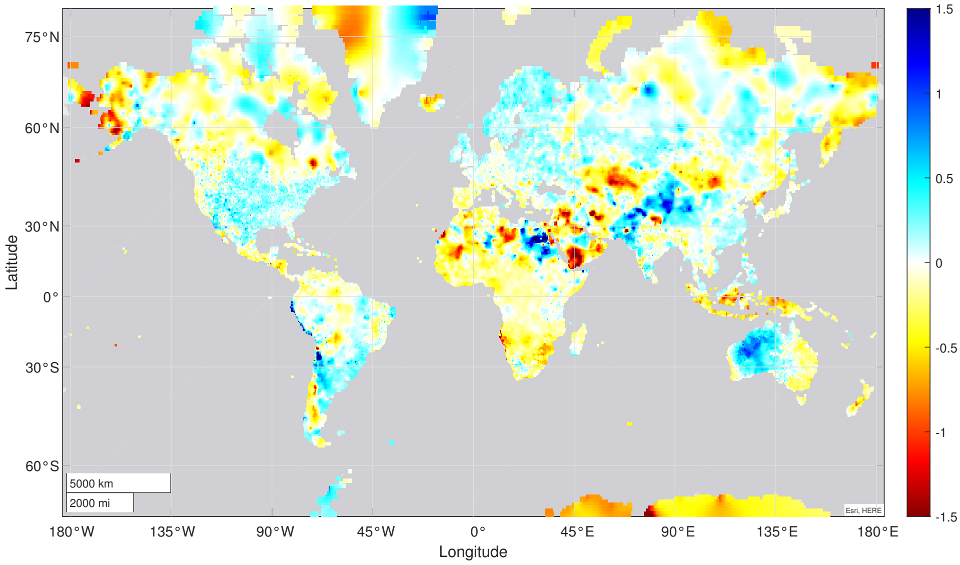


Figure 5: Average percentage change in total annual precipitation on the Earth's surface for the period 1950–2017. Values in yearly percentage.

Sources: Matsuura and Willmott (2018a) and authors' calculations.
Notes: The values shown correspond to the slope for each geographic location of the regression lines of the logarithm of the total annual precipitation, measured in mm, in the temporal variable (year), multiplied by 100. The regression is specified with location fixed effects, and with these interacted with the temporal variable. Total annual precipitation is defined as the sum over the year of the total monthly precipitation. Values truncated to the range $[-0.015; 0.015]$.

surface of the planet, with an increase over the period 1900–2017 of 0.6°C. The temperature increase from 1950 onwards was 0.0077°C per year. Due to the small size of the territory and its proximity to the ocean, the average annual temperature has a more volatile behaviour for Portugal than for the entire terrestrial surface: the temporal standard deviation is around 0.48°C for Portugal, which contrasts with 0.34°C for the entire Earth's surface.

The Portuguese case with regard to precipitation can be seen in Figure 7 and is again more benign than for the entire Earth's surface. In statistical terms the total rainfall did not show a trend in the period 1900–2017. There are no abrupt and persistent drops like the one seen for the whole of the Earth's surface from the late 1970s onwards and which lasted a decade. Annual rainfall variability is extremely high, with a standard deviation of 193 mm around an average of 849 mm. This value contrasts sharply with the standard deviation applicable to the entire Earth's surface, with a value of 18 mm. It should be noted, however, that the number of rainfall stations in Portugal used in this database has been reduced over the years, especially from 2009 on (for documentation of the problem, see Matsuura and Willmott 2018b; Herrera *et al.* 2019).

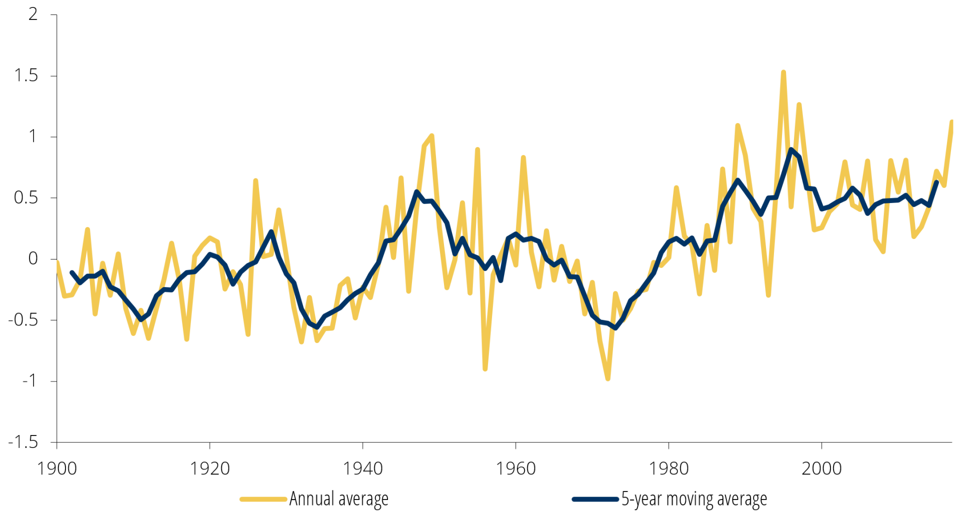


Figure 6: Anomaly of the average annual temperature in mainland Portugal for the period 1900–2017 relative to the average of the 20th century, in °C.

Sources: Matsuura and Willmott (2018a) and authors' calculations.
Notes: The annual average temperature is defined as the average over the year of the monthly average temperature on the grid points included in mainland Portugal. Values are weighted by the respective geographic cell area, and expressed as the difference from the 1900–1999 period mean.

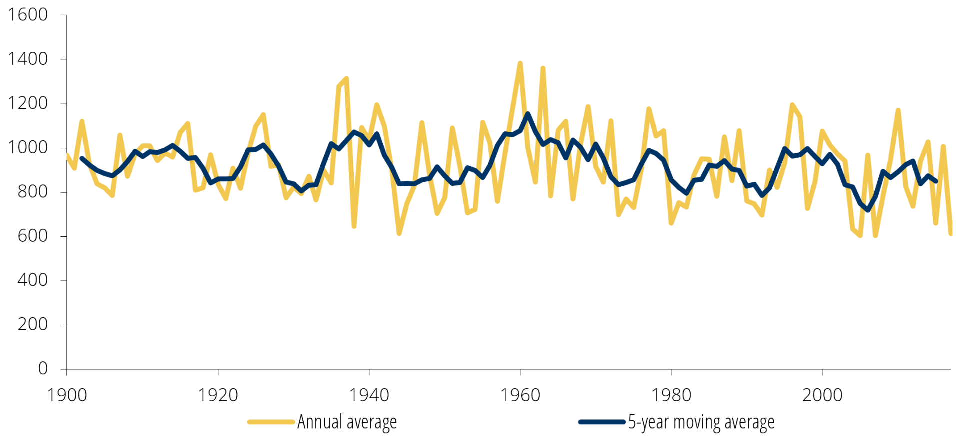


Figure 7: Average annual precipitation in mainland Portugal for the period 1900–2017, in mm.

Sources: Matsuura and Willmott (2018a) and authors' calculations.
Notes: Average annual precipitation is defined as the average for all geographic units of the accumulated precipitation value over the year. Values are weighted by the respective geographic cell area.

This panorama hides great spatial variability within the Portuguese territory. Panel (a) of Figure 8 represents the mean annual temperature variation over the period 1950–2020 for each of the cells defined in the E-OBS database. The increase appears to be greater in the northeast of the country and in the Algarve. In these regions, the estimated warming rate sometimes reaches values higher than 0.04°C for each elapsed year, which means that after ten years the estimated warming is 0.4°C. The figure shows that during this period there were no regions in mainland Portugal with reductions in average temperature. It is clear that these are estimates, and there is no guarantee that they will remain valid in the future, but these figures show that some regions may be much more affected by climate change than others, even if the general trend is towards warming. Furthermore, the estimated linear trends are sensitive to changes in the period under study and the use of alternative databases.

As for precipitation, the northern interior is a pocket of significant reduction in the 1950–2020 period, as seen in the right panel of Figure 8. Although in this region the starting point is high rainfall, there was a reduction of more than 1% per year, a value that corresponds to an annual drop of about 15 mm in total rainfall. In contrast, the entire coast and the south of the country were largely resistant to reduced rainfall. Using these data, the total precipitation of the whole continental territory showed a statistically significant decreasing trend of 0.3% per year. This value, however, is low and can be contrasted with a statistically null value obtained from the University of Delaware database for the period 1900–2017, as previously mentioned. It should be noted that rainfall has great variability from one year to the other and tends to generate more uniform extreme events in the national territory than the annual rainfall averages. For example, the south of Portugal has daily rainfall with a 50-year return (that is, it is expected to occur once every 50 years) similar to those in the north of the country, even though the annual rainfall is much lower, as documented by Fragoso (2008) and Herrera *et al.* (2019). In other words, the most extreme precipitation phenomena are more evenly distributed across the Portuguese mainland than the annual average.

Climate change is not limited to changes of magnitude such as average temperature or total precipitation. As important as the amount of precipitation that falls during a year is its distribution throughout the year and the prevailing temperature conditions. For example, Páscoa *et al.* (2021) document a pattern of longer but less intense droughts in the Iberian Peninsula in the period 1971–2015. This results not only from the tendency that we also find here for a decrease in precipitation in some locations, but from the greater intensity of evapotranspiration resulting from the secular increase in temperature. This is an additional level of analysis which is relevant to the economic impact of climate change but which falls outside the scope of this paper.

2.3.4. Measures of energy needs in Portugal. The pattern observed above clearly illustrates that climate change has very heterogeneous impacts on the territory, and consequently on the economic activities of each location. This conclusion can

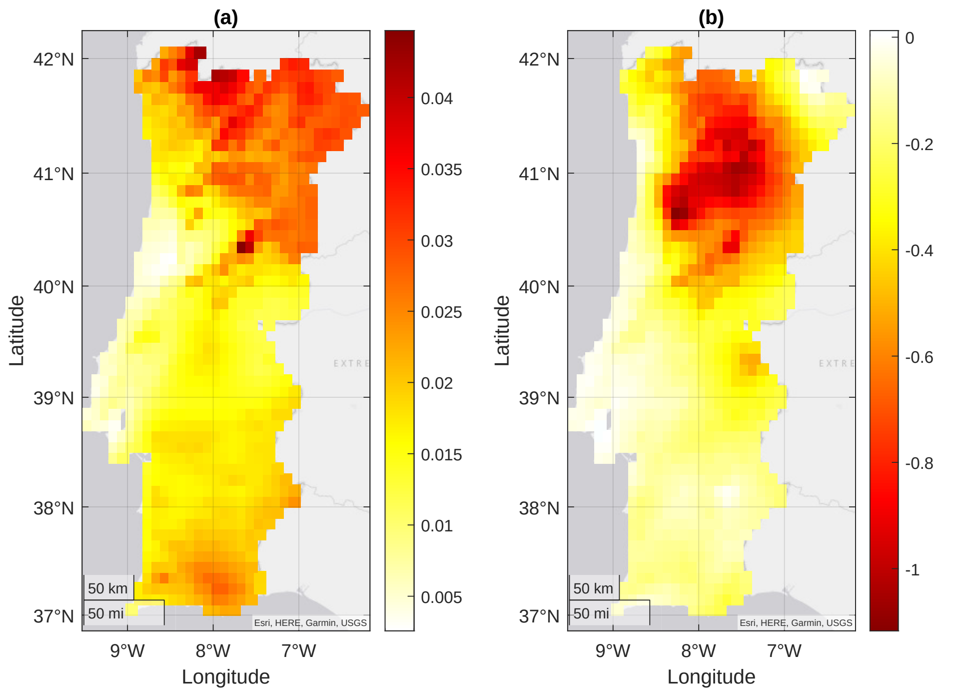


Figure 8: Average annual variation of temperature and precipitation in mainland Portugal for the period 1950–2020. Panel (a): mean annual change in mean temperature, in °C per year. Panel (b): average percentage change in total annual precipitation, in annual percentage.

Sources: E-OBS and authors' calculations.
Notes: The values shown correspond to the slope for each geographic location of the regression lines of the dependent variable (annual mean temperature or natural logarithm of total annual precipitation multiplied by 100) in the temporal variable (year). The regression is specified with location fixed effects, and with these interacted with the temporal variable. Annual average temperature is defined as the year-round average of the daily average temperature. The total annual precipitation is defined as the value accumulated over the year of the daily precipitation.

be extrapolated to the entire Earth's surface. One of the most obvious aspects of this temperature change has to do with the energy consumption for heating and cooling buildings. Although it is difficult to calculate precise measures for this consumption, it is possible to have an idea of this using standardised indicators published by official bodies. Two of the most used are the heating and cooling degree days in a particular country or region. Intuitively, they give us a measure of the heating or cooling needs of buildings to keep them at a comfortable temperature throughout the year. For example, each additional heating degree day means ones need to raise the temperature by one degree Celsius for one day, or half a degree Celsius for two days, and so on. The energy expenditure associated with these needs obviously varies with the characteristics of the buildings. If the thermal insulation of buildings improves over time, the energy required for the same level of heating or cooling in a building will be lower. This is an important margin for reducing energy needs that these measures do not capture.

With the available daily data, it is possible to compute these indicators and their evolution since 1950. Figure 9 shows the estimated variation in heating and cooling degree days over the period 1950–2020. A general increase in temperature will tend to reduce heating requirements and increase cooling requirements. Heating requirements have been reduced during this period by 3.7 degree days per year, which is equivalent to no longer being necessary to raise the temperature of buildings by one degree Celsius for three days and 19 hours, each year. This evolution implies energy savings but hides a great variability in Portuguese territory. It is especially in the north that it has become less necessary to heat buildings, with an annual reduction in some cases in excess of 10 degree days, that is, the equivalent of no longer being necessary, for each year that passes, to raise the temperature of the buildings by one degree Celsius for ten days.

The right panel of the same figure shows the annual variation in cooling requirements over the same period. There, it appears that the entire interior of the country began to show a greater need for cooling buildings, which represents an increase in energy expenditure. The average value for the total continental territory was 1.6 degree days per year.

These results are intended to document secular trends that may or may not extend into the future. That type of research should be sought in the specialised literature, particularly that using climate projection models such as those mentioned above.

2.4. Some ideas to retain

The main ideas to remember from this section are few and simple. First, there is a well-known causal mechanism associated with human activity and the resulting GHG emissions that, due to the particular thermodynamics of the Earth-atmosphere system, can lead to a progressive warming of the atmosphere.

