Using Climate Analogues for Assessing Climate Change Economic Impacts in Urban Areas

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Résumé.

This paper aims at proposing a way to get round the intrinsic deadlocks of the economic assessment of climate change impacts (absence of consistent baseline scenario and of credible description of adaptation behaviours under uncertainty). First, we use climate scenarios from two models of the PRUDENCE project (HadRM3H and ARPEGE) to search for cities whose present climates can be considered as reasonable analogues of the future climates of 17 European cities. These analogues meet rather strict criteria in terms of monthly mean temperature, total annual precipitations and monthly mean precipitations. Second, we use these analogues as a heuristic tool to understand the main features of the adaptation required by climate change. The availability of two analogues for each city provides a useful estimate of the impact of uncertainty on the required adaptation efforts. Third, we carry out a cost assessment for various adaptation strategies, taking into account the cost of possible ill-adaptations due to wrong anticipations in a context of large uncertainty (from sunk costs to lock-in in suboptimal adaptation choices). We demonstrate the gap between an enumerative approach under perfect expectation and a calculation accounting for uncertainty and spill-over effects on economic growth.

Keywords: Climate change, Climate analogues, Impacts, Adaptation, Urban areas

1. Introduction

One prerequisite for the economic assessment of climate change impacts is the availability of relevant physical indicators. Such indicators are obvious for agricultural activities : these are crops productivity or crops suitability boundaries. There is no such obvious equivalent in urban areas. This may explain why most figures about costs of climate change consider primarily agriculture. However, the fact that agriculture will certainly be one of the main channels from climate change impacts to economic damages should not lead us to disregard that the majority of the population is nowadays urban and may be sensitive to the evolution of its living conditions. Moreover, urban areas concentrate the vast majority of capital stocks (housing, water delivery and transportation infrastructures) and climate change may require costly adaptation of the design of these infrastructures to minimize amenity losses.

This is why we propose a tentative approach to assess the costs of climate change in urban areas with a focus on the interplay between the technical and institutional inertia of urban systems and the uncertainty on future climates. To do so, we first show that present analogues of future climate provides a useful heuristic tool to develop indicators relevant for economic analysis. Second, we develop a methodology to build these analogues and display the main results for seventeen European cities : Athens, Barcelona, Berlin, Brussels, Copenhagen, Dublin, Geneva, Helsinki, London, Lisbon, Madrid, Marseille, Oslo, Paris, Rome, Stockholm and Vienna. In a third section, we use Paris as a case-study to demonstrate how these analogues can help to assess economic damages due to climate change and to design adaptation policies that accounts for the immense uncertainty surrounding this issue.

2. A heuristic tool to capture the systemic nature of climate impacts

Economic assessments of environmental disruption usually project a 'no environmental change' scenario and an 'environmentally impacted' scenario. They then calculate the difference between total welfare in both scenarios. This calculation has two components clearly separated : the description of individual and collective preferences, and the costs in terms of production losses and adaptation expenditures. The first raises very difficult theoretical issues and ethical controversies about inter- and intra-generational equity or about the use of money metrics, whereas the second is generally viewed as more straightforward and grounded in less subjective parameters. But this is true only as long as technical systems can be separated, allowing one to assess each cost independently.

This assumption may therefore be misleading for urban systems, that involve indeed complex interplays between a) technical subsystems governed by very different economic dynamics ; b) existing lifestyles in specific cultural and social contexts ; c) the historical legacy, including institutions and their adaptive capacity to changing conditions. For example, air conditioning is an obvious response to higher temperatures. Its costs, however, cannot be assessed without considering that its technical definition will be for long constrained by the existing types of buildings. Moreover, the resulting changes in net amenities for current generation may have structural impacts on the urban forms themselves and on the lifestyles of future generations. Itemised cost-benefit analysis is thus confronted to the daunting task of defining both a credible reference scenario based on a systemic description of urban forms (architectural styles, transport infrastructures) and on a consistent vision of the economic and cultural drivers of the adaptation to climate change.

The solution we want to explore on urban areas makes a heuristic use of 'climate analogues', already used by Darwin *et al.* (1995) or Mendelsohn *et al.* (1999) to assess climate change impacts on agriculture. This method allows one to circumvent the absence of consistent socio-economic scenarios and credible visions of adaptation mechanisms. Indeed, we use the information provided by a city B, which is currently experiencing climatic conditions that can be considered as reasonable analogues of the future (projected) climate conditions for city A. This analogy does not mean that A in 2100 must be similar to its analogue B in 2000. It means that observing the current infrastructures and living styles in B – which can be considered as adapted to its climate – is useful and informative. While it is not trivial to translate in economic terms a climate information like "the mean temperature will increase by x °C", using climate analogues provides an intermediary tool, supporting a systemic view of adaptation requirements and of the rate of required transitions. Note that this heuristic exercise can include the uncertainty about future climates, and we will show later to what extent uncertainty matters for damage assessment analysis.

