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A Note on the Economic Cost of Climate Change and the Rationale to Limit it Below 2°C

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Abstract

This note highlights a major reason to limit climate change to the lowest possible levels. This reason follows from the large increase in uncertainty associated with high levels of warming. This uncertainty arises from three sources: the change in climate itself, the change's impacts at the sector level, and their macroeconomic costs. First, the greater the difference between the future climate and the current one, the more difficult it is to predict how local climates will evolve, making it more difficult to anticipate adaptation actions. Second, the adaptive capacity of various economic sectors can already be observed for limited warming, but is largely unknown for larger changes. The larger the change in climate, therefore, the more uncertain is the final impact on economic sectors. Third, economic systems can efficiently cope with sectoral losses, but macroeconomic-level adaptive capacity is difficult to assess, especially when it involves more than marginal economic changes and when structural economic shifts are required. In particular, these shifts are difficult to model and involve thresholds beyond which the total macroeconomic cost would rise rapidly. The existence of such thresholds is supported by past experiences, including economic disruptions caused by natural disasters, observed difficulties funding needed infrastructure, and regional crises due to rapid economic shifts induced by new technologies or globalization. As a consequence, larger warming is associated with higher cost, but also with larger uncertainty about the cost. Because this uncertainty translates into risks and makes it more difficult to implement adaptation strategies, it represents an additional motive to mitigate climate change.

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A note on the economic cost of climate change and the rationale to limit it below 2°C

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1. Introduction

There is a gap between the ongoing policy debates on the objective of limiting climate change below a 2°C global warming and the existing economic literature. Most arguments to limit global warming below 2°C rely on the argument that an overshoot beyond this temperature would have highly undesirable consequences (IPCC 2007): difficulty of ecosystems in coping with a warming larger than 2°C and resulting loss in biodiversity and valuable ecosystem services; irreversible melting of the Greenland ice sheet, leading to 5m or more of sea level rise over several centuries or millennia; increase in the extent of uninhabitable areas; climate refugees and unmanageable migrations. However, the few attempts at providing an extended cost-benefit analysis of climate policies (e.g., Nordhaus, 1998; Tol, 2002a,b; Mendelsohn et al, 2000) did not confirm this argument. Even the Stern Review (Stern 2007), which made a strong case about the likelihood of potentially very high climate change damages, refrained from suggesting greenhouse gas (GHG) emission reduction targets sufficient to maintain the extent of warming to less than 2°C.

This note reviews the limitations of current cost-benefit analyses of climate change policies and the improvements that are needed to better account for the combined effects of inertia (in climate, technical, and social systems) and uncertainty. The difficulty in taking these mechanisms into account arises from uncertainties as to how climate and ecosystems will react to increased greenhouse gas concentrations, but also from the uncertain ability of societies to detect in due time the correct climate signal—which is swamped by many other signals—and to react promptly and in an appropriate manner to this signal.

In particular, this note stresses the fact that, as global warming becomes larger, there is an increase in uncertainty in all components of the causal chain from global climate change to final welfare impact. This increase in uncertainty is due to (a) the risks of poorly-understood nonlinearity in the climate system itself beyond 2°C; (b) the possibility of rapid increases in economic costs at the sector or regional scales due to climate change impacts whose pace and magnitude may exceed the uncertain ability of societies to manage changing risks and mobilize adequate resources to do so; (c) the possibility of ripple effects and threshold effects in the economic system with potentially serious macroeconomic consequences.

This note concludes that there is an economic rationale for acting now in order to preserve the possibility of limiting global warming below 2°C. The basic argument of this rationale is the benefit of reducing the uncertainty about the final welfare impact of climate change through a reduction in climate change amplitude and pace.

2. Uncertainty and adaptation to climate change

The science of climate change and adaptation is very recent, and large uncertainties remain in all components of the analysis. One important characteristic of these uncertainties is that they increase with the amplitude and scale of climate change. This section reviews the consequences of these uncertainties on the economic cost of climate change.

2.1. Climate models and local climate changes

Climate models are based on well-known physical mechanisms (mass and energy conservation, fluid dynamics equations, etc.). But they are also partly calibrated to reproduce past and present climates. An important problem in a cost-benefit analysis of climate policies is that the level of confidence in climate model projections decreases when climate becomes very different from the present and past ones.

With an increase in global temperature below 2°C, the climate remains relatively "close" to the present one. Even with such a limited warming, there is a significant level of uncertainty about how global change will translate into local changes (e.g., in terms of temperature, precipitation and wind). But the order of magnitude of this uncertainty increases rapidly with greater warming: current climate models cannot provide fully reliable guidance on future changes in local climates that could be used to assess impacts and propose adaptation strategies. Most current models not only miss the risk of catastrophic global climate change (introduced in Weitzman, 2009), but also may miss the likelihood of local climate surprises (e.g., a drastic change in the pattern of tropical monsoon in India).

