A contribution to the study of the economic causes and consequences of climate change:

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2015

document version
Publisher's PDF, also known as Version of record

16. Conclusions and future research

This thesis examined some of the most commonly used methodologies for defining the climate change problem and its nature —that is, its detection and attribution— and those designed to help dimensioning the present and future risks of this market failure. The main conclusions and their relevance are briefly discussed in the following paragraphs:

16.1 Research conclusions

16.1.1 The detection and attribution of climate change.

Part I of this doctoral work combined econometric methods with fundamental concepts from climate physics and modeling to investigate the attribution of climate change. Here we summarize the most relevant conclusions regarding the economy-climate relationship.

Is the observed climate change anthropogenic?

The existing statistical methods for investigating the attribution of climate change were critically reviewed in Chapter 2. Chapters 3 and 4 present a new approach for investigating the attribution of climate change based on state-of-the-art econometric techniques that are appropriate for the time-series properties of global temperature and radiative forcing series.

Chapters 3 and 4 investigated the attribution of climate change in two complementary ways by analyzing observed and simulated temperature series, respectively, and radiative forcing series. Evidence regarding the existence of common features such as nonlinear trends and time ordered breaks was presented. Furthermore, it was shown that the common nonlinear trend characterizing all global, northern and southern hemisphere temperatures and the total radiative forcing series can be traced back to the radiative forcing of well-mixed greenhouse gases —one of the components of the total radiative forcing— which is mainly of anthropogenic origin. The most salient feature of global

and hemispheric temperatures is an abrupt and sharp increase in the slope of the warming trend in the mid-20th century. This feature is the outcome of the unprecedented increase in emissions and atmospheric concentrations of greenhouse gases produced by the global economic boom experienced after WWII. Anthropogenic radiative forcing defined the secular movement in the observed total radiative forcing and temperatures series, while all other radiative forcing factors only modulated this trend.

Climate simulations are the product of a controlled experiment where all forcing factors that could impart a secular movement to simulated global temperatures are explicitly identified. As such, these experiments provide an alternative way to test for the anthropogenic origin of the warming trend observed during the 20th century. Results in chapter 3 show that the ensemble mean of model simulations and observed global temperatures share the same trend and confirm that the anthropogenic forcing is the main factor imparting nonstationarity to the total radiative forcing and global temperatures. Moreover, co-trending tests constitute an alternative to the traditional "optimal fingerprinting" methods when applied to observed and simulated climate variables.

An important methodological implication of these results is that standard cointegration techniques —which are the main approach used for conducting observation-based attribution studies— may not be reliable since the data generating processes are misidentified and the existence of breaks in the trend function is neglected.

What are the causes behind the current slowdown in the warming?

Since the late 1990s there have been strong discrepancies between: 1) the ever increasing emissions and atmospheric concentrations of CO_2 and the almost imperceptible increase in global temperatures and; 2) the observed global temperature and climate models' projections. The hiatus in the warming has not only attracted the attention of the scientific community and policy-makers but also of the society at large and has increased the skepticism regarding the anthropogenic origins of the observed warming and reduced the credibility of current climate models to project future climate. Understanding the reasons behind the current slowdown in the warming has recently become one of the most active and important research topics (e.g., Tollefson, 2014).

Chapter 4 focused on describing and explaining the most relevant features of the observed warming trend. Results indicate, for the first time, that landmark socioeconomic events are important contributors to the changes in the rate of warming of global and hemispheric temperatures experienced during the last century. The major policy relevant conclusion of this chapter is that the recent decrease in warming has a direct human component. The effects of the Montreal Protocol and the changes in agricultural production in Asia can account for a considerable part of the recent slowdown of the warming. These actions show that slowing down the rate of warming can be achieved in the short term and that reducing greenhouse gas emissions other than CO_2 can be an effective way of doing so. Furthermore, the evidence presented in Chapter 4 indicates that this is not the first time that historic socioeconomic events have affected the general warming trend. The two World Wars and the Great Depression contributed to the cooling period of the mid-twentieth century.