3. Determining analogues through climate model simulations

The following methodology aims at providing answers in the form : "the best analogue to the projected climate of city A at the end of the century is either the present climate of cities B, C, D according to models l, m, p, respectively". We test this method using data from climate simulations carried out in the PRUDENCE project, for two models : the ARPEGE-Climat model, from CNRM/Météo-France, and the HadRM3H model, from the Hadley Centre. The first model is a global circulation model with a variable horizontal resolution – up to 50km in Europe ; the second is a regional climate model with a 50-km resolution, forced by a global circulation model (HadAM3). The HadRM3H model predicts a stronger global warming than the ARPEGE model, but they both lie within the range of the IPCC predictions. They both predict a warming over all Europe, with an increase in precipitation in the northern Europe and a strong drying over the mediterranean region.

Both climate projections are driven by concentrations from the SRES-A2 scenario [1] (IPCC, 2000) : ARPEGE-Climat simulation, as a global model, receives directly these concentrations as an input whereas the regional model HadRM3H is forced by the simulations of the HadAM3 atmosphere-ocean model. We derive from these simulations the 30-year monthly means of temperature and precipitations in the present climate (1960-1990) and in the 2070-2100 projected climate. To determine the present analogues of the future climate for each city we consider one grid point x corresponding to a city A. At this grid point T_i (resp. P_i) is the mean temperature (resp. the mean precipitations) for the month i. The future climate is thus defined by the 12 monthly mean projected temperatures and precipitations ($\{T_i^f(x), P_i^f(x)\}$). The present climate of the same city is similarly defined by the set $\{T_i^p(x), P_i^p(x)\}$. Characterising climates by these sets of monthly means use much more information than annual means and account for seasonal cycle.

To compare the projected climate of A $\{T_i^f(x), P_i^f(x)\}$ and the present climate at the grid point x', $\{T_i^p(x'), P_i^p(x')\}$, we use three distance metrics : a) d_T, the average of the absolute values of the differences between the temperature monthly means ; b) d_P^A, the relative difference between the annual mean precipitations, because total water availability is essential ; c) d_P^M, the average of the absolute values of the relative differences between the monthly mean precipitations, because the time distribution of rainfall determines both infrastructure requirements and lifestyles[2].

Unsurprisingly, defining analogues only with the temperature distance d_T is an easy task and leads to very low distance indicators (d_T lower than 0.2 °C in most cases). But this is at

[1] The A2 scenario is widely used in impact assessments and leads to rather high – but realistic – level of emissions during this century. It describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

[2] We use relative values for precipitations because this indicator makes sense for assessing impacts whereas the distance between absolute temperatures is more meaningful than relative changes. It is also worth noting that no inter-annual variability is considered.

the cost of a very bad fit for precipitations. This is why we defined an acceptability criterion for precipitations, in terms of upper bounds in d_P^A, at 15%, and d_P^M, at 30%. The tolerance margin may seem large for precipitations, especially at a monthly scale, but this translates their high short-scale (spatial and temporal) variability and the lower confidence we have in models precipitations. On that basis, the analogues are defined in two steps :

- First, we select the *best analogue* by finding the grid point x', that minimises the temperature distance d_T, while maintaining d_P^A and d_P^M within their acceptability ranges.
- Second, we retain this *best analogue* as an *acceptable* analogue only if d_T is lower than 1 °C.

For Barcelona for example, the annual mean temperature changes by 3.88 °C or 4.70 °C for the ARPEGE-Climat and HadRM3H models respectively, meaning that the the temperature distance (d_T) between current and future Barcelona is 3.88 or 4.70 °C. These temperature changes are associated with a 36 or 16% reduction in annual mean precipitations ($d_P^A = 36\%$ or 16%) and a 30 or 25% change in the average of the absolute values of monthly mean precipitations ($d_P^M = 30\%$ or 25%). The best analogues for Barcelona are Tunis or Algiers, depending on the model. To appreciate the validity of these analogues, we can observe that the temperature distances d_T between future Barcelona and its analogues are only 0.36 and 0.84 °C, the first precipitation differences d_P^A are only 8 and 2% and the second precipitation distances d_P^M only 21 and 30%, still for the ARPEGE-Climat and HadRM3H models respectively.

Interestingly it is not possible to find analogues for all cities. The cities for which no analogues are found are : Geneva, Rome, Helsinki and Lisbon with the ARPEGE model and Athens, Stockholm, Rome, Helsinki and Lisbon with the HadRM3H model. This absence of analogue may simply result from the spatial limitation of our analysis, the missing analogues being to be searched outside the regional model domains. But the absence of an acceptable analogue suggest also that climate change may generate climates that are not presently existing on earth[3] (*e.g.* the future climate of Rome, in ARPEGE-Climat). The underlying reason is that, whereas it is rather easy to find a *temperature analogue* B to any city A (this grid point B is often southward

[3] Note that there is no reason to consider these new climates as more "extreme" than the already existing ones.

from A because our cities are located in the Northern hemisphere), the precipitations pattern fits well only if the best analogue is located in the same type of climate than A (temperate, tropical, Mediterranean...). If the temperature analogue B is located in a different type of climate than A, the precipitation seasonal structure is different and no acceptable analogue can be found.