Second, while there have always been changes to Earth's climate systems, these are now measurable and verifiable on a much shorter time scale than in the past.

Third, throughout the 20th century and up until now, there have been material changes in important climatological variables, such as the average temperature and total annual precipitation. These changes are in the direction of a secular increase in the temperature of the Earth's surface.

Finally, changes in the most important climatic variables are spatially very heterogeneous even within relatively small geographic units such as mainland Portugal, and will produce economic consequences that are very difficult to assess.

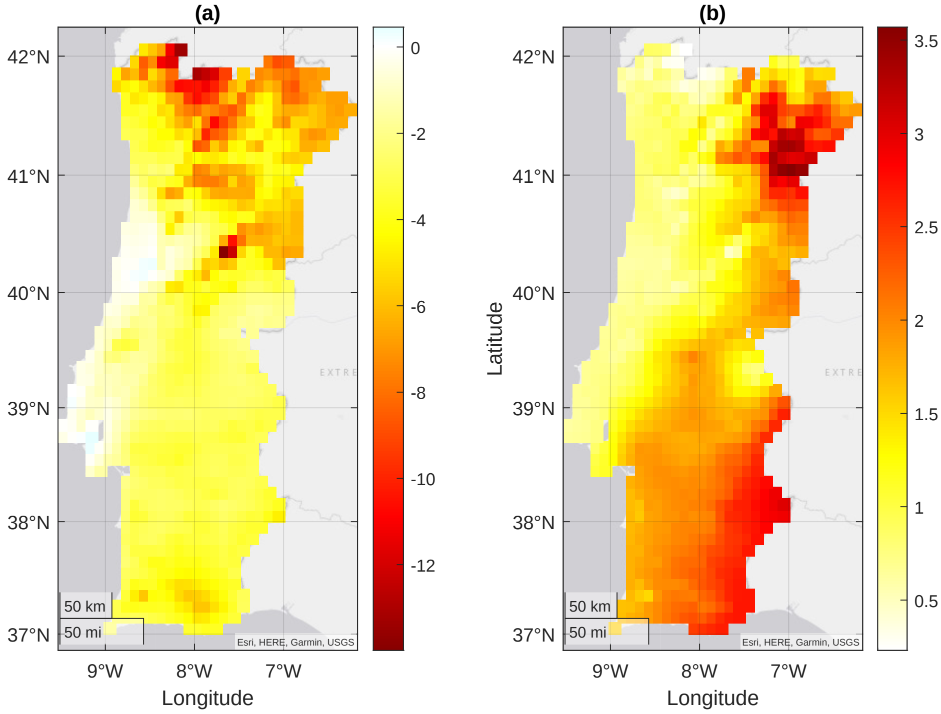


Figure 9: Average annual variation of heating and cooling degree days in mainland Portugal for the period 1950–2020. Panel (a): average annual heating change, in °C-days. Panel (b): mean annual cooling change, in °C-days.

Sources: E-OBS and authors' calculations.
Notes: The indicated values correspond to the slope for each geographic location of the regression lines of the dependent variable (heating degree days or cooling degree days) in the temporal variable (year). The regression is specified with location fixed effects, and with these interacted with the temporal variable. For each year, the heating degree days are defined as $\sum_{\{t \in A: T_t^m \leq 15°\text{C}\}}(18°\text{C} - T_t^m)$, where T_t^m is the average temperature in degrees Celsius on day t of year A. The cooling degree days are defined as $\sum_{\{t \in A: T_t^m \geq 24°\text{C}\}}(T_t^m - 21°\text{C})$.

3. Climate change from an economic perspective

This section consists of three blocks. The first documents the existing economic literature on this topic, with an emphasis on the impacts in terms of GDP of the adoption of appropriate policies to mitigate the effects of excessive carbon dioxide emissions. The second block analyses the practical problem of knowing which discount factor to apply in the analysis of mitigation policies. The third block discusses the various economic policy options recommended for this type of problem.

3.1. Economic impacts of climate change

The global nature of the phenomenon of climate change, combined with its repercussions over a long horizon, enhances the study of its implications in various domains of the economy: international trade, economic growth and development, reorganisation of production and allocation of productive factors, among others. Understanding its consequences has become imperative to inform policy responses, as impacts interact with diverse systems: physical, biological or human (IPCC 2014). This is particularly relevant for decision makers responsible for climate change policy formulation or institutions involved in macroeconomic modelling and forecasting.

A widely accepted view of the phenomenon is that the quantification of economic impacts resulting from climate change is subject to high uncertainty. On the one hand, it is a phenomenon with no historical precedent, with persistent and differentiated effects at the level of geographies (Hsiang *et al.* 2017) or sectors. On the other hand, defining a horizon for policy evaluation tends to be discretionary. The study of these impacts often relies on model estimates based on questionable hypotheses that may ignore potentially non-linear effects, thus underestimating the associated risks. One of the predominant factors in the results refers to the choice of the discount rate (Nordhaus 2007, provides a critical view). Weitzman (2009) recognises that the probability of occurrence of extreme events is not negligible and that the existence of heavy tails in the distribution of effects must be considered in cost-benefit analyses.

The literature distinguishes between two types of effects resulting from climate change: direct and indirect. The direct effects of climate change on the economy mainly refer to distortions in the normal functioning of the natural climate system that induce, for example, a rise in the level of the Earth's temperature, an increase in the average sea level or a higher frequency of extreme events such as floods, droughts or storms. The frequency of these events tends to gradually increase over time as the global average temperature rises. In turn, indirect effects result mainly from adaptation to new climate conditions and efforts to mitigate the consequences of climate change, through the transition to a low-carbon economy.

The diversity of the effects of climate change makes it difficult to effectively assess its impact on the economy. For example, the existence of agricultural crops affected by drought events or their increased growth due to an environment with more carbon dioxide makes the impact of climate change difficult to understand. Thus, some authors have proposed two aggregate indicators:

- Impact of climate change on total well-being;
- Distribution of these impacts.

Tol (2018) reviews the existing estimates in the literature of the impact of climate change for different temperature increases (Table 3), as well as the distribution of these impacts in the world. Simultaneously, the author recognises that the literature does not incorporate some important elements (such as the non-linearity of effects or currently unknown phenomena) and that the uncertainty surrounding the estimates alone motivates the reduction of GHG emissions.

Incr. mean global surf. temp. (°C)	**Number of estimates**	**Percent impact on GDP level (%)**	
		Avg. of estimates	**Estimates range**
≤ 2	4	0.3	-0.5 to 2.3
2.5	11	-1.3	-3.0 to 0.1
2.9	2	-2	-2.1 to -2
3	6	-1.7	-3.6 to -0.9
3.2	1	-5.1	-5.1
5.4	1	-6.1	-6.1
6	1	-6.7	-6.7

Table 3. Impact of climate change in world GDP.

Source: Adapted from Tol (2018).
Note: Percent impact in GDP level in 2100 relative to a scenario without climate change.

In the short term, sectors such as agriculture could benefit from the effects of climate change. However, in the long term the negative impacts are likely to far outweigh the positive ones. The most severe impacts felt in developing countries are mainly attributed to the existing poverty level. On the one hand, the exposure of these countries to climate conditions is greater due to the preponderant role of agriculture and water resources in the economy. On the other hand, these countries are located in warmer places, making ecosystems closer to the limits compatible with human habitability. The adaptive capacity of these countries tends to be more limited due to the prevailing low levels of technology, per capita income and degree of openness of the economies (Noy 2009).

It should be noted that, in a stress test context, the estimates are higher than those presented in Table 3. A recently published report (Swiss Re Institute 2021) considers not only known channels of the climate impact on the economy, but also unknown or not yet quantified channels. The methodology used is based on models developed by Moody's (2019) and applies a factor of one order of magnitude to the cumulative economic effects due to temperature increase. The costs of a carbon emissions trajectory comparable to the scenario[9] SSP2-4.5 of IPCC (2021) against a world with no increase in temperature could be in the order of 13.9% in 2050, corresponding to a temperature increase of 2.6°C. This impact would be felt mainly on Southeast Asian countries, such as Malaysia, the Philippines and Singapore, with drops of around 35%. Africa would also be very affected. In Europe the drops would be 8%. These values should be interpreted as possible, though not likely, effects and show how harmful climate change could be to the economy. However, this type

9. The base scenario is the RCP4.5 of IPCC (2014).

of approach also tends to ignore positive technological developments in tackling this problem.

3.2. Interaction mechanisms between climate and the macroeconomy

In the analysis of the impacts of climate change on the economy, it has been recurrent the assessment of each sector individually with subsequent aggregation, in order to obtain estimates of the aggregate impact on the economy in terms of social well-being. However, the interconnections of different sectors can be relevant to capture indirect effects. Changes in heating or cooling requirements can affect the price of energy, which will have repercussions for all sectors that use energy as an input. Fankhauser and Tol (2005) analyse the dynamic effects through which climate change affects economic growth and, therefore, social well-being, focusing on the mechanisms that affect savings and capital accumulation.

Despite the high uncertainty surrounding the quantification of the economic impacts of climate change, several transmission channels have been identified in the literature, with repercussions on both the demand and supply sides. In the following part, some of these mechanisms are highlighted and, whenever possible, the existing quantifications in the literature are documented. This excludes several areas potentially affected and difficult to quantify, such as the tourism sector, where it is expected that certain tourist destinations will become more or less appealing, depending on local climate changes.

3.2.1. Price and income volatility. The occurrence of extreme events can be understood as a negative shock on the supply side, with repercussions on the general price level of economies. Parker (2018) shows that extreme events such as storms and floods can cause inflation to rise in developing countries in the short term, while events such as droughts can persistently exert upward pressures on prices. Distortion in the relative prices of food or raw materials can largely affect the general price level in economies more exposed to the primary sector. An important transmission route is energy, insofar as companies that enter industries that are intensive in its use will be more vulnerable to price fluctuations. It is therefore relevant to assess the interconnections of sectors that use energy as an input in production processes.

The effect of increasing temperature on income volatility has also been documented. Deryugina and Hsiang (2014) study the impact of daily temperature variations over a 40-year period for US counties, documenting a negative effect of temperature on productivity and income above a certain threshold.

3.2.2. International trade flows. The impact of extreme events on international trade is well documented in the literature. Using a gravity model (170 countries), Gassebner *et al.* (2010) estimate a 0.2% reduction in imports (0.1% in the case of exports) as a result of a significant catastrophe and that the levels of democracy are preponderant factors for the order of magnitude of these impacts. The results of Oh and Reuveny (2010) also point to a reduction in international trade as a result of natural disasters. The severity of the effects will depend on the degree of integration of the economies in global value chains. Even economies less exposed to extreme events can be heavily dependent on external markets and are therefore affected by developments in trading partners across global value chains. This could induce a relocation of companies to less affected areas, translating into a transfer of capital stock, employment and production between countries.

3.2.3. Reduction of capital stock. The destruction of infrastructure, transport, energy and water supply networks can strongly reduce the economy's capital stock, translating into losses in the productivity of labor and the attractiveness of productive investment. For example, Fankhauser and Tol (2005) document that the frequency of extreme events affects the lifetime of physical capital, given the greater speed of depreciation of assets, thus reducing the efficiency levels of current technologies. Thus, there will be an allocation of resources from productive investment for adaptation, which may stimulate investments to replace capital stocks in the short term. For example, the transition to a low-carbon economy can lead to changes in the energy efficiency of buildings or investments in infrastructure to mitigate sea level rise.

The consequences for the insurance industry must not be overlooked. The increased frequency of extreme events can lead to certain types of risks becoming too expensive to be insured; an example is the existence of dwellings in areas vulnerable to flooding. Exposure to high or uninsurable risks in the market can lead companies and families to increase their precautionary savings.

3.2.4. Obsolescence of assets. The transition to a low-carbon economy enhances the disruption of some existing technologies, causing some assets in certain industries to become stranded, with direct consequences for employment. The level of losses generated will depend on the degree of exposure of countries to this type of assets or on the rate of adoption of alternative technologies. For example, countries with a high number of thermoelectric power plants or with carbon-intensive technologies will tend to be more affected, so an abrupt transition could cause significant losses in the value of assets, inducing substantial losses for the financial system in general. Cavalcanti *et al.* (2021) offer an estimate of the long-term costs resulting from the energy transition, concluding that they will be higher for specialised workers in sectors with more intensive use of energy-polluting technologies, and consequently for countries with greater relevance in these sectors.

3.2.5. Migrations. Labor factor mobility may intensify as a result of climate change (Rigaud *et al.* 2018). This phenomenon influences migration decisions through the usual determinants, in particular economic factors (e.g. through falling wages in rural areas or rising prices of agricultural goods), environmental and, to a large extent, political. Cattaneo and Peri (2016) conclude that the increase in temperature and the occurrence of natural disasters encourage migration in developing countries, with the exception of those with lower levels of income, where populations are unable to relocate. Behavioural factors, such as the perception of families' vulnerability to emerging risks of climate change, should also weigh on the decision to migrate.

3.2.6. Other factors. Note that climate change can cause losses that go beyond the impact on GDP. There are factors such as health risks, loss of environmental quality or disruptions in communities forced to relocate that are not captured directly when measuring this aggregate. This leads to efforts to complement GDP with satellite accounts that measure environmental and social variables that affect well-being. This will perhaps be a necessary methodological development in the next few years, along with more well-known topics such as the one discussed in the next section.

3.3. Intertemporal discounting

From an economic perspective, the assessment of the welfare of an economic agent is based on considering its current utility and discounting all its future utility for the current moment. The utility at each moment can be measured in different ways, usually related to consumption or income and the amount of leisure enjoyed in each period of time. Regardless of the measure, it has to be discounted for the present moment. Its use is implicit, for example, in the estimates in Table 3, since different discount rates will correspond to different decision-making rules of economic agents and, thus, different levels of GDP over the horizon at stake. This section addresses this theme and proposes values to be used in assessing the very long-term impacts of policies, not necessarily related to climate change.

3.3.1. Theoretical framework and international practice. The idea that future costs or benefits have less relevance than identical values today is a fundamental principle in economics. Typically, this principle is implemented by discounting a future value by multiplying it by a factor less than unity. The value today, V_0, of a flow V_t, to be generated in t years from now, is given by

$$V_0 = V_t \left(\frac{1}{1+\rho} \right)^t$$

where ρ is the discount rate. This section addresses the two main methodological guidelines that have been followed to define discount rates, as well as the choice of discount rates for the purposes of analysing public policies in various countries. In conclusion, a reference value for the discount rate to be used in economic assessments of climate change is proposed.