Regardless of whether these surprises are good or bad, this uncertainty nevertheless has a positive cost, due to the trade-off between the cost of robustness and the risks of maladaptation (see assessments in, e.g., Schneider et al., 2000; Hallegatte, 2006, Hallegatte et al., 2007a; Nassopoulos et al., 2009). This uncertainty, indeed, will force decision-makers to develop adaptation strategies that do not look for optimality in a given climate but for robustness in the face of many possible climates (Lempert et al., 2006; Dessai and Hulme, 2007; Groves et al., 2007; Hall, 2007; Hallegatte, 2009).

For example, today's buildings should not be designed as they have been in the past, based on observed climate conditions, but instead should be designed depending on how the local climate will change in the future. But because we do not know exactly how local climates will change, buildings cannot be designed today in a way that is adapted to future climate. Instead, they have to be built in a way that makes them able to cope with many possible climates, as projected by existing climate models. For instance, the future climate of Paris in 2070 is variously projected to be similar to the current climate in Cordoba, in the south of Spain (according to the Hadley Center model), or the current climate in Bordeaux, in the south of France (according to the Météo-France model) (Hallegatte et al., 2007a). Obviously, the appropriate design for buildings that are constructed in Paris today would be different under these quite different future climate regimes, and thus it depends on which of these models is correct. Because of this uncertainty, it is more difficult (and more expensive) to design buildings. And the more uncertain are local climates, the more robust building architecture has to be. From this point of view, exceeding warming of 2°C not only increases the cost of climate change *per se*, but it also increases the uncertainty and its associated costs. Of course, these costs cannot be taken into account by scholars who use models with perfect foresight and/or certain climate change.

Another illustration of this problem is the case of water management in West Africa. With climate change, it seems wise to ask climate modelers to provide model outputs for precipitation over this region up to 2100 instead of relying on observations of past precipitation and temperature to design water infrastructure. But, like with buildings, using a climate model might be dangerously misleading. Projections of future precipitation changes in Africa are very uncertain, as illustrated in Figure 1 with two climate models. Should the design of water infrastructure respond to the 20% increase in precipitation projected by the CCSM3 model or to the 30% decrease projected by the GFDL model? Again, water managers will have to trade efficiency for robustness: they need to implement strategies able to cope with many possible outcomes, but a strategy able to cope with a +20% and a -30% change in annual rainfall cannot be as efficient in the case of a 20% increase in rainfall as would be a strategy specifically designed for that scenario.

The same type of discrepancies in climate projections can be found in many other places such as a water catchments in Greece for which different climate models project from -45% to +12% in annual river runoff (Nassopoulos et al., 2009). This difference in future precipitations translates into a large difference in the "optimal" volume of a water reservoir that could be built in this catchment: this optimal volume varies by up to 27% depending on the chosen climate model, making its design and construction more difficult.

Traditional decision-making tools have not been developed to cope with such questions and have to be amended.[1] Even so, these amendments will not be capable of avoiding an increase in the cost of water supply in case of a rapid climate change.

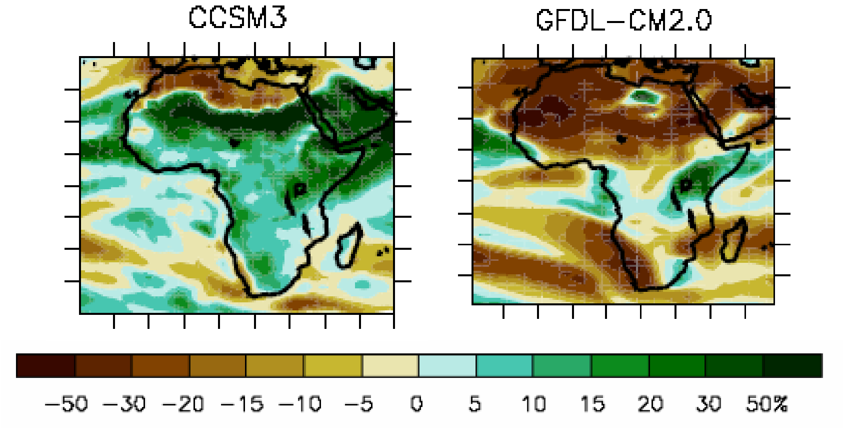

Figure 1: Change in annual rainfall in 2090-2100 in Africa according to two climate models (source: IPCC, 2007)

The problem posed by the large uncertainties about future local climates is exacerbated by the difficulty of predicting the responses of ecological systems, first because of possible nonlinearity in these responses and their site-specific nature, and second because of the absence of models integrating climate and ecological systems.

Further, we also have to add to this cascade of uncertainty the additional uncertainty about the adaptive capacity of various economic sectors. This uncertainty is neglected in most assessments, but it is likely to be one of the most important sources of uncertainty in the causal chain between climate change and welfare losses.