Figure 1 pictures the *"climate relocation"* of 17 European cities : each city is plotted at the location of its *acceptable analogue*, *i.e.* a location that presently enjoys a climate close to the one the city will experience in the end of the 21^{th} century. When no acceptable analogue is found, a cross indicates the location of the best temperature analogue, neglecting precipitations. One should mention the major role of elevation is some relocations : for instance, the Madrid analogue in the ARPEGE model seems to be very close from Madrid actual location, suggesting a small temperature increase. But in fact, the Madrid analogue is located at a much lower altitude (about 300m instead of about 1000m), and the temperature increase is larger than 4 °C. In the same way, the Helsinki analogues are located at high altitude in both models, explaining the impressive southern shift of this city.

4. Damages and adaptation costs : their drivers and their interplay

The two maps of Fig. 1, which give a synthetic view of climate change impacts, may trigger two opposite reactions. The optimistic one is that a Berliner may be very pleased that his or her grandchildren will enjoy the climate of Salamanca or Naples and that this climate shift may yield positive amenities for many Europeans. The opposite reaction is fuelled by concerns about the perspectives of such an impressive redistribution of climates : shocks at a local level, losses in amenities because a part of the population may not like to live in too warm and dry regions, losses of certain life styles, and migrations of populations. For example, the move of Barcelona or Lisbon toward very hot and dry climates may be viewed as a loss with drastic consequences for the economic attractiveness of these cities. The 'gaining' cities may in turn be