The results in this chapter suggest that the breaks found in the warming trend can be seen as the product of an ordered sequence of structural changes induced by human systems to the emission of greenhouse gases and tropospheric aerosols, to the atmospheric concentrations/radiative forcing and finally to the global and hemispheric temperatures.

Are current climate models capable of reproducing the most salient features of the observed warming?

Chapter 3 analyzed the time-series properties of a set of global temperature simulations taken from the 20c3m climate experiment produced for the Fourth Assessment Report of the IPCC. The results presented in this chapter show that, in most cases, climate models can adequately reproduce the main features of the warming trend in observed global surface temperatures. Both observed and simulated global temperatures show a slight warming trend during the first part of the 20^{th} century followed by an abrupt and large change in the rate of warming around the 1970's. Moreover, the post-break warming rates of the different simulations are shown not to be statistically different to that of the observed global temperatures although, for some models significant differences are found in the estimates of the break date and for most of them in the magnitude of the pre-break warming rate. Despite these discrepancies, it is shown that observed and simulated global temperatures, the total radiative forcing and the

anthropogenic radiative forcing share a unique common nonlinear trend. These results offer additional evidence regarding the capacity of current climate models to accurately simulate the response of the climate system to changes in external forcing factors, even if rapid or abrupt.

16.1.2 The global economic impacts of climate change

Integrated Assessment Models (IAMs) are the main tool for analyzing the economics of climate change at the global level in an internally consistent manner and are widely used for advising climate policy. Part II concentrated in analyzing and improving the impact functions used to translate changes in climate to economic impacts. These functions are commonly recognized as one of the weakest and least developed aspects of these models. The results in this thesis show that IAM projections of global and regional costs of climate change are very sensitive to implicit assumptions regarding the dynamics of the impact functions. These assumptions have been little discussed in the literature and are typically ignored in IAM modeling. Extensions of the common impact function specification are proposed to explicitly account for impact, sensitivity and adaptation dynamics as well as to allow for stochastic climate change.

Until now the validation of IAM projections continues to be problematic due to the lack of observed data on welfare losses from climate change. However, the projection of past impacts is a first step towards a better understanding of both the potential consequences of observed climate change and the differences in IAMs projections for small increases in warming. In this thesis, IAMs are used to project and, for the first time, decompose the expected impacts of climate change during the 20th century into their natural and anthropogenic components.

As described below, the research questions addressed in Part II of this thesis are centered on making IAMs more consistent with what is known about the physical and socioeconomic processes that determine the economic costs of climate change.

Are the dynamics of impacts adequately represented in the current impact functions?

Chapter 7 focused on analyzing the univariate temporal dynamics of shocks embedded in most of the impact functions of commonly used IAMs. These impact functions typically assume that the shocks caused by climate change impacts dissipate and have no persistence at all, affecting only the period when they occur. This assumption is found to be problematic since: 1) most of macroeconomic variables (e.g., GDP) show a high degree of persistence of general shocks and, although the degree of persistence of climate shocks is unknown, the "zero persistence" implied by most impact functions is an extreme assumption regarding the memory of GDP which is not supported by the observed data nor by economic growth theory; 2) the zero persistence assumption can be interpreted as an autonomous, extremely large and effective, costless reactive adaptation and limitless resilience capacities to no matter how large impacts climate change may produce in both human and natural systems and; 3) relaxing this assumption leads to considerably larger estimates of the economic impacts of climate change and, presumably, to very different climate policy recommendations. This chapter provides an easy to implement approach for incorporating the persistence of shocks in IAMs to estimate the potential economic costs of climate change.

How can adaptation and sensitivity be better represented in these models?