2.2. Uncertainty in sector-scale adaptive capacity

With limited global warming, we have ideas and information about the capacity of economic sectors to adapt. Limited warming keeps the climate close to the current one: in such a climate, the weather conditions that are already experienced today as extreme events will become frequent occurrences or constitute the new baseline. For example, the mean summer temperature in Africa in a climate that is slightly warmer than the pre-industrial climate will look like a hot summer today, and African farmers are used to cope with these occasional hot summers. Strategies to cope with these increasingly frequent weather conditions in a limited warming already exist, as they have been developed to cope with today's extreme events.[2]

But with a larger warming, even the average summer will become hotter than the hottest summers today,[3] and we will reach a situation in which no coping strategy pre-exists.

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[1] Such amendments are investigated in papers by Lempert et al. (2006), Dessai and Hulme (2007), Groves et al., 2007, Hall (2007), Hallegatte (2009).

[2] The Katrina disaster in New Orleans is, however, a reminder of the possibility of mismanaging infrastructures and public disregard of alerts in advanced societies.

[3] In Paris, a 4°C warming would result in average summer temperatures equal to those during the 2003 heat wave. It means that any future hot summer—one above that new, higher average—would correspond to

Certainly some new strategies will be developed as the climate changes but their adequacy is uncertain. The health and economic consequences of the unprecedented 2003 heat wave in Europe surprised all governments and experts. This lack of anticipation shows how difficult it is to predict the future consequences of climate conditions that have never been experienced before.

Farmers faced with limited warming, for example, will apply marginal changes in their methods of cultivation and in their selection of seeds, thereby limiting losses. But with a faster warming, these marginal adaptations may be insufficient and drastic changes in the very type of agriculture may become necessary. Will it be possible to develop such strategies at an acceptable cost? In a debate on U.S. agriculture, Mendelsohn and Reins (2007) suggested, using Ricardian methods, that adaptive capacity is very large even for high levels of warming and that climate change damages will remain limited. On the other hand, Schlenker et al. (2005) and Schlenker and Robert (2006) claim that adaptive capacity is limited for high levels of warming and that climate change damages will be large for U.S. agriculture. This debate shows just how uncertain the extent of adaptive capacity to climate change is, even in the most studied sector and the most studied region.

Finally, an archetypal example of why uncertainty imposes large adaptation costs is the case of low-lying small islands: indeed, what is the rationale to invest in expensive long-lived infrastructure (e.g., a transport network) in places that nobody can guarantee will be protected against future sea-level rise?

3. Climate change ripple effects and macroeconomic vulnerability

The previous section suggested that there are good reasons to think that the economic response to climate change's direct impacts is nonlinear and will exhibit threshold effects, and that this nonlinearity and these thresholds result in a larger uncertainty for large warming. But it is important to account not only for sector-scale impacts, but also for indirect impacts and ripple effects in the larger economy. These knock-on effects are especially important because climate change impacts will both increase the need for adaptation investments, as well as potentially decrease the capacity of the affected economy to mobilize resources to carry out these adaptation investments. Moreover, these effects are particularly difficult to predict and model, as current economic models focus on marginal economic changes, without being able to capture and reproduce more significant structural shifts in the economic system. This section reviews and illustrates such poorly-understood effects, and highlights their potential importance.

3.1. Ripple effects and inertia in mobilizing adaptive capacity

This double effect of both direct and indirect impacts is documented for natural disasters that simultaneously decrease production capacity and increase demand through reconstruction needs. Besides the human losses, natural disasters cause direct economic losses in the form of damages to buildings and to production equipment. These direct losses, in turn, lead to indirect losses, in the form of lost production. The total economic cost of a disaster consists of (i) the *direct* cost, i.e. the portion of economic output (i.e. value added) that has to be dedicated to reconstruction instead of normal consumption; and (ii) the *indirect* cost, i.e. the reduction of the total value added by the economy, because of the disaster. This distinction can also be reworded in terms of stock (direct) and flow (indirect) losses.

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temperatures that have never before been experienced in Paris. Beyond the human toll caused by heat waves (more than 15,000 deaths in France in 2003), this raises the prospect of a deep restructuring of the architecture and spatial organization of the city and shows the uncertainty on future impacts.

Indirect costs can be defined as the reduction in production of goods and services, measured in terms of value added (to avoid double-counting issues). For example, if a \$100 million plant is destroyed and immediately rebuilt, the total loss would be \$100 million; however, if reconstruction is delayed by one year, the total loss will be the sum of the replacement cost (the direct cost of \$100 million) and the forgone value added of one year of production (the indirect cost). Estimates of indirect costs include business interruption in the event's aftermath, production losses during the reconstruction period, and loss in housing services. The value of such production losses, in a broad sense, can be very high in some sectors, especially when basic needs are at stake (housing, health, employment, etc.). Moreover, one cannot estimate these production losses using a classical production function, as this would underestimate the economic indirect losses caused by disasters by a factor up to three (see Box A).