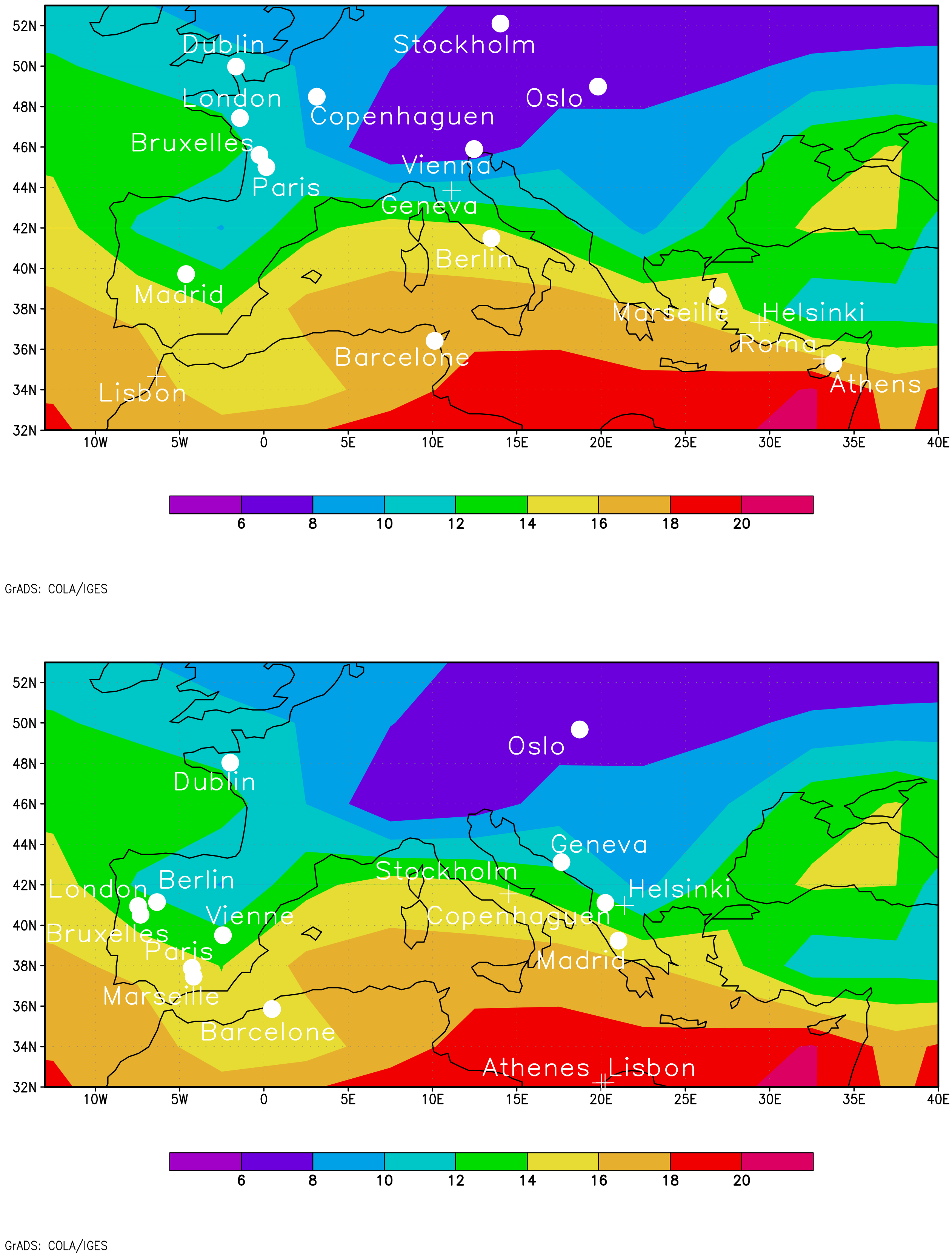

FIG. 1 Map of Europe and the Mediterranean basin, with a few cities represented by circles, at the location of their acceptable analogue, *i.e.* a location that presently enjoys a climate close to their future climate. When no acceptable analogue is found, a cross denotes the location of the best temperature analogue, neglecting precipitations. The background shows the mean annual temperature in the present climate. The upper panel is for the CNRM ARPEGE-Climat model, bottom panel for the Hadley Centre HadRM3H model.

negatively impacted by the propagation of shocks on the 'loosing' cities (uncontrolled migration flows, negative economic spill-overs...).

To try and avoid endless controversies between the tenants of each attitude, our starting point is to consider that 'amenities' delivered by a more sunny and drier climate depend on the way the infrastructures of the cities can be adapted in due time and at reasonable costs to these new conditions. Given the uncertainties at stake, this is enough to justify the precautionary behaviour which favours the current climate regime over unknown alternatives. In this sense, the distance between the projected city and its current analogue provides a synthetic indicator of the importance of the adaptation to be operated and of the risks involved in various transition paths toward a fully re-adapted city.

Damage assessment demands therefore a prior clarification of the economic contents of adaptation. It would, indeed, be misleading to treat it only as 'end of pipe' adjustments such as air conditioning or insulation. Comparing cities with very different climates shows how, over the very long run, they have adopted appropriate infrastructures, street geometries and building architectures. Second, climate predictions at a local scale are rather uncertain : the best analogue for the Paris' climate in 2100 is either the present climate of Bordeaux or the one of Cordoba. If the first possible outcome would suggest a fairly esay adaptation, the second one would represent a deep change in climate conditions. For example, the 2003 heat-wave over France, which was similar to an ordinary summer in Cordoba, was responsible for more than 15,000 premature deaths in France and for more than 13 G€ of economic losses. This disaster is obviously due to the ill-adaptation of the structure and urbanism of northern French cities to such a hot summer, together with a weak preparation of the rescue and health services to such unusual extremes. This *'natural experiment'* highlights the vulnerability of the societies to climate change and shows the necessity of a long adaptation process. It does not prove, however, that Paris should really undertake huge modifications of its infrastructure : would Paris solely 'move' to the climate conditions of Bordeaux, such heat-waves would remain exceptional.

5. Adaptation measures and costs under perfect expectation

In this section, we focus on the case of Paris and its vicinity, l'Ile-de-France, (herafter Paris-IDF) that represents 20% of the French population and 40% of the France's GDP. We present four sets of adaptation measures that can be mobilised in this city to cope with higher temperatures and water scarcity. Note that we ignore here all other climate change impacts (*e.g.*, extreme events like floods), even though they may be very significant.

- *S1* : Installing air conditioning (AC) in sensitive places (hospitals, subway, apartments for elderly people). These measures can be implemented in some months, the only constraint being the availability of equipments, which can be augmented to a desired level within a few years. This 'end of pipe' adaptation generates moderate costs over the short term. We consider it as sufficient if the magnitude of the long run climate shift is moderate (the 'Bordeaux' assumption). The strategy *S1* requires only marginal investments in the electric supply system, to adapt to a reduction in the winter peak and a slight increase in summer demand.
- *S2* : Generalising AC in almost all places. Displaying air conditioning in all dwelling places can be done in one or two decades, the main constraint being the development of new electric-production capacities and the diffusion of equipments among low-classes dwellings. The key difference between *S1* and *S2* stems from the fact that generalising AC would cause a large summer peak in electricity consumption. EECCAC (2002) projections of AC diffusion in a no-climate-change scenario show that AC increases very regularly with GDP in the warmest european countries (Greece, Spain...) : in these warmest countries, AC is used as soon as the population can afford it. Since Paris-IDF is a wealthy region, these projections suggest that AC per capita would rise very quickly if temperatures increase. Assuming that, over the long run, Paris-IDF will reach the same AC pattern as the US[4]

[4] 64% of the households in the US have some type of AC (Energy Information Administration, U.S. Department of Energy : http ://www.eai.doe.gov). For Europe in the next decades, this is a rather conservative estimate.

leads to an additional electricity demand of 10 TWh/yr. This strategy would thus require to invest in additional capacity to satisfy a 10 GW summer peak in electricity demand. With a 30%-nuclear/70%-gaz technical mix, coping with this peak would require an investment of 7 G€, *i.e.* 1.2% of Paris-IDF GDP, not to speak of the additional operating costs, averaging 400 M€ a year. By the way, the resulting increase of electricity bills would affect the welfare of low income families who live in the less thermally-efficient houses.