Climate change takes place over very long horizons, at least tens of years. This means that it is within this long time horizon that any economic assessment of the effects of climate change, as well as the costs and benefits of public policies aimed at mitigating its impact, should be framed. As the costs generated by such changes are projected into the future, and as the costs and benefits of public policies will tend to occur at different times, it is necessary to establish how economic values will be evaluated over time, that is, how future values will be discounted.

The choice of the discount rate in advance is a crucial requirement of any economic assessment and can become a sensitive issue. A high discount rate reduces the current value of future flows, minimising their relevance. A low value results in opposite consequences. For example, the Stern *et al.* (2006) report was heavily criticised for having used an annual discount rate of 0.1%, a value considered to be excessively low and therefore inflated the discounted values of future costs associated with climate change .

In the Portuguese case, the problem of choosing the discount rate is further affected by the lack a legal framework or an established tradition to define the discount rate to be used in the analysis of public policies. In the case of other countries, the choices are clearer and more explicit, as there are officially defined reference rates.

For the US, the official reference discount rates are defined by the *Office of Management and Budget* (OMB), and the values currently used were established in 2003.[10] The methodology adopted in the case of the US is based on the concept of opportunity costs and on a positive approach (as opposed to a normative approach, to be mentioned below), using empirical estimates of the relevant parameters. OMB recommends using two rates, 3% and 7%, which should be constant over the horizon of analysis. The first rate corresponds to the historical average, estimated in 2003, of the real value of the yield on 10-year government debt securities. This value is interpreted as an estimate of the pure intertemporal discount rate, that is, of society's preferences. To the extent that public policies have an impact on the future consumption trajectory of households,[11] the rate of 3% was seen to be an estimate of the opportunity cost of these changes in consumption. On the other hand, the rate of 7% was, at the time, the historical average of the gross rate of return on private investments and, to that extent, the estimated value for the opportunity cost of capital. Since public policies change the values of private investment, the rate of 7% corresponds to the relevant opportunity cost. The difference between the two values is justified, among other reasons, by the existence of taxes and risk premia. The rationale adopted by the OMB is that the reference discount rate for the analysis of a specific public policy should be a weighted average of the two mentioned rates, with the weights being determined by the proportion of public policy funding arising from reductions in consumption and the proportion from reductions in private investment.

A critical perspective of the rules followed in the US necessarily implies two distinct themes. The first is the validity of the estimated rates in 2003, in a world in

10. OMB Circular A-4, of 17 of 17 September 2003.

11. For example by using policies to encourage savings and their use to finance public projects, or by policies reducing consumption through tax increases and reduced disposable income.

which current real yields on public debt securities are much lower, even negative in several countries, and with little prospect of such a situation changing significantly in the short and medium term (Council of Economic Advisors 2017). The other theme is methodological and ethical in nature. Assessing the consequences of climate change and the policies that face it requires very long horizons and consideration of costs and benefits for future generations. A positive approach such as that adopted by the OMB may be suitable for typical horizons in private capital markets, for example ten years, but fails on substantially longer horizons, as future generations do not participate in contemporary capital markets, i.e. taking into account that capital markets are necessarily incomplete.

Ethically, public policies with long horizons should adopt a methodology where the interests of future generations are taken into account. The direct implication is that it is more appropriate to have a methodology defined by normative criteria than a positive methodology based on empirical estimates of opportunity costs in incomplete markets. The methodology preferably adopted in these cases follows the ideas of Ramsey (1928) and is based on estimates of marginal rates of substitution between consumptions in different periods, in an aggregate model with economic growth. The basic equation in this analysis is

$$\rho = r + \gamma\mu\,, \tag{2}$$

where μ is the growth rate of per capita consumption, γ is the elasticity of the marginal utility of consumption, r is the pure intertemporal discount rate (the one that should be used to update the utility of consumption rather than consumption directly) and ρ the social discount rate. The product $\gamma\mu$ is generally referred to as the wealth effect.

This methodological approach is officially established in the case of the United Kingdom, where the official reference discount rate is defined by the HM Treasury Green Book (H.M. Treasury 2020). According to the Green Paper (pp. 46) the discount rate representing intertemporal social preferences has two components. First, a rate that reflects the pure intertemporal preferences r, that is, the impatience of economic agents.[12] This component would define the social update rate in a society without economic growth and is assigned a value of 1.5%.

However, there is an expectation that per capita consumption will grow in the future, which by comparison makes the marginal utility of present consumption higher. Growth adds a wealth-effect component to the discount rate. This is the component $\gamma\mu$ in the Ramsey equation, where the value of 1 is assigned to the elasticity of marginal utility γ and the value of 2% to μ, the rate of per capita consumption growth.

Adding the two components, namely the pure intertemporal preferences and the wealth effect, the actual benchmark discount rate chosen in the UK is 3.5%.

12. The value also includes a catastrophic risk premium. The Green Paper considers additional scenarios (for example for health) with specific values.

It should be noted that, from the official perspective of the United Kingdom, the social discount rate is explicitly seen as being independent from the cost of financing public entities, either through taxes or through the use of public debt.

The Green Paper also contains rules that apply to the case of updating at very long periods. The contributions of Weitzman (1998) showed that in case there is uncertainty about what is the appropriate discount rate, in the very long run the rates should gradually decrease to the lowest of all plausible values. The Green Book adopts this result, recommending the aforementioned rate of 3.5% for horizons of 30 years, a rate of 3% to be applied incrementally for horizons between 31 and 75 years and 2.5% for horizons between the 76 and 125 years.

In France, the official reference for the social discount rate is established by *France Stratégie*, following the values proposed in the Quinet (2013) Report. An additional relevant consideration in the literature and already considered in this report is the extension to uncertainty in the trajectory of future consumption, which Gollier (2002) applied to Ramsey's approach, when considering how uncertainty in the future evolution of consumption affects the rate of discount. The modified Gollier equation is

$$\rho = r + \gamma\mu - \frac{1}{2}\gamma^2\sigma^2\,, \tag{3}$$

where, in addition to the variables already defined in the equation (2), σ is the standard deviation of the per capita consumption growth rate. The equation (3), adjusted for uncertainty in future consumption growth, adds a negative term and therefore tends to reduce the original estimate of the social discount rate, albeit by small amounts. The change is usually interpreted as being motivated by precaution: as future consumption growth is more uncertain, there is a compensation that penalises the future less and induces a greater reduction in consumption today, in exchange for more consumption tomorrow.

The approach followed in France is thus similar to that of the United Kingdom, that is, it is based on the Ramsey equation (with the adjustment for risk) although the value currently chosen is 2.5%, which in part is due to the sharp reduction in recent years of the real yields of the financial markets and the indications that this phenomenon indirectly gives about the values of the pure intertemporal discount rate. As in the British case, for long time horizons, above 30 years, the discount rates in France are decreasing, progressively to 1.5%. The above mentioned discount rates may be increased by a risk premium of 2%. This risk premium decays over time to 1.5%.[13]

3.3.2. Calibration. The next step of the analysis is to calibrate the equation (3) in order to obtain an estimate of the discount rate to be used. It is not obvious whether the relevant perspective should be defined more narrowly, specifically

13. The Quinet (2013) report addresses additional risk adjustments inspired by the *Capital Asset Pricing Model* financial models, taking into account the characteristics of the sectors where the public investment will be made.

taking into account the Portuguese situation, or more broadly, adopting the euro area perspective. Bearing in mind that both perspectives can be valid, in alternative circumstances, the results to be presented include both cases.

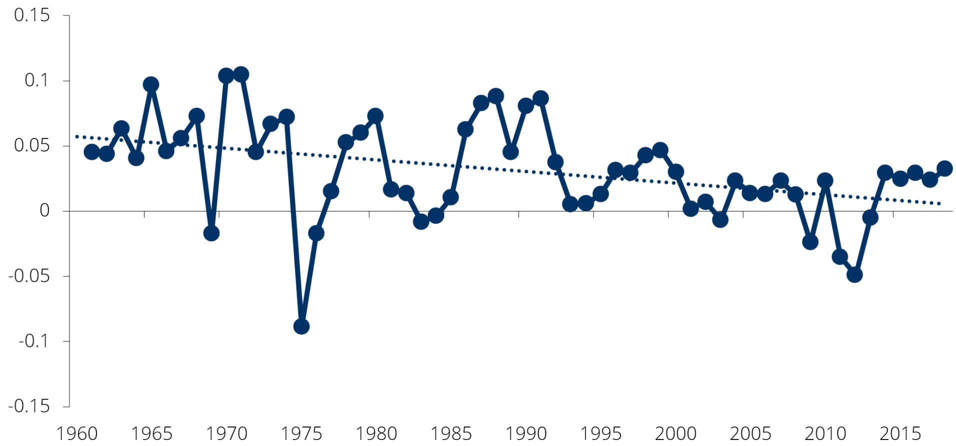
The equation (3) requires four inputs to determine the discount rate. Two of them are predictive in nature: the average growth rate of consumption and its standard deviation. The pure intertemporal discount rate can be inferred from the real return on after-tax risk-free investments, although the data is "noisy" and affected by monetary and economic policy interventions that generate deviations, even if transitory. Finally, the elasticity of the marginal utility of consumption can be calibrated by reference to choices made by other countries.

The conceptual problem that concerns us at this stage is choosing the most appropriate consumption measure. A first choice will naturally be private consumption. However, over the years, the relative weight of the public sector has grown, which is why the weight of public consumption in GDP has also increased. Part of this growth may not be directly relevant for determining the discount rate, but there are types of consumption – such as education, health care, transport and possibly other areas – where there has been a growth in public consumption over the years and which can be considered as replacing private consumption. For these reasons, one could contemplate the case of total consumption, where the private and the public are added together. However, the differences found when considering only private consumption are not qualitatively relevant and, therefore, we chose to use only the latter.

From data on the historical evolution of private per capita consumption in Portugal and in the euro area, we compute the annual series of growth rates (operationalised as log differences) and the respective averages and standard deviations. The result can be seen in Figures 10 and 11. Consumption growth rates show a declining trend over the period under analysis. This trend is relevant insofar as the intended objective is to estimate the future evolution of the average and volatility of consumption growth rates. The comparison between Figures 10 and 11 suggests that the volatility of consumption growth rates is greater in Portugal.

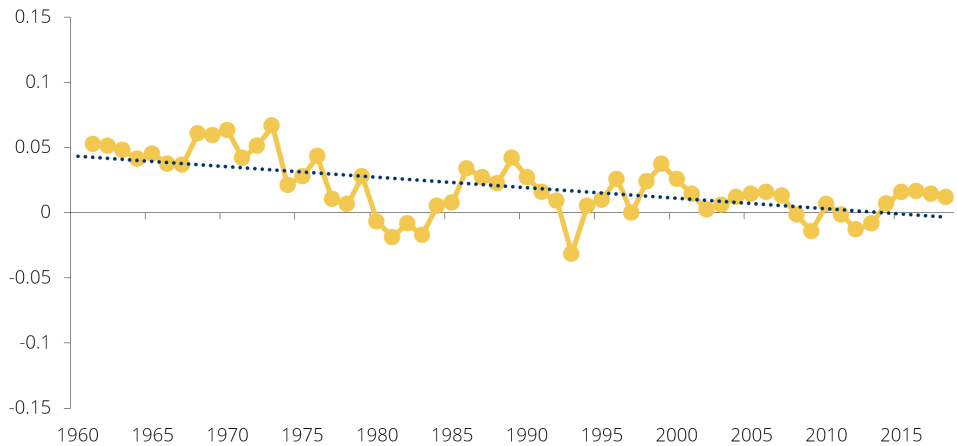
Table 4 reports the averages and standard deviations of consumption growth rates for the total sample period, 1980-2018 and 2000-2018. The results confirm the downward trend in consumption growth rates and show that the means and standard deviations of these rates differ between the Portuguese and the euro area cases. Bearing in mind that the 2000-2018 period is affected by the great recession and the sovereign crisis, it would be prudent to assume that the future will improve consumption growth rates. A reasonable reference point for future developments could be an average value for the growth rate of consumption in Portugal of 1.6% and a standard deviation of 2.7%. For the euro area an average value for the consumption growth rate could be 0.8% with a standard deviation of 1.3%.

The next step is to estimate the pure intertemporal discount rate. There is no obvious way to estimate this parameter, or more precisely how this parameter eventually evolves over time. In the case of the discount rate choices made in the US, UK and France, the estimate of the pure intertemporal discount rate is based



Sources: PORDATA and authors' calculations.

Figure 10: Per capita consumption growth rate in Portugal. Values in natural units.



Sources: PORDATA and authors' calculations.

Figure 11: Per capita consumption growth rate in the euro area. Values in natural units.

on the real risk-free interest rate after tax,

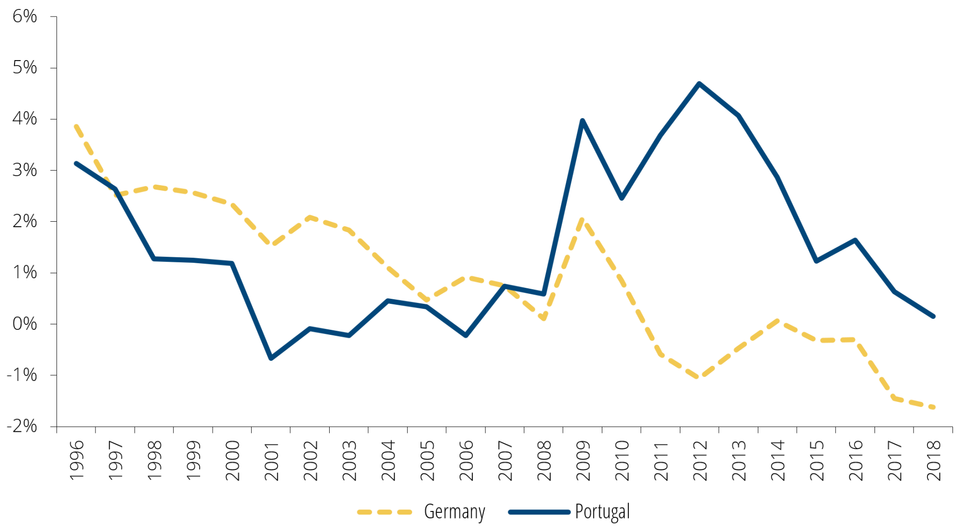
$$r = \frac{i(1-t) - \pi}{1+\pi}$$

where r is the pure intertemporal discount rate, π is the rate of inflation, i is the gross nominal rate of risk-free assets, and t is the marginal tax rate paid by households on the interest received. The empirical variable usually used as an approximation of the risk-free nominal rate of return is the rate of return on public debt with maturities between five and ten years. To this information it is necessary to add an average marginal tax rate. The estimates presented below, for the cases

		Euro area	Portugal
1960-2018	Average	0.019	0.03
	Standard deviation	0.022	0.037
1980-2018	Average	0.009	0.023
	Standard deviation	0.016	0.031
2000-2018	Average	0.007	0.008
	Standard deviation	0.011	0.024

Sources: PORDATA and authors' calculations.