Of course, the indirect cost increases with the direct cost. In the U.S. state of Louisiana, for instance, an economic modeling exercise suggests that the economy is able to cope (with little or no ripple effects) with natural disasters causing up to \$50 billion of direct losses; for disasters causing direct losses larger than \$50 billion, indirect impacts appear and rapidly become large. For disasters causing \$100 billion of direct losses, indirect losses reach \$50 billion, i.e. 50% of the amount of direct losses (Hallegatte, 2008; see Fig. 2). Similar results are found in the city of Mumbai: for every 2.5-fold increase in the direct losses caused by an urban flood, indirect losses are found to increase 4-fold (Ranger et al., 2009). In both cases, the nonlinearity arises from the impossibility of the economy mobilizing an increasingly large fraction of output to disaster reconstruction. For, the sectoral structure of output is very inert: increasing the output of the construction sector, for instance, requires equipment and qualified workers that are not always available[4] and this raises the price of reconstruction.

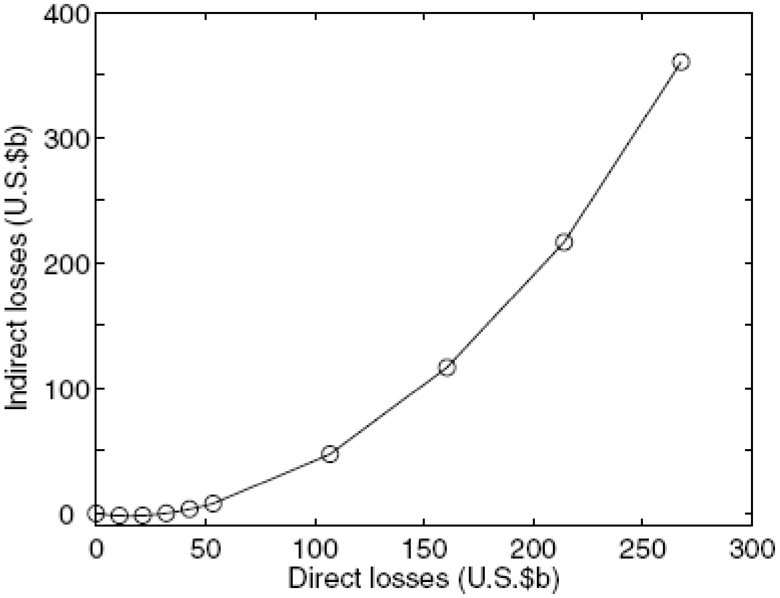

Figure 2: The direct losses – indirect losses relationship in Louisiana for Hurricane Katrina-like disasters. (source: Hallegatte, 2008)

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[4] The lack of qualified workers in areas affected by disasters (e.g., roofers after hurricanes in Florida in 2004, glaziers in Toulouse in 2001 after the chemical accident at the AZF plant) often lead to wage and price inflation and increase in reconstruction cost, a process known as "demand surge" in the insurance industry.

Box A. An underestimation bias in estimating natural disaster costs with classical production functions.

Hallegatte et al. (2007b) discuss several possible biases resulting from disaster impact modeling and propose modeling alternatives to avoid them. Because disasters mainly destroy the stock of productive capital, a natural approach to representing disasters' consequences is to treat them as an instantaneous reduction in total productive capital ($K_0 \rightarrow K_0 - \Delta K$). This approach, however, amounts to treating an post-disaster economy as equivalent to an economy in which past investments were lower. In other words, in such a model, it would be equivalent for an economy to invest a lot and then have some fraction of its capital destroyed by a disaster, or for the economy to have originally decided to invest less. Obviously, this is not the case: when investors decide to invest less, they continue to make the most productive investments but decide not to pursue the less productive ones; however, when a disaster hits, it does not selectively destroy only the less efficient capital.

But, because of decreasing returns in the production function, using a classical production function amounts to assuming that only the less efficient capital is destroyed by the disaster. In a Cobb–Douglas setting ($Y=AL^{\lambda}K^{\mu}$), indeed, the post-disaster production level would be $Y_1=AL^{\lambda}(K_0-\Delta K)^{\mu}$, and an x-percent loss of equipment would reduce production by less than x-percent (see Fig. A.1).

To account for the fact that disasters may affect all capital, independently of its productivity, Hallegatte et al. (2007b) propose to modify the Cobb–Douglas production function by introducing a term ξ_K, which is the proportion of non-destroyed capital. This new variable ξ_K is defined such that the effective capital is $K=\xi_K \cdot K_0$, where K_0 is total potential productive capital, in the absence of disaster. The new production function is:

$$Y_2 = \xi_K f(L,K_0) = A\, \xi_K\, L^{\lambda} K_0^{\mu}$$

With this new production function, an x-percent destruction of the productive capital reduces production by x-percent (see the dashed line in Fig. A.1).