- *S3* : Upgrading building standards and urban planning to make new buildings less vulnerable to higher temperatures and/or air conditioned at low costs. Beyond an improved thermal insulation other options are (Oke, 1987) : reduced building densities ; lower building height, spacing and street orientation to increase shade, reduce insulation receipt and enhance natural ventilation ; increase effective solar shading using trees and vegetation ; use of high-albedo (reflective) building materials ; and incorporation of large areas of vegetation within the urban landscape. This strategy strongly reshapes the infrastructure and is consistent only with large warming. Assuming that the rate of temperature rise does not require costly modifications or even earlier replacement of existing buildings, the *S4* time-scale is about 150 years[5]. The permanent capital cost of this strategy would be small, since the ratio of the construction costs of a low-class building to an upper-class one is only 1 to 2 (the bulk of the price discrepancy between both being primarily due to location amenities). Assuming that appropriate new standards will increase the construction costs by 10% and given that the building sector in France represents 4% of GDP, with 2% for new construction and 2% for maintenance and renovation (BNP-Paribas, 2000), the permanent additional construction costs could be about 0.2% of GDP, *i.e.* about 1.2 G€ per year for Paris-IDF.
- *S4* : Adapting existing buildings to enhance their resilience in case of a drastic and rapid warming. Because of the low pace of implementation of *S3*, it may be necessary to invest in the adaptation of existing buildings (*e.g.* enhanced thermal insulation). The cost of this type

[5] The French Ministry of Ecology and Sustainable Development estimates that 33% of the building existing in 2050 will have been built after the year 2000.

of measure is huge : assuming a mean rehabilitation cost per apartment of 25,000 € yields 80 G€ for Paris-IDF, *i.e.* almost 15% of its GDP. This cost, and other constraints such as the availability of skilled workers, explains why this strategy has a medium timescale (at least 20 years) and is politically difficult. It allows, however, to cope with climate change of almost the same magnitude than *S3*, larger than *S1* and *S2*, and above all to reduce the electricity demand due to both winter heating and summer cooling.

In addition to investments in air conditioning, another significant adaptation measure concerns water management : the amount of capital in operation in France is estimated at 200 G€, with 5 G€ of annual investment[6]. Assuming that 40% of this capital is used in Paris-IDF, and that 10% has to be prematurely replaced, it means an additional investment amounting to 8 G€.

6. Adaptation measures and costs in case of uncertainty

The economic assessment of climate change damages cannot be carried out without defining behavioural assumptions concerning adaptation to a changing climate in a context of large uncertainty : imperfect foresight may actually entail over-protection (investments *ex post* proven to be useless, the so-called sunk-costs) or under-protection (implying in a later course an acceleration of adaptation efforts and/or higher amenity losses).

So far, monetary estimates of climate change damages (Mendelsohn *et al.*, 2000 ; Nordhaus and Boyer, 2000 ; and Tol, 1999 a&b) have not considered the cost-multiplier effect of uncertainty and assumed that the best adaptation options are timely implemented. We propose to examplify the contrary, in the case of adaptation to heat waves for Paris-IDF.

To do so, let us come back to our climate analogues : following the two considered models, the future climate of Paris can be either Bordeaux-like or Cordoba-like. Comparing these cities — Paris, Bordeaux, Cordoba — provides an insight on the required level of adaptation. Such

[6] Report of the Assemblée Nationale n°3081, December 2000, by Yves Tavernier.