Table 4. Summary statistics of the growth rate in the euro area and Portugal during the period 1960-2018 and selected subperiods.



Sources: Ameco (*Nominal long-term interest rates*, ILN, and Harmonised Index of Consumer Prices growth rate, ZCPIH).
Note: Marginal interest rate of 28% is assumed.

Figure 12: Real interest rates net of tax in Portugal and Germany.

of Portugal and Germany, both use the marginal rate of 28% in force in Portugal for capital income, which in the German case is only an approximation.

Figure 12 shows the evolution of the annual average of real rates net of tax for public debt in Portugal and Germany.

The use of this information requires some prior judgment. First, despite negative net real rates of return, it will be assumed that this is not a good long-term estimate. Averages will be calculated to which negative values contributed, but an evolution with a sustained continuation of negative rates is not projected. Second, in the years 2009 to 2014 the interest rates on Portuguese debt were very high compared to previous and subsequent years due to an acute situation of country risk. It is unreasonable to use the values of Portuguese debt interest rates in those years to estimate an interest rate on risk-free assets. Instead, it is decided to eliminate these years in the calculation of the reference rate of return. The possibility that the relevant risk-free interest rate for Portuguese society could be that of German debt or that of Portuguese debt (in this case relating to less exceptional years) could continue to be raised. It turns out that the question is empirically less relevant than one might think. Taking the years between 2009 and 2014 from the Portuguese sample, and calculating the net average real yields for public debt in Portugal and Germany since 2000, the value is the same for both countries: 0.44%. Rounding up and in conclusion, it may be reasonable to use 0.5% as an empirical estimate of the real return on after-tax risk-free investments. This rate is appropriate for evaluating public policies from a Portuguese perspective, and it is sensible to consider other values, such as 0 or 1%.

The final parameter whose estimate is needed to use the equation (3) is γ, the elasticity of the marginal utility of consumption. Assuming isoelastic utility functions, we obtain empirical estimates of γ from studies of intertemporal substitution elasticities, on risk behaviours (such as the management of the composition of assets between assets with different risk profiles), or even studies on the progressivity of the tax system. As we do not know representative studies estimating γ for Portuguese preferences, the alternative is to import estimates from other countries that can serve as a reference. The aforementioned British Green Book specifies the value $\gamma = 1$. In the French case, the Quinet (2013) report does not specify the value of γ, but the previous Lebègue (2005) report had used $\gamma = 2$. The European Commission's 2008 *Guide to Cost-Benefit Analysis of Investment Projects Economic Appraisal Tool for Cohesion Policy*, in Table B2 of Annex B (cited by Economides *et al.* 2018), reports values of γ for 11 European countries, between 1.12 and 1.79 with an average and median of 1.44. It appears from these data that a value of 1.5 can be an adequate reference both for the Portuguese case and for the case of the euro area.

3.3.3. Results. Assuming an average growth rate for per capita consumption of 1.6%, a standard deviation for this rate of 2.7%, an elasticity of marginal utility of income of 1.5, and a pure intertemporal discount rate of 0.5%, we obtain, via equation (2), the central estimate of 2.8% for the real discount rate to be used in the analysis from a Portuguese perspective. On the other hand, using an average per capita consumption growth rate of 1% with a standard deviation of 1.3%, with the other parameters being the same as in the Portuguese case, we arrive at a discount rate of 1.7% for the euro area.

Table 5 shows the result of a sensitivity analysis, with the different values obtained for the discount rate, starting from different values for the various relevant parameters. The values in the table vary approximately between 0.66% and 4%, a range too wide to allow for certainties. The quantitative part of Section 4 uses the upper bound of this range.

$\gamma = 1.5$		σ				
r	μ	0.01	0.013	0.02	0.027	0.028
0	0.005	0.0074	0.0073	0.0071	0.0067	0.0066
0	0.01	0.0149	0.0148	0.0146	0.0142	0.0141
0	0.015	0.0224	0.0223	0.0221	0.0217	0.0216
0	0.02	0.0299	0.0298	0.0296	0.0292	0.0291
0.005	0.005	0.0124	0.0123	0.0121	0.0117	0.0116
0.005	0.01	0.0199	0.0198	0.0196	0.0193	0.0191
0.005	0.015	0.0274	0.0273	0.0271	0.0267	0.0266
0.005	0.02	0.0349	0.0348	0.0346	0.0342	0.0341
0.01	0.005	0.0174	0.0173	0.0171	0.0167	0.0166
0.01	0.01	0.0249	0.0248	0.0246	0.0242	0.0241
0.01	0.015	0.0324	0.0323	0.0321	0.0317	0.0316
0.01	0.02	0.0399	0.0398	0.0396	0.0392	0.0391

Source: Authors' calculations.
Note: The discount rate is given by (3).

Table 5. Alternative values for the discount rate as a function of the calibration parameters. μ is the consumption growth rate, γ is the elasticity of the marginal utility of consumption, r is the intertemporal discount rate of the utility and σ is the volatility of the consumption growth rate.

3.4. Economic policy and climate change

To the extent that emissions stemming from the use of fossil fuels exert negative externalities on economic agents, it is possible to devise policies aimed at mitigating their effects and inducing greater welfare. This section addresses this problem from two perspectives: the general economic policies appropriate to the problem, and the specificities related to the financial system and to central banks.

3.4.1. Carbon taxes and tradable emission allowances. The intervention most widely mentioned to address climate change is the imposition of a price on carbon and other GHG emissions. The idea behind this intervention is that the higher the amount paid for GHG emissions, the smaller the quantity of emissions occurring. If economic agents have to pay for carbon emissions, they are encouraged to reduce emissions, either by reducing GHG generating activities or by innovating to reduce the dependence of economic activity on energy sources such as fossil fuels. For a given aggregate reduction in GHG emissions, the total costs borne by society are lower if carbon price mechanisms are used than they would be in the case of interventions for the direct regulation of economic activities, generally referred to as *command and control*, as the same emission reduction can be achieved at a lower cost as no additional distortions are created.

There are at least two alternative mechanisms for imposing a price on carbon. The first mechanism consists of introducing corrective taxes, the so-called Pigou tax: goods and services are subject to (additional) taxes whose value depends on the amount of carbon emitted in production and distribution. An example in Portugal is that the cost of a litre of fuel includes a tax corresponding to the associated carbon emission. The quantification example in Section 4 is largely based on such a policy.

The second mechanism is the reverse of the previous case: instead of setting a price, an aggregate amount of carbon emissions is set, corresponding to a given amount of tradable licenses, an approach proposed by several authors inspired by the analysis of externalities and Ronald Coase's delimitation of property rights. Purchasing one of these licenses grants the right to emit a unit of carbon. The most relevant mechanism of this type is the European emission permit system (European ETS, called *Emissions Trading System*), where the base unit is the metric ton of CO_2. This type of system is known as *cap and trade*: authorities define a total number of licenses (*cap*), which can be bought and sold by economic agents (*trade*).

In a no-uncertainty scenario, the two mechanisms are equivalent. For a given time trajectory of the tax per unit of CO_2, economic agents demand certain amounts of emissions. For a given trajectory in the quantities of emission allowances available, the demand for allowances determines the trajectory of the prices of these allowances. It is possible to find the carbon price in a tax mechanism that results in the aggregate amount of desired emissions and it is possible to find the amount of allowances to be emitted that result in an equilibrium with the desired price per unit of CO_2.

Another relevant consequence of these mechanisms is the revenue raised by the Government. Here, too, there is an equivalence, since the revenue from Pigou taxes can be obtained from the sale of emission licenses in auctions. Even in the most complex case, where parts of the licenses are granted free of charge to economic agents based on experience,[14] it is possible to define taxation schemes with exemption from inframarginal emission quantities, which have a similar impact on the Government's revenue.

In scenarios with uncertainty, some differences between the two mechanisms exist. If the demand for emissions fluctuates, for example due to fluctuations in economic activity, the existence of a fixed carbon price will generate volatility in the amount of emissions carried out. On the other hand, in a *cap and trade*

14. Allocating licenses based on historical experience is referred to as *grandfathering*, and usually occurs in the initial periods of operation of *cap and trade* mechanisms to facilitate their political viability by reducing opposition from companies covered by the scheme. To the extent that the most efficient or innovative firms manage to reduce their emissions, they will be able to sell excess allowances. Firms that need to emit more must buy licenses. These transactions explain why the initial distribution of licenses does not compromise the efficiency of the mechanism, although such distribution could raise apparent equity issues, either from a redistributive point of view, or from the point of view of comparing incumbent companies and new companies with no track record of emissions. Even if *grandfathering* is used initially, as *cap and trade* systems mature and become institutionalised, the percentage of licenses sold at auction will increase.

scenario, the amount of emissions is fixed by design, but the fluctuation in demand are reflected in the volatility of emission allowance prices.

What is the most economically efficient system? The answer depends on the sensitivity of the environmental costs and the costs of reducing emissions to the amount of emissions. Adapting the classic analysis on the issue of taxes versus licenses, see Weitzman (1974), it is possible to conclude that if environmental costs are more sensitive to the amount of emissions than the costs of reducing emissions, it is preferable to reduce the uncertainty in the amount of emissions, which points to a *cap and trade* mechanism. On the other hand, if the sensitivity of emission reduction costs is greater, it is preferable to reduce the uncertainty in this cost, which points to the superiority of a carbon tax mechanism (Adar and Griffin 1976). Since environmental costs depend on the GHG stock and this is not much affected by emissions in a particular year, some argue that the sensitivity of environmental costs to the amount of emissions is less than the sensitivity of the costs of reducing emissions, which would mean a superiority of the use of taxes from Pigou. However, this superiority emerges only in a short-term logic and is not necessarily valid over the long term. On the other hand, Stavins (1996) studied the correlation between fluctuations in emission reduction costs and environmental costs, concluding that this correlation implies a superiority of the *cap and trade* mechanism.

Other relevant issues are related to the transaction costs and administrative costs of the two mechanisms under analysis. In both cases, the availability of good information and the capacity to monitor economic agents' emissions and punish deviations are necessary for the correct functioning of these mechanisms. It is generally agreed that a tax mechanism has less administrative costs and less complexity than a *cap and trade* mechanism. This is true when taking into account the start-up and management costs of distributing allowances in an active market and monitoring them. On the other hand, many countries already have structures that manage fuel taxation. Furthermore, it is possible that non-competitive behaviour and market manipulation could weaken the ability of *cap and trade* to achieve efficient control of global GHG emissions. On the other hand, *cap and trade* adjusts more quickly and flexibly to changes in the costs of reducing emissions, something that could require changes in taxes that are more difficult and slower to implement. The possibility of saving the licenses acquired for use in later periods (so-called *banking*) or the creation of reserve systems for price stabilisation (as in the case of the European ETS) help mitigating the problems of price volatility that *cap and trade* systems are subject to. Additionally, there is the possibility of imposing minimum or maximum limits on license prices. In practice, most of the existing ETS currently have adopted PSAM (Price or Supply Adjustment Mechanisms) to reduce the occurrence of spikes (positive or negative) in license prices. Another disadvantage of *cap and trade* is that this mechanism presents more incompatibilities than carbon taxation when considering interactions with complementary interventions, such as the implementation of fuel standards or favouring "green" investments in financial markets; see also Section 3.4.2.

The tendency of interest groups or sectors of economic activity to achieve special tax treatments indicates that there is a possibility that carbon taxes, in practice, solve imperfectly the problems for which they were created. This situation is exemplified by the use of GHG-generating fuels that not only do not pay for emissions, but are even subsidised.

Both the application of taxes and the requirement for licenses can affect entities at the top of the energy chain, making it possible to reduce the scope of application from millions of emitters downstream to substantially smaller numbers upstream. Possibly, this upstream incidence will be easier in some areas than others, and *cap and trade* may work well in reducing emissions for large companies (e.g. electricity producers) whereas taxes may work better in the areas of transport or in the thermal characteristics of dwellings. Another area in which taxes are presented as a necessary instrument is in border adjustments, resulting in taxing imports from producers who do not bear reasonable costs with carbon emissions. An alternative to border adjustments would be more downstream taxation in economic circuits, for example in the use and consumption of imported products by final consumers.

There are two conclusions that have been drawn from this set of considerations. One is that the implementation details of the carbon tax or *cap and trade* are potentially more important than the conceptual differences between the two mechanisms. The second conclusion is that the best way to impose prices on carbon requires a system with the simultaneous use of *cap and trade* and carbon taxes. This hybrid system matches the current situation, particularly in Europe.[15] The European ETS covers only a part of economic activities, in particular in sectors such as power generation, foundries, pulp mills, cement and, more recently, aviation. In general, only large companies are part of the ETS. Simultaneously, in many European countries there are carbon taxes levied on economic activities not covered by the ETS, namely land transport.

Despite the existence of ETS and the application of carbon taxes in various regions of the world, the global percentage of CO_2 emissions that pay a price is still small. The prices charged are very heterogeneous when comparing the various countries and regions. Actual prices, weighted by coverage rates, are low: William Nordhaus[16] estimated at \$1.7 the effective price of a ton of CO_2, a value that contrasts with prices in the \$40–\$80 range that various analyses report as necessary to obtain the desired long-term results in the concentration of GHG in the atmosphere and in limiting increases in temperature to 2°C.

15. The 27 EU countries participate in the European ETS, in addition to Norway, Liechtenstein and Iceland. Switzerland has established a link by integrating its ETS into the European ETS. In turn, the UK created its own ETS to replace the previous participation in the European ETS. A recent positive development is that in July 2021, the ETS began operating in full in China, the country with the highest CO_2 emissions in the world, and it is estimated that this market covers around 40% of the country's emissions.