(continued)

(Box A. continued)

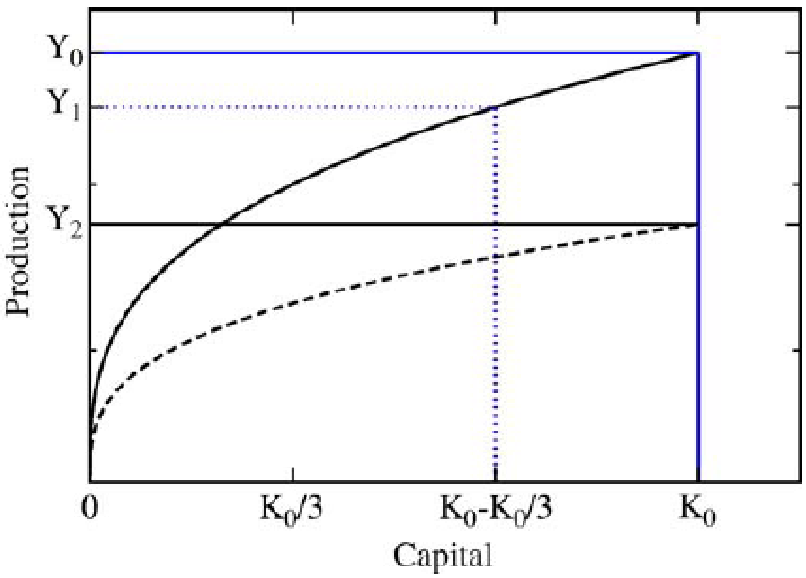

Figure A.1 Production with respect to productive capital for different modeling assumptions. The solid curve shows the production given by a Cobb–Douglas production function with fixed labor input. In this case, when one-third of productive capital is destroyed by a disaster, K_0 is decreased and the production function is unchanged: production is thus reduced from Y_0 to Y_1. With the modified production function, the disaster changes the production function from the solid curve to the dashed curve, without changing what is now the *potential* productive capital K_0. Production is, therefore, reduced from Y_0 to Y_2, which is much lower than Y_1.

(source: Hallegatte et al., 2007b)

3.2. Ripple effects and macroeconomic cycles

In addition to uncertainty about the extent of supply-side inertia, another cause of uncertainty about the magnitude of ripple effects is that the consequences of an external shock depend on the pre-existing disequilibria experienced by the affected economy. This is disregarded if models only consider balanced growth pathways with almost no transition costs. Using an endogenous business cycle model, Hallegatte and Ghil (2008) find to the contrary that the timing of the shock is a key driver of its ultimate consequences. Disasters occurring in the expansion phase of the business cycle can indeed lead to losses several times larger than the same disaster affecting an economy at equilibrium. Alternatively, this disaster can lead to almost no economic losses if it affects a depressed economy,[5] at least as long as it does not come to a point at which it undermines the growth engine of the economy.

This vulnerability paradox is easy to explain: a disaster that occurs when the economy is depressed triggers the stimulus effect of the reconstruction, which activates unused resources. In this situation, employment is low and additional hiring for reconstruction purposes will not drive the wages up to a significant extent. Moreover, goods inventories are larger during the recession than at equilibrium; a disruption of production, therefore, can be damped by inventories. Finally, in a phase of under-investment, producers have margins of freedom they

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[5] In this analysis, many categories of losses are disregarded in spite of their importance (human losses, social network disruption, psychological trauma, cultural losses, political destabilisation, environmental losses, etc.).

can mobilize for reconstruction activities. In this case, the economic response is able to damp the lasting costs of the disaster.[6] Conversely, a disaster occurring during an ascending phase of the cycle exacerbates pre-existing supply shortages. First, the inventories are below their equilibrium value and cannot compensate for reduced production. Second, employment is at a high level and hiring more employees to help reconstruct induces wage inflation. Finally, because capital markets are tight, producers may lack financial resources to increase investments.

This vulnerability paradox, in which a healthy economy with high growth appears to be more vulnerable to disasters than a depressed economy, boils down to a Keynesian mechanism whereby reconstruction boosts an economy in which some resources were previously unused.[7] It is not much different to increase demand through fiscal or budgetary policies than through the destruction of houses and productive capital, which then need to be replaced as rapidly as possible. In the latter situation, agents increase their consumption and reduce their savings, thus leading to a rise in demand.[8] It is also well known that such an increase in demand is counterproductive and only lead to inflation if the supply is constrained, for instance during the expansion phase of the business cycle.

This paradox does not mean that a fragile economy will adapt more easily than a robust one; it only explains why the ultimate impact of a shock is cycle-dependent. This analysis assumes, however, that the shock does not undermine the underlying growth engine. This is why we must take one further step and examine whether this engine can be threatened by climate shocks.

3.3. Hysteresis effects of repeated climatic shocks

One primary factor that may undermine the long-term resilience of the economy and magnify climate change damages is the constraints on reconstruction capacity due to institutional and technological factors in case of a series of disasters and extreme events. Again, this is linked to the fact that reconstruction is constrained by inertia in the production system, which cannot modify its structure rapidly to increase the production in the sectors involved in reconstruction (e.g., construction, manufacturing).