Currently, the impact functions in IAMs implicitly assume that the sequence of impacts a system is exposed to is unrelated to how the system will respond to further changes in climate. The only time-dependent factor determining the impacts in these functions is climate, while the systems' sensitivity and adaptive capacity are static and combined in an inseparable way. Chapter 8 extended the study of the dynamics in the impact functions in Chapter 7 by using a theoretical approach to develop a new type of damage function that allows feedbacks and interactions between impacts, autonomous and planed adaptation and vulnerability by explicitly modeling adaptation and sensitivity as dynamic processes. Contrary to most of the current impact functions, this new type of impact function maps economic losses in terms of the time-varying capacity of a system to deal with climate conditions experienced at a certain period in time, instead of fixed proportional damages produced by absolute changes in climate. The economic losses are a function of how extreme global temperature changes are in relation to the capacity of a system to deal with the climate conditions experienced at a particular period of time. This chapter argues that representing sensitivity as a dynamic process provides mechanisms that reconcile the apparent disconnect between the low to moderate

economic costs projected by IAMs and the severe physical impacts that are frequently projected for large changes in climate.

How can the impact functions be extended to investigate the impacts of stochastic climate change?

The future impacts of climate change will be a function of both anthropogenic climate change and natural variability. However, impact functions in IAMs are designed for projecting the impacts of smooth climate change. Chapter 6 derived impact functions for stochastic climate change and showed that these functions have the same shape and similar parameterization to the original deterministic impact functions. Although the monetary impacts are therefore similar for both types of functions, allowing for stochasticity does increase the estimates of welfare impacts. Moreover, Chapter 5 showed that when estimating the costs of climate change, the interaction effects between natural variability and external forcing factors can be large, making the current approach for projecting future impacts based on idealized climate change trajectories potentially biased.

These effects can be particularly large in the case of low-frequency variability. As has been recently discussed (see Chapter 4) it has been shown that the amplitude of climate variability can be comparable in magnitude to the climate signal for the observed and the projected short- and medium-term warming rates. As such, the actual warming that may be experienced in the coming decades —which has a disproportionate weight on the present value of the costs of climate change— can be significantly different from that of smooth projections. Chapter 5 and 6 represent a first step towards using more realistic climate projections in integrated assessment modeling.

Can the estimates of the impacts of observed climate change be decomposed into natural and anthropogenic contributions?

The projection of past impacts is relevant for understanding better both the potential consequences of observed climate change and the differences in IAMs projections for small increases in warming. More importantly, decomposing the observed impacts into their natural and anthropogenic components helps comparing the magnitude of the impacts that are attributable to different factors and evaluating the importance of their interaction effects for projecting climate change costs. Chapter 5 combined the results

obtained in Chapter 4 with IAM models to decompose, for the first time, the expected impacts of climate change during the 20th century into their natural and anthropogenic components.

The decomposition of the estimated impacts of observed climate revealed a clear anthropogenic influence that at the end of the century becomes even larger in magnitude than the impacts of natural variability. The contribution of natural forcing to the total estimated impacts is one order of magnitude lower than that of the anthropogenic forcing or that of the internal interannual variability. In the intra- and inter-decadal scales, the amplitude of the impacts associated to natural variability is considerably larger than that produced by anthropogenic factors during the first half of the century. These non-monotonic impacts are mostly determined by the low-frequency variability modes and persistence of the climate system.

The effects of anthropogenic forcing in agriculture account for most of the economic benefit in the past century. Benefits attributable to the anthropogenic forcing are also found for the energy sector, while this forcing imparted economic losses in human health and water resources. Results suggests that the contribution of anthropogenic forcing to the estimated number of deaths per thousand people is dominant in the case of diarrhoea, respiratory diseases and malaria.

16.1.3 The impacts of climate change at the regional/local scales.

Regional and local assessments of the present and future impacts of climate change represent a significant part of what is currently known about the consequences climate change. These studies are the main source of information for calibrating more general models such as IAMs. Part III of this thesis is concerned with different aspects of the investigating the impacts of climate change at the regional and local scales including the detection of a climate change signal in observed losses from extreme events, modeling epistemic uncertainty and the use of downscaling methods. New methodological approaches were proposed to address these issues.

Has observed climate change increased weather related disaster damages?