16. See https://bcf.princeton.edu/events/williamnordhaus/.

According to current estimates, only 21.5% of global emissions are covered by ETS or carbon taxes. The same source reports that only 3.76% of global emissions pay a carbon price above $40 per ton of CO_2.

There is great heterogeneity across countries. According to the World Bank, Portugal will have, in 2021, around 29% of its CO_2 emissions covered by carbon taxes, a value lower than that of Scandinavian countries (Norway 66%, Sweden 40%) but higher than other EU countries (Poland 4%, Spain 3%). In turn, the European ETS covers about 39% of emissions in the European Union.

Presently, the main objective of public policies should be to expand the scope of measures that result in a price of carbon emissions, in order to cover a greater proportion of emissions. The effective price should be higher than currently and more homogeneous geographically. This price must be adequate to the environmental damages generated and in line with the established global objectives for the reduction of GHG emissions. Other policy options, such as the regulation and supervision policies of financial markets, should complement these objectives, either strengthening their implementation or addressing the correction of other market failures.

3.4.2. Implications for the financial system. Complementing fiscal measures, the role of the financial system in reducing GHG emissions has been recognised, given its fundamental role in the allocation of resources in the economy. While acknowledging the greater effectiveness of fiscal measures, it should be stressed that measures related to the financial system can, in principle, result in a better overall policy mix. In fact, there remains uncertainty about the assumptions that determine the specific design of fiscal measures and the desirable level of taxation. There are also relevant political economy considerations, related to the nominal incidence of taxes and their redistributive effects, which may justify a greater role attributed to other policies. For a deeper analysis of this topic, see Adão and Lourenço (2021).

From an economic point of view, the first step in the analysis of measures aimed at the financial system must be to identify the market failures to which they may respond. In this context, market failures commonly identified result from: i) insufficiencies in the report of information on the environmental effects of certain industries or firms and also on their susceptibility to climate change, which can generate little recognition of the risks associated with them and too much investment; and ii) externalities of certain activities, which will be negative if they generate GHG emissions that are too high compared to what would be socially desirable (see Section 3.4.1), and positive in the case of too low investment in the development and adoption of renewable energy technologies, characterised by gains in mass production or network economies.

The first failure can be overcome with additional disclosure of information; the latter can be addressed with fiscal, or equivalent, measures. The lack of granular, prospective and verifiable environmental information persists, especially in small firms. Furthermore, although some companies set their own emission reduction targets, this information is not always publicly disclosed, which makes it difficult to gauge their role in combating climate change. Thus, suitable measures in the regulation and supervision of the financial system, aimed at ensuring credible and comparable information, standardised disclosure of environmental data by firms and their correspondence with a globally accepted taxonomy would contribute to a better assessment of climate risks and the environmental impact of firms by consumers and investors. However, it is necessary to ensure that the quality of the required reporting is verifiable and that the related costs are not too high. This guidance can be complemented with the role of central banks as monetary authorities – i.e., even when they are not supervisors –, as the design of monetary policy (e.g. corporate bond purchase programs) may be conditioned by reporting by banks and firms that obtain funding in the capital markets.

Reporting issues are relevant for measuring and controlling risk, a dimension that has played a relevant role in the design of policies directed at the financial system. In this context, and in the case of the banking system, proposals have also emerged on granting a more favourable regulatory treatment, in terms of capital requirements and others, to "green" credit, or credit to firms or projects that are classified as such. Note, however, that the purpose of capital requirements is to ensure that banks are able to absorb losses. In principle, there is no reason to believe that green projects are less risky than other projects. In fact, this type of policy seems to aim at synthesising a subsidy for green activities. In any case, they raise relevant issues of implementation and effectiveness.

First, there is an enormous difficulty in characterising projects or companies according to their green character.

Second, the existence of a more favourable regime creates incentives for so-called regulatory arbitrage, which, in this case, will be directed towards classifying any project or firm as green. Failure to do so would require an additional layer of scrutiny over the supervision of the financial system, which can result in a significant expenditure of resources. From the point of view of banks, resources would also be spent on exploring the difference in regulatory treatment between types of credit. In general, this cost would be higher the more favourable the regulatory treatment of green projects turned out to be.

Third, it is difficult to guarantee that specific funding is intended for a specific purpose within a firm or business group. In fact, funding to a parent company or a subsidiary may be channelled to less green group (or even external) companies, countering the objectives of the measures.

Finally, even if it were possible to implement a rigourous and effective system of control in the aforementioned dimensions, nothing prevents non-bank forms of financing or financing originating in more lenient jurisdictions in this dimension, in a context of free capital flows, from continuing to support the less green activities. This should occur because these measures are ineffective in reducing the gap, which can be very significant, between the private and social return of GHG intensive projects. If the gap persists, funding flows will not cease. Only more general measures, such as the fiscal measures analysed earlier, even if they require international coordination, have the potential to visibly reduce this difference.

Central banks also have a role in the possible subsidisation of green activities, through the purchase of green bonds or, in the context of bank refinancing operations, providing a more favourable treatment of green credit posted as collateral, e.g. by applying lower haircuts. This could result, in particular, in the subsidisation of energy production based on renewable sources. Note, however, that the use of green energy subsidies can have counterproductive effects. Hassler *et al.* (2020) show that the use of green energy subsidies translates into higher total energy consumption, but has limited effects in mitigating the rise in global temperature.

In the case of refinancing operations, once again, there are motivations related to the subsidisation of greener sectors or companies, which, however, are justified by the risk incurred by central banks. If the concerns are exclusively related to risk, it is not necessary to partition credit into green and non-green; it suffices to measure the additional risk posed by climate change to firms and incorporate it into the collateral framework. In any case, and once again, the beneficial effect of this type of intervention presumes there is a correct identification of this type of risk. But even if this identification is correct, it should be noted that the marginal incentive to grant credit to green projects is, through this channel, very low. The only benefit comes from using green credit portfolios as collateral in eventual future refinancing operations with the central bank. Only in specific situations (crisis) are these credit portfolios typically used in these operations. And even if they were used more regularly, the haircut differences between green credit and other credit would not, as a general rule, result in relevant restrictions on financing amounts.

In the case of asset purchase programmes focussing on corporate bonds (to become eventually tilted towards green projects or firms), one should point out that this is a recent tool with the specific objective of reinforcing the accommodative nature of monetary policy. When these programs did not exist, monetary policy had the capacity to transversally affect the different segments of the financial markets, including the financing of non-green firms. Maybe an effect of green purchases will exist, but it could be low. Furthermore, these programmes are intended to meet inflation or macroeconomic stabilisation targets, ceasing when these targets are met. The existence of permanent asset purchase programmes with certain characteristics could conflict with monetary policy objectives and central bank mandates. The attribution of green responsibilities to monetary policy, in a context where its effectiveness is limited, could result in a threat to the independence of central banks. Claiming an active role in responding to climate change could translate into high reputation costs, undermining central bank action in the future. Furthermore, the independence of a central bank is granted under the condition that it operates within a limited sphere of competence.

The above does not prevent central banks, as relevant organisations, from complying with sustainability and corporate responsibility criteria. In this dimension there will certainly be a lot of work to be done. In the case of Banco de Portugal, note its commitment to sustainability and sustainable financing, its participation in the Network for Greening the Financial System (NGFS) and in the National Roadmap for Adaptation 2100, and its participation in green funds of the Bank for International Settlements. The reader is also invited to consult the documents already published in the context of the recent review of the ECB's monetary policy strategy, which list the various initiatives underway and to be started in this area.

This analysis does not include some general and sectoral policies that seek to mitigate climate change, as well as those that seek to adapt existing production systems to those changes that may occur. One example is the incentives for research and development activities aimed at mitigating carbon emissions or adapting to its effects. The results of this type of initiative are uncertain, but the ingenuity and capacity for innovation of scientists and entrepreneurs should not be underestimated. This category includes efforts to make energy production technologies cleaner, increase the energy efficiency of production processes and transport, energy storage systems, technologies or processes for sequestering carbon from the atmosphere, among other examples. The policy prescriptions described above and based on taxes or emission permits already provide incentives for this type of investment.

4. Prospective assessment of mitigation policies: an example

This section discusses climate change in the world and in Portugal using a model that integrates the global economy and climate in a single analytical framework. The section is built around the article by Adão *et al.* (2021), which investigates the optimal transition from a world economy that uses essentially fossil fuels to a world economy powered by renewable energy, using an IAM model. Based on the results for the world economy, the Portuguese economy is studied in terms of temperature increase and costs in GDP for the different policy trajectories.

This exercise is a first attempt to assess the potential effects of climate change on the global economy and on the Portuguese economy in the very long term. Issues such as the shorter-term impact (of the order of a few years) from the expenditure required for the energy transition, the effects on the distribution of wealth and income, among others, are left out of this analysis. Future work will surely address these and other topics in the context of climate change.

In the model, energy can be produced using fossil or renewable sources. The fossil fuel sector generates a negative externality – the economic effects of CO_2 emission –, and research and development (R&D) in the renewables sector benefits from synergies, which generate a positive externality. The presence of these externalities leads, in net terms, to an excessive use of fossil fuels and an underinvestment in renewable energy. The optimum can be decentralised by a policy that includes a Pigouvian tax like the one mentioned in Section 3.4.1 on carbon emissions, in conjunction with a tax on underinvestment in R&D in renewable technologies, rebated lump sum to the company owners, which are the families.[17] One of the most salient features of this work is the degree of substitutability between carbon taxes and taxes on subinvestment. Using a calibrated model, the quantitative importance and potential complementarity between the two policy instruments are investigated, studying their effects individually and when both are implemented.

The results for the global economy suggest that the Pigouvian tax almost manages, by itself, to implement the optimal equilibrium. This does not mean that the synergies of investment in R&D in renewable energy are quantitatively irrelevant throughout the energy transition. There are complementarities between carbon taxes and the tax on underinvestment in renewable energy, with considerable welfare gains when both policies are present. Shifting from the status quo – defined as the evolution that will occur without substantial changes in economic policy relevant to carbon emissions – to the optimal Pigouvian tax by itself would result in an equivalent welfare gain in consumption of 1.02%. On the other hand, the comparison between the status quo and the situation in which the two policies are applied suggests an equivalent welfare gain in consumption of 1.43%, confirming the decisive importance of the carbon tax.

The transition to a global economy that uses only renewable energy sources will happen in 2070 if both policies are followed. In case there are no changes in the current policies, the global economy will only depend exclusively on renewable energies in 2130. The counterpart of this is that the cumulative consumption of fossil fuels will be much smaller if the optimal policies are adopted, corresponding to less than half of the cumulative consumption in the status quo scenario, in which the two government instruments — the Pigou tax on carbon and the policy for the adoption of new renewable energy technologies – are unchanged.

In relation to the pre-industrial level, the global temperature will increase around 2°C in the case of simultaneous adoption of the Pigouvian optimal tax and the tax on underinvestment in the renewable sector. This value will be 2.2°C if only the optimal Pigouvian tax is adopted, but will increase to about 2.8°C if none of the instruments are implemented.

In the Portuguese case, changes in temperature will be smaller in all scenarios. This is because it is estimated that for each degree Celsius increase in global temperature the average temperature in Portugal will increase by about 0.6°C. Thus, if the optimal Pigouvian tax is adopted, the increase in temperature will be 1.2–1.3°C, with the smallest value corresponding to the case where the optimal policy for renewable energy is in effect. Otherwise the increase will be about 1.7°C. Economic losses can also be limited, between 0.4% and 0.8% of GDP in 2100.

17. In the model, the rate of underinvestment in renewable energy is neutral in relation to tax revenue because, in equilibrium, companies in that sector choose the level of investment in renewable energy that exempts them from any tax. This policy can also be implemented through a subsidy to these companies financed by lump sum taxes on households.

However, consumption will, on average, be about 0.4% higher than in the status quo.

The reader less interested in the theoretical and methodological details of the exercise can ignore Sections 4.1 to 4.2. For readers interested in quantitative hypotheses about climate, carbon emissions and economic losses from climate change, it is recommended to read Section 4.1 through Section 4.1.3.

4.1. Model

The model has four modules: climate, carbon cycle, costs, and economy. The economic module is made up of consumers and producers. Their actions are decisive for carbon emissions, which increase the amount of carbon in the atmosphere. The cost module establishes how the economy is affected by climate. The carbon module models the dynamic relationship between carbon emissions and the concentration of carbon in the atmosphere. Finally, the climate module establishes the relationship between carbon concentration in the atmosphere and climate. Below, each of these modules is presented in detail and their interactions are described.

4.1.1. Climate. The purpose of the climate module is to determine how the amount of carbon in the atmosphere determines climate. The simplest description of climate – the global mean atmospheric temperature of the Earth's surface – is modelled as a function that relates it to the amount of carbon in the atmosphere. The mechanisms underlying this relationship and the geophysical data presented in Section 2 document that global mean temperature is an increasing function of the amount of carbon in the atmosphere. A simple relationship between the two quantities is considered, as has been frequently done in the literature on climate change:

$$T(S_t) = \frac{\lambda}{\ln(2)} \ln\left(\frac{S_t}{\overline{S}}\right), \tag{4}$$

where S_t indicates the amount of carbon in the atmosphere at t, $\overline{S}$ is the pre-industrial amount of carbon level in the atmosphere, and λ is a sensitivity parameter. According to IPCC (2013) the value for λ will be "probably in the range 1.5–4.5°C". As Golosov *et al.* (2014) and Acemoglu *et al.* (2016), we assume $\lambda = 3$°C and $\overline{S} = 581$ GtC.[18] Figure 13 shows the relationship between carbon concentrations and changes in temperature. The x-axis ranges from 600 GtC, which roughly corresponds to pre-industrial levels, to 3000 GtC, which is the highest estimate for total available fossil fuel reserves. According to this function, if, for example, the atmospheric carbon stock increased to 1200 GtC, there would be a 3°C increase in global mean temperature relative to pre-industrial temperature.

18. This value, although coming from a different source, corresponds approximately to a carbon concentration in the atmosphere of 274 ppm, close to the value of 285 ppm estimated for 1850 and mentioned in page 16 of Section 2. This small discrepancy has no impact on the results of this analysis.