Hallegatte et al. (2007b) and Hallegatte and Dumas (2008) show why the long-term GDP losses due to series of natural disasters are small, provided that the reconstruction capacity of the economy is large enough, and/or the frequency and intensity of the disasters that impact it are low enough (see Figure 3 “below the red line”). If reconstruction capacity is high, even very large disasters remain short-term events that perturb the economy over a few months or years, but do not have long-run consequences.

But, if reconstruction capacity is too limited in light of the incidence and intensity of disasters, which is more likely in poor developing countries or regions, then natural disasters are not just short-term events. They will have long-term consequences on an economy’s long-run growth if its reconstruction capacity is not sufficient to reconstruct entirely between two events. In this case, the economy remains in a state of perpetual reconstruction, making it impossible to accumulate the capital and infrastructure stock needed for economic development. As an example, Guatemala experienced an impressive series of weather

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[6] This effect is cited as a damping effect after the Marmara earthquake in Turkey in 1999 (World Bank, 1999).

[7] This conclusion, however, applies only to a given economy and does not extend to the comparison of two distinct economies: an overall flourishing economy is clearly more robust than an economy that is weak overall.

[8] The shift in savings ratio can be carried out either directly by the agents, or through the intermediary of insurance companies that sell assets to pay claims.

catastrophes[9] that severely inhibited economic development during a long period. In the same region, the Honduran prime minister said that the single hurricane Michelle in 2001 "put the country's economic development back 20 years" (IFRCRCS, 2002).

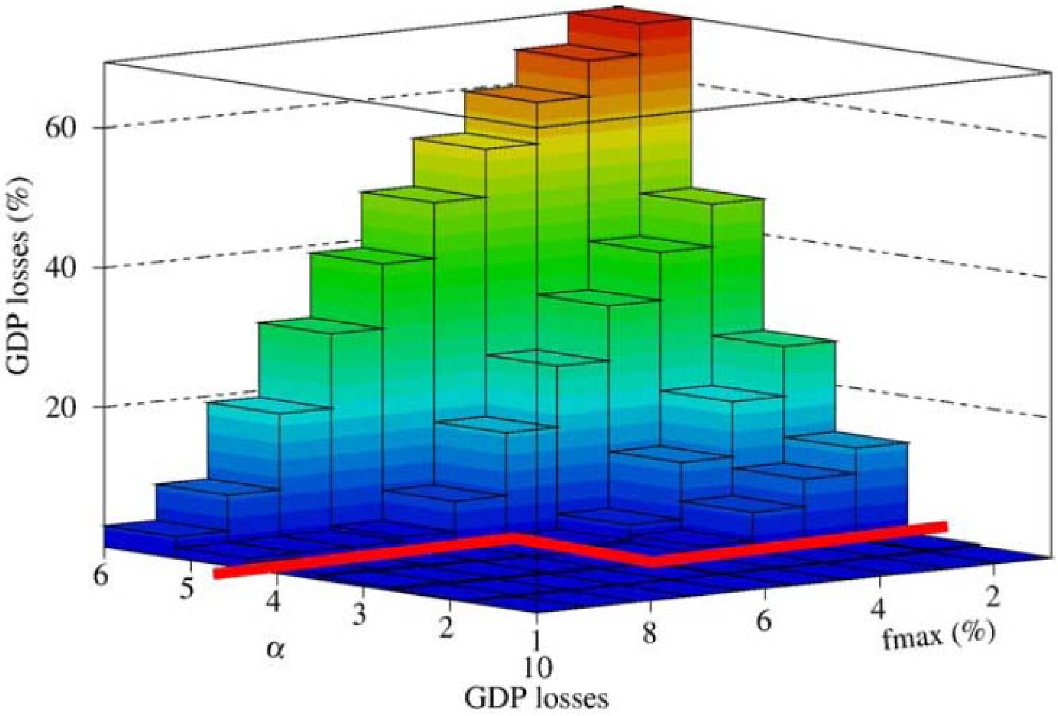

Figure 3: Relationship between the frequency and intensity of extreme events (measured by the parameter α), the capacity of the economy to mobilize resources for reconstruction (measured by f_{max}), and the mean long-term GDP losses due to these extreme events. The red line delimits the domain where losses are below 1% of GDP. Beyond this limit, the economy does not have enough resources to cope with disasters and long-term GDP losses increase nonlinearly. (source: Hallegatte et al., 2007b)

This mechanism is one candidate to explain the existence of poverty traps in some developing countries (e.g., in Central America, where natural disasters are particularly frequent and reconstruction capacity rather limited; see Benson and Clay, 2004).