The literature has almost unanimously ruled out the existence of a climate change signal in the observed economic losses from extreme events. According to these studies, the upward trend commonly shown by weather related disasters is in its entirety explained by the observed increases in wealth and population in areas prone to experience such events. However, most of the available studies rely on the adequacy of ad-hoc normalization methods and basic statistical analysis that could easily lead to spurious results. A regression-based normalization procedure is proposed for estimating the value of the normalization coefficients, instead of imposing arbitrary values as is currently done in the literature. Chapter 9 analyzed the economic losses from hurricanes in the US and showed for the first time the existence of a possible climate change signal that was obscured by the methodological approach undertaken in previous studies. By 2005 climate change could have already contributed in the order of $2-$14 billion to the recorded annual losses, about 2%-12% of the normalized losses in that year. Empirical evidence suggests that the upward trend in both the number and intensity of hurricanes in the North Atlantic is related to the observed warming trend represented by the smoothed global average surface air temperature. Hurricane losses in the U.S. could increase by $19-$88 billion for 1ºC rise in global temperature.

How can epistemic and aleatory uncertainty be better represented in impact assessment studies?

Existing methods for the assessment of the potential impacts of climate change on economic activities and sectors are usually limited to point estimates that do not consider the inherent variability and uncertainty of climatic and socioeconomic variables. This is a major drawback given that only a limited and potentially biased estimation of risk can be expected when ignoring such determinant factors. This thesis presented a simulation based method to produce probabilistic impact scenarios that are consistent with the current state of knowledge and the available subjective "expert" information. The proposed method for the probabilistic assessment of the potential impacts of climate change differs from other simulation based methods in that the subjective information used to represent epistemic uncertainty is explicitly stated. The main objective is to transform probability distributions of uncertain model inputs into meaningful expressions of the decision-maker's beliefs as opposed to impersonal, one-size fits all, statistically inadequate devices.

How can the methods currently used for projecting local and regional climate change be improved to adequately model the relationship between non-stationary time series?

A critical part in impact assessment and adaptation studies is properly representing the changes in local and regional climate. The results of these assessments are in general highly sensitive to changes in the magnitude and spatial distribution of change in climate variables. The purpose of statistical downscaling in climate change is to generate relevant information for the assessment of the potential impacts of this phenomenon on human and natural systems at the local scale that would help to guide policy making. Therefore, the possible implications of using statistically inadequate models for this task can have non-trivial consequences as shown in chapters 13 and 14 which analyze the methodological approach used in Mexico's national climate change documents.

In this thesis it is shown that even though downscaling is usually considered as a problem in the physical sciences, this is another area of opportunity for interdisciplinary studies. Econometric methods can provide new and more robust approaches for statistical downscaling. Chapter 11 and 12 illustrate the usefulness of econometric concepts and models for downscaling climate change scenarios. Chapter 11 introduced the Probabilistic Reduction approach and the concept of statistical adequate models for producing downscaling climate change scenarios while Chapter 12 presented a new methodology for generating climate change scenarios at the local scale. By combining multivariate time series models and restricted forecast techniques, this methodology offers considerable advantages over the current statistical downscaling techniques as: 1) it provides a better representation of climate at the local scale; 2) it avoids the occurrence of spurious relationships between the large and local scale variables; 3) it offers a more appropriate representation of variability in the downscaled scenarios; and 4) it allows for compatibility assessment and combination of the information contained in both observed and simulated climate variables. In addition, the proposed methodology is useful for integrating scenarios of local scale factors that affect the microclimate. As such, the convenience of different public policies regarding, for

example, land use change or atmospheric pollution control can be evaluated in terms of their effects for amplifying or reducing climate change impacts.

16.1.4 Evaluating the robustness of the science behind national climate change documents.

The social relevance of climate change science depends to a great extent on its usefulness for decision-making. National documents, financed by different government agencies, are some of the most relevant sources of information for supporting decision-making on issues considered of prime importance for the country. As such, the academic evaluation of these documents, and of the methodologies they are based on, is a necessary prerequisite for the development of sound climate policy.

Is the grey literature such as National Communications and other official documents a source of information for guiding national climate policy?