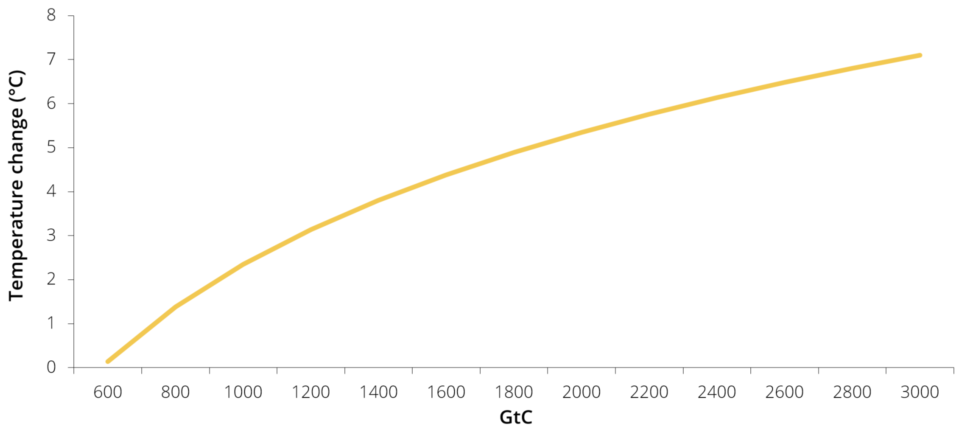


Figure 13: Change in average global temperature as a function of the amount of carbon in the atmosphere.

The potential scale of environmental damage from burning fossil fuels trivially depends on how much fossil fuel remains to be burned. This value is not strictly known and estimates depend on the definitions used. The most restrictive definition consists of proved reserves, which are those whose geological and engineering data demonstrate with reasonable certainty that they are recoverable in future years from known reservoirs under existing economic and operational conditions. As technology and prices change, this amount typically increases over time.

Given different definitions and estimates, the estimated quantities differ and will change over time. British Petroleum (2015) reports that the global proven reserves of oil and natural gas are approximately 200 GtC and 100 GtC, respectively. Given the current rate of emissions of around 10 GtC per year (Friedlingstein *et al.* 2019) these reserves would last for 30 years. In relation to coal, the proven reserves are around 600 GtC. Less restrictive definitions of reserves estimate larger quantities. For example, McGlade and Ekins (2015) estimates the recoverable reserves of oil, natural gas and coal to be around 600 GtC, 400 GtC and 3000 GtC, respectively.

The statistical relationship between the average global terrestrial temperature and its equivalent in Portugal can be obtained using the historical data referred to in Section 2.3. The relationship between the global temperature, T_t, and the temperature in Portugal, $T_{P,t}$, is estimated using the linear statistical model

$$T_{P,t} = \overline{T}_P + a \times T_t + \varepsilon_t \,, \tag{5}$$

where $\overline{T}_P$ is the constant of the model, a is the sensitivity of the average temperature in Portugal to the average global terrestrial temperature and ε_t is the error term. Annual average temperatures from 1900 to 2017 in Portugal and worldwide are considered as coming from Matsuura and Willmott (2018a). The temperature for Portugal corresponds to the annual average of the 40 grid points of the database that are located in mainland Portugal (Figure 6), while the global terrestrial temperature corresponds to the annual average temperature of all points of the grid, including Antarctica (Figure 2). The estimates for the model are $\overline{T}_P = 9.65$ and $a = 0.59$, and both values are statistically significant. For a 1°C increase in global temperature, the average temperature in Portugal rises by 0.59°C. This sensitivity was also calculated using the decade average of global and Portuguese temperatures, with similar results.

4.1.2. The carbon cycle. The carbon cycle module is a simple relationship between carbon emissions over time and the concentration of carbon in the atmosphere. We follow Golosov *et al.* (2014) and Acemoglu *et al.* (2016):

$$S_t - \overline{S} = \sum_{n=0}^{t-t^*} (1 - d_n) f_{tn}, \qquad t > t^*, \tag{6}$$

where $d_n \in [0; 1]$ and f_{t-n} indicate the carbon emissions in the period $t - n$, with each period being ten years. The term $1 - d_n$ represents the fraction of carbon emitted n periods ago that is still in the atmosphere, and t^* defines the beginning of industrialisation. Out of the emitted carbon, a fraction φ_L remains in the atmosphere forever, a fraction $(1 - \varphi_0)$ of the remaining emissions is captured by the biosphere, and the remaining part, $(1 - \varphi_L)\varphi_0$, decays at the geometric rate φ. Mathematically,

$$1 - d_n = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^n . \tag{7}$$

Thus, the level of carbon in the atmosphere can be decomposed into a permanent part, S_t^p, and a part subject to depreciation, S_t^d:

$$S_t = S_t^p + S_t^d , \tag{8}$$

where

$$\begin{aligned} S_t^p &= S_{t-1}^p + \varphi_L f_t \\ S_t^d &= (1 - \varphi) S_{t-1}^d + (1 - \varphi_L)\varphi_0 f_t . \end{aligned} \tag{9}$$

As explained in Archer (2005), Golosov *et al.* (2014) and Acemoglu *et al.* (2016), this specification approximates the complex dynamics of carbon concentration in the atmosphere. The three parameters of the carbon model are calibrated to replicate three stylised facts. We take $\varphi_L = 0.2$ because the 2007 IPCC report (Solomon *et al.* 2007) indicates that about 20% of any emission will remain in the atmosphere for thousands of years. As in Golosov *et al.* (2014), we take $\varphi = 0.0228$ because according to Archer (2005) the excess carbon that does not stay in the atmosphere "forever" has a half-life of about 300 years. Again according to Solomon *et al.* (2007), about half of the carbon that reaches the atmosphere is removed

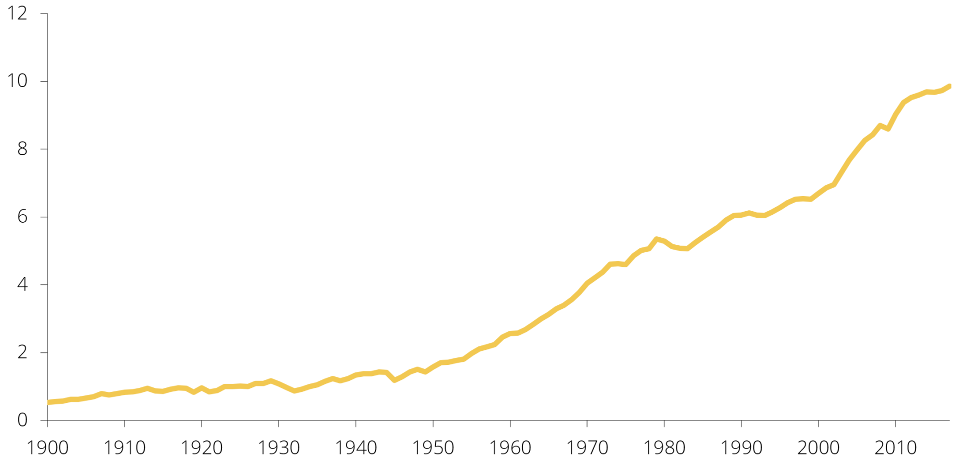


Figure 14: Annual carbon emissions, in GtC.

Source: Global Carbon Project, `http://www.globalcarbonatlas.org/en/CO2-emissions`.

after 30 years. This implies $d_2 = 0.5$ in the formula (6); after replacing φ and φ_L we get $\varphi_0 = 0.393$.[19]

Figure 14 shows global emissions, f_t, from 1900 to 2017. At the beginning of the century, annual emissions were around 0.5 GtC, reaching almost 10 GtC in the most recent years (Friedlingstein *et al.* 2019).

Figure 15 shows in the dashed line the concentration of carbon in the atmosphere, while the solid line represents the atmospheric concentration predicted by the model. The global concentration of carbon in the atmosphere has been augmenting at an increasing rate. It was about 630 GtC in 1900 and rose to about 860 GtC in 2017.

4.1.3. Economic losses. The third part of the model specifies how the economy is affected by climate change. We assume, like many others, that economic losses from global warming are proportional to GDP, and a function of global average temperature (Nordhaus 1991, 1993; Nordhaus and Boyer 2000; Nordhaus and Sztorc 2013; Golosov *et al.* 2014; Acemoglu *et al.* 2016). Normally, it is assumed that economic losses are a convex function of temperature, that is, the slope of the loss function, $D(T)$, increases with the level of temperature. Instead, we assume that the damage function takes carbon concentration as an argument, S.

19. Acemoglu *et al.* (2016) use a different strategy to identify these parameters. Setting $\varphi_L = 0.2$, they use the 30-year half-life of carbon and carbon emissions over the period 1900–2008 to estimate φ and φ_0.

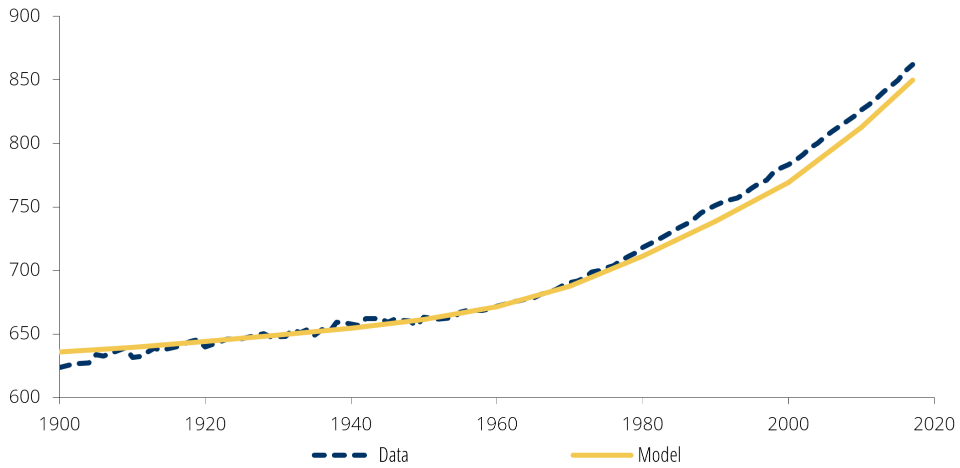


Figure 15: Atmospheric carbon concentration, in GtC.

Sources: Website https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions and authors' calculations.

For example, the Nordhaus damage function is specified as

$$1 - D_N(T_t) = \frac{1}{1 + \varphi T_t^2}, \tag{10}$$

where T_t is the global average increase in temperature above the pre-industrial level, with $\varphi = 0.0028388$.[20] The combination of a concave relationship between carbon concentration and temperature – equation (4) – and a convex relationship between temperature and economic losses – (10) – implies in this case a marginal effect approximately constant between carbon concentration and losses. As in Golosov *et al.* (2014) and Acemoglu *et al.* (2016) it is assumed

$$1 - D(T(S_t)) = \exp\left(-\pi\left(S_t - \overline{S}\right)\right), \tag{11}$$

with $\pi = 5.3 \times 10^{-5}$. This equation implies that the marginal loss measured as a share of GDP per marginal unit of carbon in the atmosphere is constant and given by π. Figure 16 shows the relationship between carbon concentration and net losses.

The horizontal axis range is from 600 GtC, which corresponds to pre-industrial levels, to 3000 GtC, which corresponds to the highest estimates for the total amount of extractable fossil fuel. This calibration for π gives moderate GDP losses. For example, if in an unrealistic scenario the 900 GtC of fossil fuel corresponding to

20. Trivially, the damage function D_N becomes, above a very high temperature, concave because its upper limit is unity.

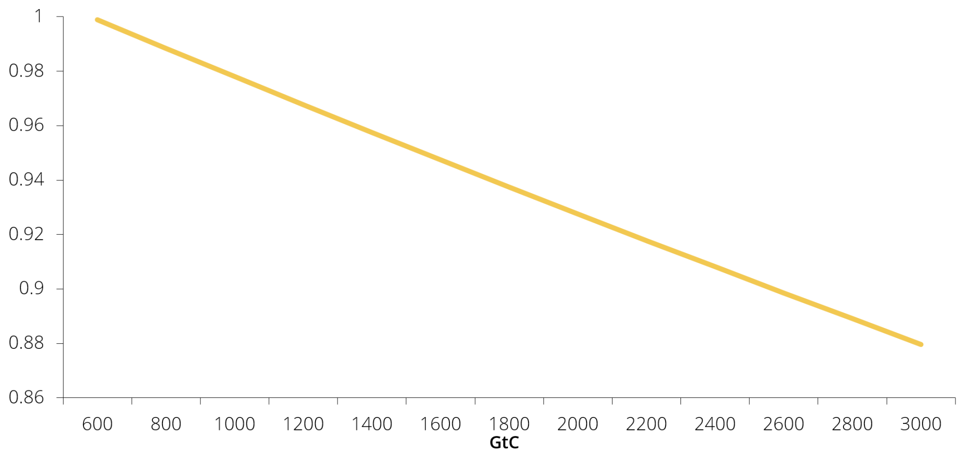


Figure 16: GDP as a function of the concentration of CO_2 in the atmosphere, measured as a fraction of the case without an increase in temperature.

Sources: Golosov *et al.* (2014), Acemoglu *et al.* (2016) and authors' calculations.

total reserves immediately available (British Petroleum 2015) were used in a very short period of time, then the concentration of carbon in the atmosphere would rise to 1323 GtC, decreasing thereafter according to the expressions described above.[21] For this amount of carbon concentration in the atmosphere, the maximum GDP losses would be around 3.8%.

There are many other ways in which climate change can affect the economy that are not taken into account in our formulation. For example, many of the costs do not have a market price. Additionally, carbon emissions will likely affect the climate for a long time, which implies that the weight given to future generations is very important to quantify the costs. A third example: there is a very large degree of uncertainty in how climate change might affect the economy. Some of these concerns can be accommodated in this type of analysis by adjusting the intertemporal discount rate, but in other cases this is not possible.

4.1.4. The economy. In the model, energy, capital and labour are inputs in the production of the final consumption good. Energy can be produced from fossil or renewable sources. Both types of energy require capital, which is also used in producing the final good. At any given time, productivity in the production of renewable energy can increase as a result of the replacement of capital by a more modern version. The technological improvement benefits from synergies arising

21. This value corresponds to the sum of 860 GtC, the current concentration, plus the increase in concentration resulting from the issuance of 900 GtC which, according to the calibration described above, is approximately equal to $463 = 900 \times (0.8 \times 0.393 + 0.2)$ GtC.

from the aggregate investment in the renewable sector. This indirect effect alone would lead to an underinvestment in renewable energy. In addition, investment creates costs associated with decommissioning and replacing old equipment, modelled as a temporary adverse productivity shock to the production function of renewable energy companies. It is important to note that these costs are higher the more capital is replaced.