An important consequence of this mechanism is that, if the frequency or intensity of disasters increases, controlling long-term losses will require an increase in reconstruction capacity through, for example, the introduction of insurance schemes, or an increase in production capacity in the construction and infrastructure sectors. Depending on whether developing countries will be able to do so, climate change impacts may remain limited or increase significantly and nonlinearly.

3.4. Hysteresis effects of infrastructure impacts

Along the same line, economic modeling suggests that climate change's total cost will depend on the ability to mobilize resources to cope with its direct impacts on infrastructure. This is shown in Dumas and Hallegatte (2009) who use a two-sector model with the infrastructure sector (transportation, energy, water, housing, etc.) and the rest of the economy (see Box B). This infrastructure sector can be referred to as the social overhead capital "comprising those

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[9] Hurricane Mitch in 1998, 3 years of drought from 1999 to 2001, and Hurricane Michelle in 2001.

basic services without which primary, secondary and tertiary activities cannot function" (Hirschman, 1958). Beyond the fact that they are often directly dependent on environmental and climatic conditions, infrastructure sectors pose a specific problem because they have a very long capital lifetime and thus cannot be easily modified to adapt to climate change without early—and costly—capital retirement. In other sectors, productive capital is replaced more frequently and thus can be modified as a function of observed conditions or of relatively short- to medium-term predictions. By contrast, the design of infrastructure needs to take into account how climate conditions will evolve over the long-term, which is particularly difficult considering the uncertainty about local and regional patterns of climate change (as shown in section 2.1 above).

Box B. A two-sector model to take into account infrastructure specificities in the assessment of climate change impacts

The model is a simple two-sector model. The first sector is the infrastructure and housing sector, producing energy, housing, and transportation services. Its capital is composed of buildings, power plants, and energy, water, and transportation networks, which have a long lifetime. This sector is essential for economic activities but does not produce final goods; its production is entirely consumed by the second sector. The second sector is the composite sector that includes production of all other goods and services. Its capital is composed of machinery, vehicles, and other short-lived capital goods. It consumes all the first sector output, and produces composite goods that can be used for investment in both sectors and for consumption.

The first sector only uses capital, and the production function is a simple AK production with constant returns. The composite-sector production function is a nested CES function: capital and labor are combined using a Cobb-Douglas function, and the resulting output is then combined with the intermediate consumption of infrastructure services using a CES function to produce the output, with a low elasticity of substitution. Production functions are:

$$Y_i = \alpha \cdot K_i.$$

$$Y_c = \left(\lambda \cdot Y_i^{\rho} + \mu \cdot \left[(P \cdot e^{\nu t})^{1-\eta} K_c^{\eta}\right]^{\rho}\right)^{1/\rho} \quad \text{with } \sigma = \tfrac{1}{1-\rho}.$$

Y_i and K_i are the production and the capital stock of the infrastructure sector; Y_c and K_c are the production and the capital stock of the composite sector; P is population with labor productivity increasing at rate ν. Parameters μ and ρ (or σ) represent the elasticities of substitution in the production functions.

Investment in both sectors is carried out such that the marginal productivity of each capital is equated to the interest rate, which is fixed exogenously. In the model, climate impacts are modeled using the impact-adaptation damage function from Hallegatte (2005). Adaptation is assumed faster in the composite sector than in the infrastructure sector. Impacts are represented through a reduction in productivity and a reduction in capital lifetime.

Moreover, even though the infrastructure and housing sector represents only a fraction of total economic production in developed countries, it represents a major part of installed capital[10] and replacing this capital would represent a significant burden for the economic system. As a consequence, it is quite possible that an important part of the economic damages caused by climate change will arise from ripple effects, from this sector to the rest of the economy.

In a stylized modeling exercise, Dumas and Hallegatte show that impacts in the infrastructure sector do not necessarily lead to large macroeconomic losses, provided that significant additional investment is carried out quickly to compensate for climate change impacts. In the absence of an adequate amount of investment in the infrastructure sector, total economic losses would increase drastically, with consumption losses over the 21st century increasing by 25% (see details in Dumas and Hallegatte, 2009). The model is too simple to provide a precise quantitative statement, but shows the importance of adequate investment in infrastructures and housing to reduce climate change impacts. This fact is crucial, given that infrastructure investments today are far from being optimal both in level and quality (see for instance the drainage infrastructure in Mumbai that cannot cope with the heavy rainfalls that occur every year and are responsible for regular floods in the city).

Considering the fact that infrastructure and housing are strongly regulated sectors, and most of time heavily supported by governments, these results stress both the need for an adequate public response to reduce climate change impacts and the uncertainty of climate change damages created by the mere existence of public policy failures.

3.5 Marginal economic impacts, "shifting capacity", and structural economic impacts

The difficulty of investing sufficiently rapidly in infrastructure is an issue that can be generalized to other types of impact. As an example, some regions have developed their economies based on a single sector, like tourism or agriculture. In most general equilibrium models used to assess the macroeconomic cost of climate change, if this dominant sector becomes less profitable because of climate change, resources (labor and capital) shift to other, more profitable sectors and climate change leads to a change in economic structure with no significant loss in total production and income. For instance, in models that assume full employment, an inter-sectoral economic shift cannot lead to a surge in unemployment and a large drop in output.