The last three chapters took some of the most relevant national climate change documents of Mexico as case studies to investigate the robustness of the science that is expressly conducted for supporting national climate policy. Chapters 13 and 14 critically reviewed the downscaling methodology used for Mexico's Fourth National Communication to the United Nations Framework Convention on Climate Change, the Fourth National Report to the Convention on Biological Diversity and The Economics of Climate Change in Mexico. Results show that this downscaling methodology destroys the patterns produced by the climate model associated with climate change, and replaces them with random patterns and magnitudes. A direct consequence is that the impact and adaptation assessments that were conducted using these scenarios should be revised and therefore, these national documents are inadequate for supporting national decision-making.

The second case study is The Economics of Climate Change in Mexico which was meant to guide Mexico's stance on climate change issues and international negotiations and benefited from the support of members of the Stern Review team. Furthermore, this study had an important regional impact and served as a model for other national climate

change documents in Central and South America. Chapter 14 showed that the study has important conceptual and methodological deficiencies that make it inappropriate for supporting decision-making. In fact the main policy recommendation of this document —to adopt significant mitigation actions (50% emissions reduction in 2100 with respect to 2002)— was shown to be inconsistent with the estimates of costs and benefits provided in the same study.

The results of these two case studies point to the need of rethinking how to strengthen national climate change documents in terms of scientific rigor and critical evaluation. This is particularly important given the role of these documents as a prominent source of information for supporting national decision-making on climate change policies.

16.2 Implications for policy making

The main implications for policy making of this thesis are:

1) The attribution of climate change to anthropogenic activities is strongly supported by observations and climate model simulations. Moreover, not only the general warming trend can be accounted by the anthropogenic forcing but also the observed changes in its rate of growth can be linked to landmark socioeconomic events such as the two World Wars, the Great Depression, the success of the Montreal Protocol, and large changes in agricultural production in Asia. International actions can affect the warming trend in a relatively short amount of time.
2) As has been discussed in the literature, the current estimates of the economic costs of climate change are very uncertain and highly sensitive to a variety of underlying assumptions (e.g., Van den Bergh and Botzen, 2014; Tol, 1996). The results of this thesis suggest that 1) the available estimates should be carefully interpreted when used for guiding climate policy and 2) more research should be devoted to improve these models.
3) This thesis offers evidence for the existence of a possible climate change signal in the observed economic losses from hurricanes in the U.S. Current methodologies for normalizing that are widely applied to analyze loss data can

potentially be masking a climate change signal in other regions and other types of extreme events as well. The presence of a warming signal in extreme events losses could reshape the perception of risk of both policy-makers and the general public and have major implications for national and world climate policy.

4) The development of sound national climate policy can be hindered by the lack of appropriate review processes of the science-supporting official documents on climate change. This is likely to be more severe in developing countries and can significantly limit the usefulness of international funds directed to support the creation of local scientific information. Given the influence that national documents can have on a wide variety of decision-makers and social agents, as well as for developing national and international public policy, it is argued that the review process for these documents should be, at least, as rigorous as it is for scientific publications.

16.3 Future research

Climate change is not easily separable into its disciplinary components due to the existence of numerous interdepencencies, circularities and shared uncertainties. The economics of climate change is far from an exception. This is still an emerging research field and, as is typical when dealing with so-called wicked (or super wicked) problems, it calls for blurring disciplinary boundaries and provides a fertile ground for the development of new ideas and methodologies. The way forward in the study of the economic causes and consequences of climate change is therefore to expand on interdisciplinary and integrative research. Not doing so would translate into a missed opportunity for increasing the relevance of climate change research.