In the economy there are companies that produce the final good and companies that produce energy. The production function of the final good is Cobb-Douglas:

$$\begin{aligned} y_t &= A_t(k_t^g)^{\theta_k}(l_t)^{\theta_l}(e_t)^{1-\theta} \\ &= (1-D(S_t))\widetilde{A}_t(k_t^g)^{\theta_k}(l_t)^{\theta_l}(e_t)^{1-\theta} \\ &= \exp\left(-\pi\left(Y_t-\overline{S}\right)\right)\widetilde{A}_t\left((k_t^g)^{\theta_k}(l_t)^{\theta_l}(e_t)^{1-\theta}\right), \end{aligned} \tag{12}$$

where k_t^g, l_t and e_t are capital, labour and energy, respectively, and $\widetilde{A}$ is a productivity parameter such that $A_t = (1-D(S_t))\widetilde{A}_t$, where θ, θ_k, $\theta_l \in [0;1]$, and $\theta_k+\theta_l=\theta$.

It is assumed that energy can be produced using fossil or renewable sources, and that the two types of energy are perfect substitutes in producing the final good.[22] The fossil fuel-derived energy production function is given by

$$e_t^f = (f_t)^{1-\alpha_f}\left(k_t^f\right)^{\alpha_f}, \tag{13}$$

where f_t and k_t^f are the quantities of fossil fuel and capital, respectively, and $\alpha_f \in [0;1]$. The amount of fossil fuel, w_t, evolves according to the equation:

$$w_t = w_{t-1} - f_t\,. \tag{14}$$

The sector of companies producing renewable energy is competitive. Renewable energy producers can improve their productivity, which is in turn subject to synergies arising from aggregate investment in the renewable sector. It is well known that this effect leads to an overall underinvestment in renewable energy. The renewable energy production function for company j is given by

$$e_{j,t}^r = \Psi(i_{j,t})\left(\mathcal{E}_{j,t}\right)^{1-\alpha_r}\left(k_{j,t}^r\right)^{\alpha_r}, \tag{15}$$

where $\mathcal{E}_{j,t}$ is a measure of the company's productivity, $\mathcal{E}_{j,0}$ is given for all j, $\alpha_r \in [0;1]$, $k_{j,t}^r$ is the capital used by the firm and $i_{j,t}$ is its rate of adoption of new technologies. Firm productivity increases with $i_{j,t}$,

$$\ln\mathcal{E}_{j,t+1} = \xi i_{j,t} + (1-\xi)\frac{\int_0^1 i_{j,t}k_{j,t}^r dj}{\int_0^1 k_{j,t}^r dj} + \ln\mathcal{E}_{j,t}\,, \tag{16}$$

22. High substitutability between energy sources seems a reasonable assumption in the long run, as renewable energy storage is expected to be available in the coming decades.

where $0 \leq \xi \leq 1$ parameterises the intensity of synergies. For example, $\xi = 1$ corresponds to the case where there are no synergies, while $\xi = 0$ implies that productivity is entirely determined by synergies arising from investment in renewables. In the expression above, we normalise the aggregate adoption of new technologies by the amount of capital, to abstract from any advantage that may arise from the size of companies. Finally, the function $\Psi(i_{j,t})$ captures the cost of adopting the technology. It is assumed that the adoption of newer technology reduces current production,

$$\Psi(i) = \left(1 - \left(\frac{i}{\bar{i}}\right)^{\psi}\right)^{1/\psi}. \tag{17}$$

Ψ is such that $\Psi\left(0\right) = 1$, $\Psi'\left(\cdot\right) < 0$, $\Psi''\left(\cdot\right) < 0$, and $\Psi\left(\bar{i}\right) = 0$, for a positive value of $\bar{i}$.

The economy is perfectly competitive. The representative family owns all the companies in the economy, capital and fossil fuel. It rents capital to companies and sells fossil fuel to companies in the non-renewable sector. The household chooses a consumption trajectory that maximises utility $\sum_{t=0}^{\infty} \beta^t u(c_t)$ and satisfies its budget constraint by taking prices as exogenous. Companies take prices as given and maximise profits. All markets are in equilibrium. In each period, the factors of production are freely allocated between sectors. The total capital used in the economy equals the total supply; that is, for all t,

$$k_t^g + k_t^f + \int_0^1 k_{j,t}^r dj = k_t\,. \tag{18}$$

The demand for labour is equal to the supply of labour:

$$l_t = 1\,. \tag{19}$$

The energy used in the production of the final good is equal to the total energy supply:

$$e_t = e_t^f + \int_0^1 e_{j,t}^r dj\,. \tag{20}$$

Consumption, c_t, plus investment, $k_{t+1} - (1-\delta)k_t$, where δ is the capital rate of depreciation, is equal to final good supply:

$$c_t + k_{t+1} - (1-\delta)k_t = A_t(k_t^g)^{\theta_k}(l_t)^{\theta_l}(e_t)^{1-\theta}\,. \tag{21}$$

The competitive equilibrium is characterised by underinvestment in the renewable energy sector, due to synergy effects, and excess production in the fossil fuel energy sector, due to the environmental externality of carbon emissions. Both distortions can be fully accommodated using two independent instruments:

1. A tax on companies in the renewable energy sector proportional to their level of underinvestment in R&D, rebated lump sum to households;

2. A Pigouvian tax that offsets the externality of carbon emissions, rebated lump sum to households.

In equilibrium, companies in the renewable sector choose the optimal level of investment in R&D so that this rate does not generate tax revenue; Adão *et al.* (2021) provide the details of the two mechanisms.

4.2. Calibration

The calibration of the environmental damage has already been detailed above. In this section the remaining parameters of the economy are specified. The instantaneous utility function is specified as $u(c) = \ln(c)$. Setting the length of each period to 10 years, a discount rate $\beta = 0.96^{10}$ is used. This value, which corresponds to an annual discount rate of 4%, is at the upper threshold indicated in Section 3.3. In Section 4.3 there is a brief discussion of the changes in the results that would occur if a smaller future discount was used.

Given the number of years in each period, it is assumed that capital depreciation is complete, that is, $\delta = 1$. In relation to the final good production function, the fraction of capital income is $\Theta_k = (1/3) \times 0.95$, while the fraction of labor income is $\theta_l = (2/3) \times 0.95$. The energy share is then given by $1 - \theta = 1 - (\theta_k + \theta_l)$. The participation of capital in the production of energy is $\alpha_r = \alpha_f = 0.5$. The productivity growth rate in the final product sector is defined so that the long-term growth rate is 2% and the population growth rate is nil. To calibrate Ψ, we need to assign values to its two parameters, $\bar{\imath}$ and ψ. These two parameters are determined from three conditions: (i) the expression for the optimal asymptotic long-run growth rate of technology adoption, (ii) the requirement that the long-run growth rate in the renewable energy sector and final good are equal, and (iii) that the technology adoption cost function is concave. The calibrated value for the upper bound on the adoption rate implies a maximum attainable renewable technology annual growth rate of about to 5% (for more details, see Adão *et al.* 2021).

We define 2015 as the starting year of the exercise. The four parameters related to the energy sector that have yet to be calibrated are the amount of fossil fuel existing, in the sense discussed in Section 4.1.1, w_0, the productivity of the renewable sector, $\mathcal{E}_0$, the initial Pigouvian tax, τ^f, and the spillover of adopting renewable technology, ξ. In the calibration we set $w_0 = 923$ GtC. The initial amount of oil and gas is 253.8 GtC, while the initial amount of coal is 666 GtC (for a detailed explanation of these values, see Section 4.3 of Li *et al.* 2016).

The values of $\mathcal{E}_0$, τ^f and ξ are jointly determined so as to match three values taken from the data: (i) the initial portion of renewable energy in total energy production, s_0, (ii) the initial fossil fuel consumption, f_0, and (iii) the change in the share of renewable energy in the last period, that is, since 2005, $s_0 - s_{-1}$.

Optimal policy has to correct the two distortions in the economy. There is underinvestment in the renewable energy sector due to positive spillovers, and there are social costs associated with the externality of carbon emissions. Both distortions can be completely resolved using two instruments. In the first case, the solution is a policy that taxes companies in the renewable sector in proportion to their underinvestment. Such a policy implements the optimal level of investment by making companies indifferent between paying the tax and choosing the socially optimal level of investment. In the second case, the solution is a Pigouvian tax that internalises the externality of carbon emissions. As in Golosov *et al.* (2014), if the utility function is logarithmic and the depreciation of capital equals 100%, as this text admits, then the tax rate does not depend on the growth of the economy. This implies that the simulations in this section will assume that the optimal policies are initiated instantly.

Optimal policy has interesting implications. The policy used in companies that produce renewable energy does not generate tax revenue, and induces additional innovation in relation to the competitive equilibrium by implementing the level of investment corresponding to the case in which there are spillovers, that is, $\xi = 1$. The Pigouvian tax reduces companies' profits in the non-renewable energy sector, but the transfer to households by the same amount means that their budget constraint does not change.

In what follows, we denote by τ^f the value of the Pigouvian tax as a percentage of its optimal level, and by ξ the index for the spillover effects, with $\xi = 1$ corresponding to the no spillovers case and $\xi = 0$ corresponding to the maximum spillovers case. Taking $\mathcal{E}_0 = 14.92$, $\tau^f = 0.63\tau^*$ and $\xi = 0.54\xi^*$, the model reproduces the initial fossil fuel consumption values, $f_0 = 100$ GtC, the current fraction of renewable energies, $s_0 = 10.2\%$, and the rate of growth of the fraction of renewable energies, $s_0 - s_{-1} = 2.3\%$. This last figure includes all modern and traditional renewable energies, including biomass. An initial 10-year growth rate of 4.7% is estimated for renewables, with a corresponding rate of 2% for the entire energy sector. Nuclear power is not included in this calculation.[23]

The initial productivity of the renewable sector affects the share of renewable energy in total energy production. In turn, the spillovers of the adoption of renewable technologies affect the change in productivity of the renewable sector and, consequently, the change in the share of renewable energy. In addition, the Pigouvian tax affects the use of fossil fuel and, consequently, the fossil fuel and renewable sources shares of total energy production.

4.3. Results

Calibrating the policy parameters (the Pigou tax rate, τ^f, and the initial rate of technology adoption, ξ) allows us to assess the effect of the emissions tax and the policy targeted to the adoption of renewable energies separately, as well as in conjunction. The model is simulated considering different scenarios for the two policy parameters. Figure 17 shows the trajectories for the share of renewable energy (top panel), accumulated fossil fuel consumption (middle panel) and global

23. See `https://www.ren21.net/reports/global-status-report/`.

temperature (bottom panel), in each policy scenario. The different lines indicate the different types of policy, that is, the status quo, the optimal technology adoption policy, the imposition of the optimal Pigouvian tax, and the two optimal policies implemented simultaneously.

The first panel shows the fraction of renewable energy in energy production over time for different policy scenarios. The renewable energy adoption policy (dashed line) reduces the share of renewable energy in the short term compared to the status quo case (dotted line). On the other hand, energy production becomes fully based on the renewable part sooner than the status quo. In contrast, with the Pigou tax at its optimal level and in the absence of the optimal policy for the adoption of renewable technology (dash-dot line), the share of renewable energy increases immediately. In the situation where both policies are implemented simultaneously (solid line), the share of renewable energy does not change immediately. However, the transition to a fully renewable global economy takes place in 2080, earlier than in the other three scenarios.

The second panel describes the evolution of the cumulative consumption of fossil fuels in the same four scenarios. Interestingly, without the optimal Pigouvian tax, the cumulative consumption of fossil fuels is initially a little more intense if the technology externality is internalised (dashed lines) than in the case of the status quo (dotted lines). This is because the faster growth in renewable energy productivity allows the economy to fully rely on renewable energy sooner. Likewise, in the scenario where the Pigouvian tax and technology adoption are optimally defined (solid lines), the economy reaches the full renewable energy regime sooner, and more fossil fuel is left unused. Consistent with the "green paradox", this also implies a higher use of fossil fuel initially than in the case where only the optimal Pigouvian tax is in effect (dash-dot lines).

The third panel shows the trajectories of global temperatures in the four policy scenarios. Consistent with the use of fossil fuel in the top panel, the global temperature rises in both the status quo scenario and the ideal technology adoption scenario, reaching about 2.8°C above the pre-industrial level. The temperature under the technology adoption policy (but in the absence of an optimal Pigouvian tax) drops a little faster than under the status quo. In the case of the optimal Pigouvian tax, and the case with both optimal policies, global temperatures peak around 2.2 and 2.0°C above the pre-industrial level, respectively, and then slowly decrease over time.

We now proceed to the analysis of welfare under these scenarios. Following Robert E. Lucas (1987), the welfare gain is calculated in terms of the percentage consumption equivalent for each of the policies, relative to the status quo case. Changing from this baseline scenario via optimal technology adoption alone would imply an equivalent consumption gain of 0.25%. This corresponds to saying that an agent would be indifferent between benefiting from the optimal consumption trajectory and having a consumption trajectory equal to the status quo increased by 0.25%.