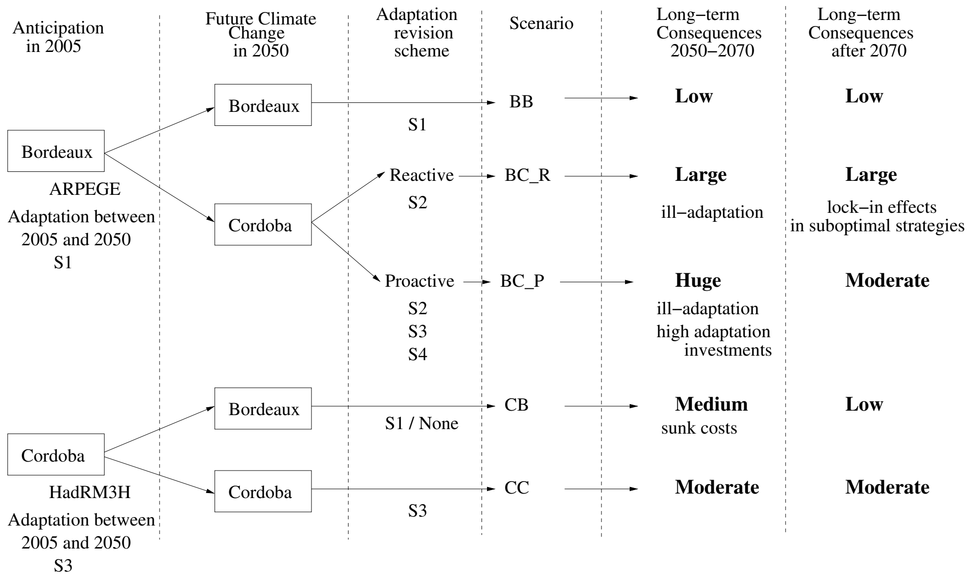

FIG. 2 Different scenarios, depending on what is anticipated in 2005, what is the actual climate change (to be revealed in 2050) and what is the adaptation scheme.

insight is difficult to derive from numerical values from climate models, such as the change in annual temperature : what is the required level of adaptation if the annual mean temperature increases by 3.1 °C (ARPEGE) or 4.1 °C (HadRM3H) ? The answer is anything but trivial. Our analogues suggest that the *S1* strategy could suffice if ARPEGE is right (Paris faces the climate of Bordeaux) but they also suggest that this solution would be inadequate if HadRM3H is right (Paris faces the climate of Cordoba). In this latter case, strategies *S2,S3,S4* would be necessary.

To keep it simple we will examine the adaptation scenarios illustrated in Fig. 2, which encompass the set of possible behaviours assuming that the actual climate change will be revealed in 2050.

6.1. *BB* SCENARIO

In the *BB* scenario, the 'planner' of Paris is totally confident in the ARPEGE results and acts as if he or she was certain that the future climate of Paris will be Bordeaux-like. Thanks to their short timescales, the *S1* measures can be planned in function of the observed temperature increase, even under myopic expectations, and the economic cost of adaptation is null.

6.2. *BC* scenario

In the *BC* scenario, the same beliefs prevail at first period but ultimately the actual climate change is proven to be closer to the climate of Cordoba. In this case, a revision of the *B*-type adaptation strategy will take place. The features of this revision can be encompassed into two polar extremes, the *reactive adaptation* and the *proactive adaptation*.

- The *reactive adaptation* (*BC_R* scenario), in which the revision is operated under the pressure of climatic accidents. History of environmental crises demonstrates that, in this case, the feeling of urgency often leads to over-reaction. This situation would result into an accelerated mobilisation of the *S2* measures. If this effort is carried out in 10 years, it would amount about to 700 M€ per year, *i.e.* almost 1% of the overall Paris-IDF annual investment flows. To what extent this effort will be easily funded remains an open question since, contrary to the situation prevailing in the seventies and eighties when high investments in the electric system were carried out, the new regulation of electric systems deprives electricity providers from the insurance given by the former status of public monopoly.

  Ultimately, this scenario would result into a progressive lock-in in adaptation through AC only, which, in case of more drastic warming, will not suffice to maintain a high level of amenity in the region and to prevent a decrease in real estate prices.
- The *proactive adaptation*, in which the revision of concerns is strong enough to allow for a pro-active adaptation (*BC_P* scenario), aiming at preventing the losses due to possible technical lock-in. This *adaptation policy* would be composed of a mix of (1) *S2* because of urgency and of individual responses to warmer temperatures; (2) *S3* because higher building standards are rational in a context of warmer temperatures; (3) *S4* because of the long time scale of *S3* and to avoid a lock-in in *S2*. In this scenario, *S2* is implemented

only as a transient solution. This policy mix is the best response over the long-term but it implies huge efforts.

During the first decades after 2050, the effect of *S3* is negligible because of the slow building turn-over; an *S4* type program is therefore necessary. If we assume that, to preserve the value of assets and the attractiveness of the region, this program is achieved in 20 years, total investments would amount to about 4 G€ per year, *i.e.* about 0.7% of the Paris-IDF GDP and about 4% of the Paris-IDF annual investments flow. It represents nearly a 50% increase of the annual renovation costs in this area. These investments have to be added : (i) to the *S3* strategy (1.2 G€/year); (ii) to the additional investments in the energy system due to *S2*, *i.e.* roughly 1% of the Paris-IDF annual investments flow. The total yields an increase of 6% in the investment between 2050 and 2060 and then of 5% between 2060 and 2070.

Note that in both hypotheses, (BC_P and BC_R), other effects may be significant. For instance, the water management system would have to be adapted as well. It means an additional cost of 8 G€, spread over a few decades. Hence, an additional cost of about 400 M€ per year over 20 years for water management (*i.e.* a 20% increase of annual investments in water management) is very possible.