Integrated assessment, in its wide sense, is based on the combination of knowledge from different disciplines to address issues that are at the same time scientific and policy relevant. Two complementary integrated assessment frameworks were used in this thesis for investigating highly complex, dynamical systems and their interactions: the combination of economics, statistics and climate sciences and the use of integrated assessment models (IAMs). Future research should aim for a wider interdisciplinary scope and continuously critically revise and improve the frameworks, methods and

procedures used in climate change research. Some general areas of opportunity for expanding and improving our understanding of the economic causes and consequences of climate change are related to:

- The generation of new and improved estimates of the vulnerability to, and potential impacts of, climate change as well as of the adaptative capacities of different regions and sectors in order to advance IAM design and calibration.
- The development methodologies for the evaluation of IAMs projections.
- Improving the understanding and modelling of the relationships, dynamics and interactions between vulnerability, impacts, adaptation and mitigation.
- Understanding and modelling the synergistic effects between climate change and other concurrent socio-environmental processes that may alter the potential impacts and risks in significant ways.
- Modelling the transimision among regions of the impacts of climate change.
- Improving the representation of socieconomic systems and processes in IAMs.
- Improving the understanding and management of uncertainty from both socioeconomic and natural sources.
- Increasing the understanding of natural climate variability and its interactions with external forcing.

In addition to the general future research areas listed above, the following paragraphs describe some particular extensions of the work presented in this thesis that are already being address by my coauthors and me:

A relevant extension of the work presented in Part I of this thesis is to use econometric methods to test the "missing heat" hypothesis (e.g., Tollefson, 2014) proposed as a possible explanation for the slowdown in the warming experienced since the late 1990s. According to this hypothesis a large part of the energy produced by the enhanced greenhouse effect is being transferred to the deep oceans. As is expected from complex systems such as climate, the hiatus in the warming is unlikely to be explained by a single cause, and investigating the evolution of the observed ocean heat content can complement the findings of Chapter 4.

Chapter 2 concludes that climate models can adequately represent the observed warming trend. However, the large discrepancies between model simulations and observations during the last two decades suggests that a more detailed evaluation of this period as well as of the effects of models' internal variability over the simulated warming trend is required. As is shown in Chapter 4, important characteristics such as the timing of the break and the magnitude of the post-break slope can be importantly modified by natural variability. In particular, the differences in the break date in global temperatures change from the late 1970s to the early 1960s once the main mode of natural variability is filtered out and the magnitude of pot-break slope decreases from around 1.5°C to 1.0°C. The fact that climate models' simulations closely reproduce the characteristics of the unfiltered temperature series is to some extent unexpected given that the models internal and observed variability have no reason to be in phase with observed climate variability. This could imply that climate models could be underestimating the true climate variability and possibly overestimating the warming trend.

Our findings provide further evidence regarding the high sensitivity of IAM projections to some of the implicit assumptions contained in the specification of their impact functions. In particular, the assumptions about the temporal dynamics of impacts are shown to have a considerable effect on the estimates of the costs of climate change. A natural extension is to generalize the dynamics of impacts to both time and spatial domains, allowing impacts to be transmitted among regions depending on, for example, their level of economic integration.

Results in Chapter 5 indicate that the interaction effects of natural variability and natural and anthropogenic forcing are important when estimating the economic costs of climate change. Current IAMs project future climate change based only in anthropogenic forcing, implicitly assuming that the effects of the different natural and anthropogenic forcing factors as well as those of natural variability are linearly separable. Furthermore, as discussed in this thesis and in the literature, the magnitude of low-frequency variability is comparable to the warming that has been experienced and not too different from the warming projected to occur in the next few decades. Given that the impacts of

climate change are discounted using a positive rate, the short- and medium-term have a disproportionate effect on these estimates.

Even though the methodological approaches proposed in this thesis contribute to improve the downscaling of climate change scenarios, they themselves have important limitations regarding their applicability for large downscaling exercises. The VAR approach proposed in Chapter 12 is only applicable in practice when the downscaling is going to be conducted for a limited number of local time series. As a consequence, the proposed methodology needs to be complemented with regionalization procedures when used in practice. Future research will explore alternative multivariate models that require a smaller number of parameters to be estimated.

Another important extension is to make the estimation of statistically adequate models more accessible to the climate change community by developing user friendly interfaces for this purpose or by expanding the existing ones. This would not only benefit the generation of downscaling scenarios but also the creation of statistical impact models and the empirical analysis of climate data.