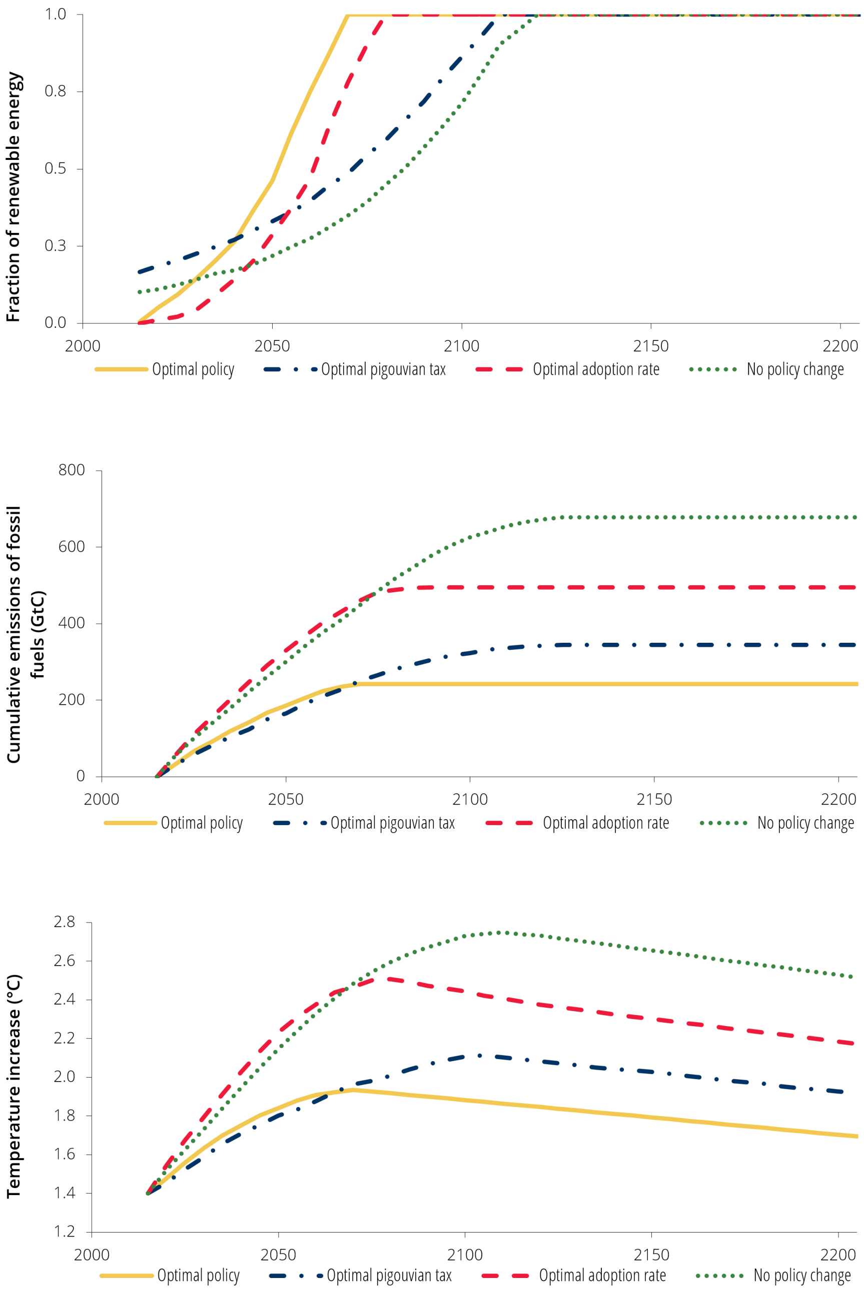


Figure 17: Fraction of total renewable energy, fossil fuel consumption and global temperature.

With the optimal Pigouvian tax implemented alone, a gain of 1.02% is obtained, confirming the relative importance of the carbon tax. Comparing the status quo

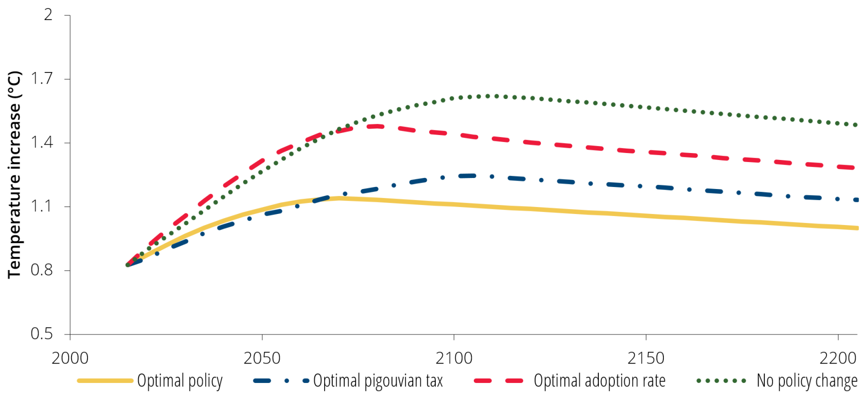


Figure 18: Temperature variation in Portugal compared to the initial situation.

with the situation in which the two policies are applied results in an equivalent consumption welfare gain of 1.43%. The difference between the sum of the welfare gains of the isolated application of each policy and the welfare gain of its simultaneous implementation is about 0.16%. This suggests considerable complementarity between the two policies.

The previous results show that stimulating the optimal level of R&D in the renewable sector is not an alternative to carbon taxes. Such policy in isolation provides relatively small benefits. This model suggests that there are complementarities between the two policies, that is, that considerable welfare gains can be obtained when the policies are adopted simultaneously.

The results for the global economy suggest more limited effects in Portugal. Judging by past dependencies, the change in temperature in Portugal will be less pronounced than in the planet as a whole. Using regression (5), the temperature variation in Portugal, $\Delta T_{P,t}$, is related to the global temperature variation, ΔT_t, according to

$$\triangle T_{P,t} = 0.59 \times \triangle T_t \, . \tag{22}$$

Figure 18 shows the evolution of temperature in Portugal for the four scenarios. Given that the variation in global temperature will be between 2 and 2.8°C, depending on whether climate policies are adopted or not, the expected variation in temperature in Portugal will be between 1.2 and 1.7°C.

Losses in GDP can also be relatively low. Assuming that the Nordhaus damage function (10) is valid for Portugal, the losses in terms of GDP will be between 0.4% and 0.8% compared to the status quo. The consumer welfare gain in Portugal from adopting the optimal policies in relation to the status quo is about 0.4%. Even so, this value means that the estimated welfare gain compared to the status quo would correspond to a trajectory of Portuguese private consumption with around 520 million additional euros permanently, at today's prices.

4.4. Additional considerations

This section provides estimates of the impact of climate change in four scenarios: status quo, optimal Pigouvian tax, optimal R&D investment policy for firms operating in the renewable energy sector, and both policies simultaneously. The best result is obtained in the latter case. Inducing the optimal level of technological innovation in renewable energy – often considered an easier policy to implement – is, by itself, ineffective, while the optimal Pigou tax is already, even alone, very effective in reducing carbon emissions.

The estimates obtained are subject to many uncertainties. The relationship between carbon emissions and extreme weather events has not been taken into account. The relationship between carbon and temperature may be non-linear due to so-called "inflection points", that is, levels of increase capable of inducing additional positive feedback mechanisms, as discussed in Section 2.1.3.

Only the loss of GDP is considered, but other costs not quantified by the markets, such as conflicts arising from migratory movements of people or the loss of biodiversity, must also be considered. On the other hand, future technological improvements could allow the sequestration of carbon, not only from emissions, but also from carbon in the atmosphere. For these reasons, these estimates for the impact of climate change on the economy must be considered very imprecise assessments of the values that will one day come to pass.

As mentioned above, the discount factor used in this analysis is located at the upper limit of the values proposed in Section 3.3. How would these results change with lower discounts, that is, giving more weight to the future? The generic answer is that the long-term effects on climate and output would be less pronounced because future generations, living in a steady state, would have to have greater well-being than in the current exercise. This would be achieved in principle with a faster adoption of new technologies induced by higher carbon taxes. The innovation policy would also be based on a scheme inducing a total internalisation of the companies' investment effects. In this perspective, the values given in the previous section are upper bounds on the total effects but, given the uncertainty surrounding the entire exercise, they can only be seen as conservative estimates of effects that can be much worse. And a non-negligible aspect is that, due to the dynamics of the adoption of new technologies, the setting of higher-than-optimal carbon taxes does not induce significant losses in the economy: it is better to err on the side of excess and face low costs for this error, than who miss by default and face huge welfare losses (Hassler *et al.* 2020).

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Appendix: Temperature and precipitation on the Earth's land surface and in mainland Portugal

This appendix (Figures A.1–A.3) presents the average temperature and precipitation for the Earth's land surface and for the territory of mainland Portugal. It is not the objective of this work to characterise the climate of these geographic units. The reader is referred to the abundant literature on this topic and, in the Portuguese case, to the works on Fragoso (2008) and de Lima *et al.* (2013).

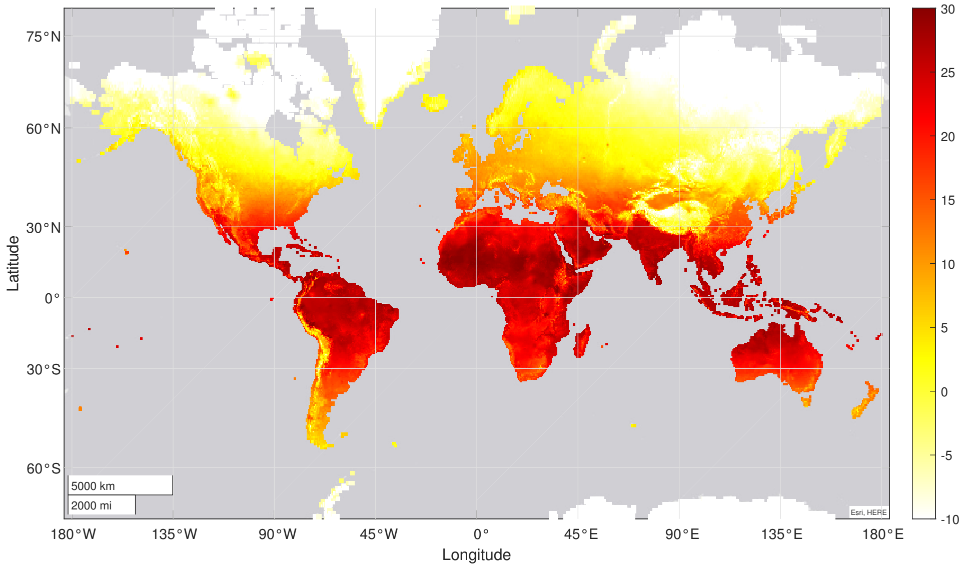

Figure A.1: Average annual temperature at the Earth's land surface for the period 1950–2017. Values in °C.

Sources: Matsuura and Willmott (2018a) and authors' calculations.
Notes: Average annual temperature is defined as the year-round average of the monthly average temperature. Values in °C truncated to the range $[-10; 30]$.

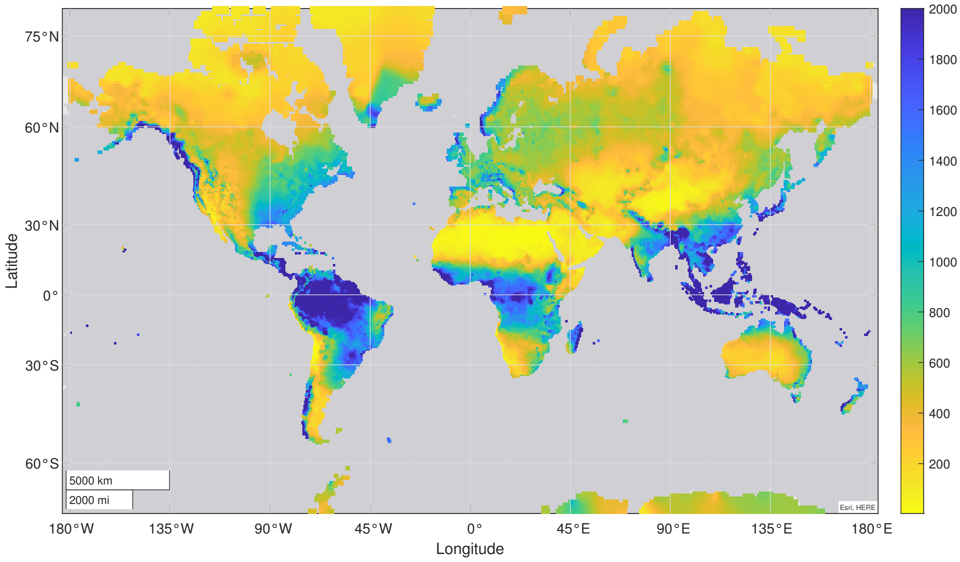

Figure A.2: Average annual precipitation on the Earth's land surface for the period 1950–2017. Values in mm.

Sources: Matsuura and Willmott (2018b) and authors' calculations.
Notes: Average annual precipitation is defined as the temporal average of the amount of precipitation accumulated throughout the year. Values in mm truncated to the range $[0; 2000]$.

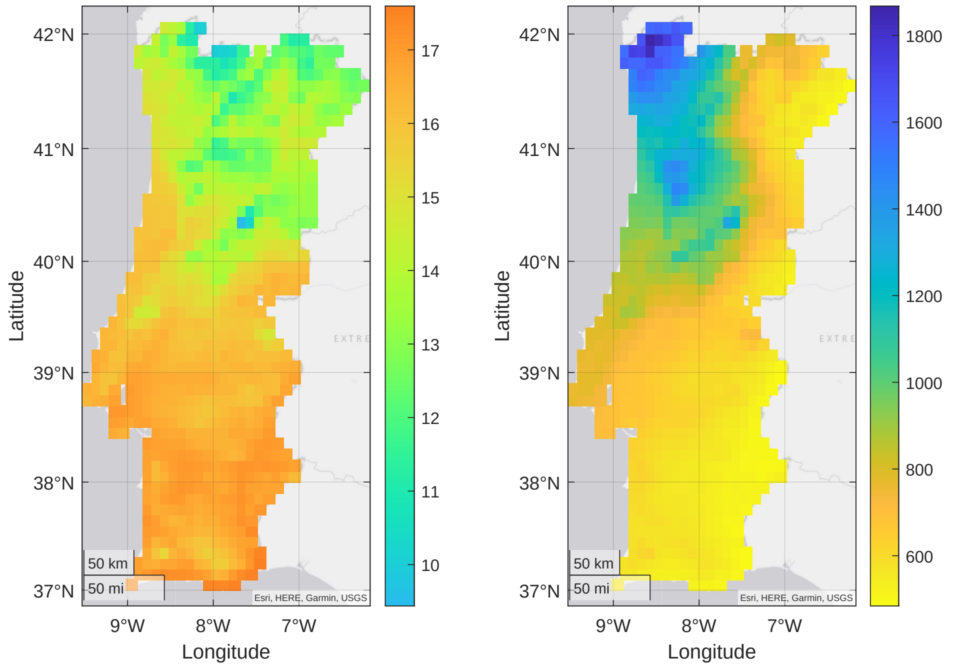

Figure A.3: Average annual temperature and total annual precipitation in mainland Portugal for the period 1971–2015. Panel (a): annual average temperature, in °C. Panel (b): total annual precipitation, in mm.

Sources: E-OBS and authors' calculations.
Notes: Average annual temperature is defined as the year-round average of the daily average temperature. Total annual precipitation is the cumulative value of precipitation throughout the year.

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