6.3. *CC* SCENARIO

In the *CC* scenario, the 'Paris planners' are totally confident, from 2005 onward, in the HadRM3H model results and in the fact that Paris in 2100 will face the present climate of Cordoba. In this case the best option is to display immediately *S3*. Since it does not necessitate to rise significantly the investment but only to increase them at the margin to make new buildings less vulnerable. This option is likely to be the best choice, since its main negative impact would be a marginal short-term worsening of the housing market, one order of magnitude lower than the medium- to long-term amenity losses in case of non-adaptation. Because of its timescale, however, these measures are only efficient over the very long-term. Between 2005 and 2050, only about one third of the buildings can be adapted. Some additional adaptation investments from the *S4* strategy will thus be necessary (*e.g.* in historical quarters). Assuming that half of these 'not-yet-adapted' building will require a renovation between 2005 and 2070, one third of the total *S4* costs will have to be invested. In total 25 G€ are required over 65 years (38 M€/year) to which 8 G€ should be added (100M€/year) to cover the adaptation of water management infrastructures.

6.4. *CB* SCENARIO

In the *CB* scenario, the 'planners' believe that present Cordoba is the right analogue for the future climate of Paris but discover by the middle of the century that the new climate of Paris will ultimately be the climate of Bordeaux. In this case, additional investments are made up to 2050 but will ultimately be proven in major part useless. In this case, sunk-costs will likely outweigh the direct costs of global warming.

These four simple adaptation scenarios show that, in this uncertainty context, the most robust and cost-effective adaptation, *S3*, is difficult to undertake. Presently, because of the thorny situation of the housing market in Paris-IDF, public policies refuse to implement any measure that could increase building costs : their main objectives in this field is to promote the construction of new buildings. The trade-off between long-term uncertain benefits and short-term obvious costs strongly works against any long-term adaptation strategy[7]. As a consequence, uncertainty on future warming may result in a very costly *non-voluntary lock-in* in *S2*, which can

[7] The same processes can be observed in flood management. Facing difficulties in prohibiting house building in flood-prone areas, it has been preferred for decades to build dams. But if climate change is predicted to make these dams inefficient in the future, it is urgent to change this policy and to modify urbanism plans rather than to increase the dams height as floods become more intense, as it is likely to be a non-robust adaptation strategy.

TAB. I Summary of the annual investment costs (in M€) in Paris-IDF for climate change adaptation under different scenarios concerning the intensity of climate change and the adaptation strategy. These figures are not the climate change damages, since they take into account only the costs of adaptation, excluding the benefits of adaptation and the climate change direct damages.

Scenario	First period (2005-2050)				Second period (2050-2070)			
	Building		Energy	Water	Building		Energy	Water
	New norms	Renovation			New norms	Renovation		
BB	0	0	0	0	0	0	≈ 0	0
BC_R	0	0	0	0	0	0	700	400
BC_P	0	0	0	0	1200	4000	700	400
CC	1200	400	0	100	1200	400	0	100
CB	1200	400	0	100	0	0	≈ 0	0

be considered as a wrong adaptation strategy, less robust to larger climate change, more costly over the long-term and more energy-consuming.

7. From adaptation investments to macroeconomic costs and implications on welfare

Investment costs for each of these 5 scenarios are given in Table I. Discounting the expenditures leads to a very low present value for the second period investments and, as a consequence, this table suggests that following a B strategy in the first period (2005-2050) appears as more cost-effective. After 2050, in a BC situation, the BC_R adaptation strategy seems to be more efficient than the BC_P strategy.

But the overall economic impact of each strategy cannot boil down to summing up discounted adaptation expenses : Table I does not reproduce the benefits of adaptation, nor the indirect consequences of adaptation expenditures, nor the residual damages. Additionally, one major pitfall of the current monetary evaluations of climate change damages is to sum direct impacts on productive activities, ecosystems and human settlements without taking into account their potential propagation through socio-economic systems and their implications on investment dynamics. This pitfall justified the criticism by Fankhauser (1994) against the *enumerative* approach, adopted in the majority of cases.

It is probably premature to use general equilibrium models to quantify the impacts of climate change on GDP, wealth and future growth, while taking into account these interconnections. As a first attempt, however, we can show, in a simple numerical experiment, the importance of two mechanisms that may amplify social costs of climate change :

- The first is the decrease in the real estate value caused by amenity losses and risks[8] and its potentially large macroeconomic effect (Lhomme, 2003) : (i) reduced rentals can be responsible for numerous defaults in loan repayments with strong consequences on the banking sector ; (ii) reduced consumption and rise of the saving ratio. To give an order of magnitude, the building renovation investments in the BC_P strategy, *i.e.* 4 G€ per year over 20 years, have to be compared with the 500 G€ of the Paris real estate value : a 16% decrease in the real estate asset prices of Paris would be enough to justify a BP_P adaptation strategy, and this figure is lower than the 30% price decrease in Paris during the real estate crisis in early 90's.
- The second is the long term macroeconomic impact of investing in adaptation instead of productive capital, *i.e.* a replication of the crowding-out controversy about mitigation policies. Let us start, to understand the orders of magnitude at stake, from a conventional AK growth model (Rebelo 1991) ; its drawback is to overestimate the long-term consequences

[8] To give an example of such effects, Hallstrom and Smith (2005) showed that housing values decreased by 19% after the hurricane Andrew landfall in the US in 1992, in hurricane-prone locations that have *not* been impacted by Andrew. According to these authors, Andrew conveyed risk information to homeowners, leading to this significant price decrease.

of a shock on an economy but its advantage, for this illustrative exercise, is its analytical simplicity and its capacity to support very simple calculations.

The AK growth model reads :

$$Y = A \cdot K \ , \tag{1}$$

$$I = \gamma Y \ , \tag{2}$$

$$\frac{dK}{dt} = I - \delta K \ , \tag{3}$$

where Y is the global production, K is the stock of productive capital, I is the amount of investment. The parameter δ is fixed at 0.05 (productive capital lifetime about 20 years), $\gamma \approx 20\%$ and $A \approx 0.4$ (scaling coefficient).

This model defines a growth pathway $Y(t) = Y(t = 0) \cdot e^{(A\gamma - \delta)\cdot t}$. The annual economic growth is $g = A\gamma - \delta \approx 3\%$. A change $\Delta\gamma$, corresponding to the part of investment diverted to adaptation, reduces growth by $\Delta g = A \cdot \Delta\gamma$.

Thus, taking into account only investments in energy, water management and buildings, the BC_P scenario would imply investments amounting to 6 G€ per year from 2050 to 2060 and 5 G€ from 2060 to 2070. If this amount (about 1% of Paris-IDF GDP) is removed from productive investment, it would reduce annual growth rate by 0.4% over 20 years and cause a 8% decrease in GDP in 2070, compared with a scenario without adaptation investments[9].

An aggregate synthesis is made difficult because of the impossibility to find a credible proxy to assess numerically reductions in consumers' surplus due to amenity losses. Table II provides however a synthetic picture mixing numerical and qualitative indicators to demonstrate that, depending on the content of the information received at this date, Paris will be exposed to a very difficult trade-off in 2050 between triggering immediately a costly adaptation program and

[9] The amount of necessary investments in % of GDP is assumed not to be changed in the next century, because the increase in production and technical change are assumed to be followed by an increase in the quality of housing and in its price.

TAB. II Summary of the costs (in terms of investment, amenity losses and growth) of climate change in Paris-IDF under different scenarios concerning the intensity of climate change and the adaptation strategy. Investment costs are in M€.

	Short-term (2005-2050)		Medium-term (2050-2070)			Long-term (2070-)	
Scenario	Adaptation investments	Macro costs growth red. (%)	Amenity losses	Needed investments	Macro costs growth red. (%)	Amenity losses	Energy costs
BB	none	none	Low	none	none	Low	Low
BC_R	none	none	High	1100	0.07%	High	High
BC_P	none	none	High	6300	0.4%	Low	Low
CC	1700	0.1%	Low	1700	0.07%	Low	Low
CB	1700	0.1%	None	none	none	Low	Low

accepting the possibility of high amenity losses over the long run. This trade-off may make the C strategy (assuming a Cordoba-like climate from the outset) not so irrational since the order of magnitude of the cost of overprotection in the CB case (the climate is proven to be Bordeaux-like) is far lower than the costs of the lock-in 2050 due to the selection of a B strategy at first period.

8. Concluding remarks

This paper shows, in absence of reliable and non-controversial monetary estimates of climate change damages, the interest of climate analogues as a heuristic tool to picture the magnitude of climate change risks and to set the stage for a discussion concerning adaptation to an uncertain climate change.

They provide an operational way to translate a complex and abstract amount of information from climate models into metrics more usable for decision-makers and stakeholders than a crude set of climate indicators, which are difficult to interpret in economic and social terms. In addition to mapping climate change, analogues allow one to appreciate the magnitude of uncertainties about its level, rate and location. These uncertainties are indeed crucial to discuss costs of climate change and adaptation because of their interplay with the inertia of infrastructures.

A tentative essay on the case of Paris-Ile-de-France shows first that the static and enumerative approach to monetary damage valuation tends to underestimate their actual costs for future generations because it neglects important mechanisms such as a crowding-out of productive investment or a depreciation of real estate assets which can dampen economic growth.

Second, a major conclusion is that introducing climate uncertainty modifies drastically the costs of climate change impacts, when compared with a perfect-forsight situation. More specifically, risks of lock-in in sub-optimal solutions exist and may lead to significant costs. They arise from the present ignorance about the future climate, adaptation will have to respond to, or from difficulties to overcome in due time the political acceptability constraints on appropriate policies. These costs should be taken into account in the assessments of climate change damages, against which mitigation costs are weighted to define a precautionary strategy.

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