In reality, however, past examples suggest that specialized economies are very vulnerable to changes in the profitability of their main economic sector: in the French regions where mining disappeared in the 1970s, or in deindustrialized regions in the U.S., the economy remained depressed over long periods of time in spite of the large financial support received from the national level.

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[10] In France, investment represents about 25 percent of GDP; investments in infrastructure (including housing) represents about 50 percent of total investment (Louvot, 1996); and the lifetime of infrastructure is about 55 years (100 years for buildings, 30 years for roads, 60 years for electric plants, etc.). Assuming that capital increases by 2 percent a year, we have: $0.125*GDP - K_{infra}/55 = K_{infra}*0.02$. Infrastructure capital, therefore, is approximately equal to 3.3 times GDP. As another way of estimating the value of infrastructure France, one can add transportation infrastructure (several hundreds billion euros), energy infrastructure (about 400 billion euros), water management (200 billion euros), flood protection (a few tens of billion euros) and housing (about 2500 billion euros). The total of this incomplete list already exceeds 3,000 billion euros, i.e. 2 times French GDP. In India, according to the GTAP database, the value of the capital stock is worth 2.13 times annual GDP. Assuming that 75 percent of the capital stock is for infrastructure and housing, and recognizing the difficulty in measuring capital stock (especially public capital stock) and the uncertainty surrounding this value in economic databases, the stock of infrastructure and housing in India is likely to exceed 1.6 times the Indian annual GDP.

These experiences show that an economy can deal with profitability shocks by shifting its resources to new sectors, up to a certain level, beyond which the "shifting capacity" is exceeded. Limits to this shifting capacity could arise, for instance, from an education level among workers in the shrinking sector that is too low to support the development of new sectors; or limited investment capacity in the new sectors could makes it impossible to provide the equipment and infrastructure required to absorb the influx of workers arriving from the negatively affected sector.

Such economic shifts would be particularly difficult in regions that cannot count on significant large-scale solidarity and in which the education level is low. Again, to understand climate change impacts, we have to distinguish between marginal perturbations (which general equilibrium models can model) and the structural changes that large climate change may require (and which no model can reproduce in a satisfactory manner so far).

A general conclusion of these analyses is that the cost of climate change will largely depend on the ability of economies to mobilize resources to address the climate change challenge: extreme events will require more resources to reconstruct; changing climate conditions will require more resources to invest in robust, adapted infrastructure; adverse productivity changes in key sectors will require more resources to develop alternative sectors and sources of income. In optimal economic models, where resources are allocated in an optimal manner without taking into account any technical and institutional constraints, the difficulty of mobilizing these resources is simply disregarded.

The current situation in many countries, however, shows that these constraints are real and binding. In the absence of these constraints, damages caused by the largest natural disasters would be repaired in months, not in years as is observed. In absence of these constraints, infrastructure funding would not meet the problems that we observe in developing and developed countries. In absence of these constraints, regions that lose their main economic sector and source of income would develop alternative activities in years, not in decades as it is often observed.

A sound cost-benefit analysis of climate change damages should incorporate some judgment (including in the form of probability) as to the impact of these constraints. It is very likely that there is a threshold beyond which adaptation—at the macroeconomic level—becomes much more difficult and expensive. Unfortunately, the position of this threshold is impossible to determine with current knowledge. Here, also, it is crucial to note that the uncertainty about "macroeconomic adaptive capacity" increases with climate change's pace and amplitude.

4. Conclusion: which cost-benefit analysis now, for lack of anything better?

This note highlights reasons to limit climate change as much as possible; they are fundamentally linked to the large increase in uncertainty triggered by large warming.

First, if the global average temperature becomes very different from the current one, it will be more difficult to know how local climates will evolve. This uncertainty would make it necessary to implement adaptation strategies that can cope with many different possible futures. Such strategies exist but they are less efficient than would be those strategies designed with perfect knowledge of future climate. There is a cost, therefore, associated to this uncertainty. Such costs are obviously ignored by models assuming perfect knowledge of how climate will change.

Second, the adaptive capacity of economic sectors is largely unknown. We know that such capacity exists for limited warming, because natural variability has made it necessary to cope with extreme events in the past. For greater warming, however, there is greater uncertainty about how various sectors will be able to cope with climate change and, again, there is a cost associated to this uncertainty.

Third, the adaptive capacity at the macroeconomic scale is also difficult to assess and we suspect that there are thresholds beyond which the total macroeconomic cost may rise rapidly, increasing the risk that the most vulnerable societies fall into poverty traps. The existence of these thresholds is supported by past experience, including economic disruptions caused by natural disasters, observed difficulties to fund needed infrastructure, and regional crises due to rapid structural economic shifts induced by new technologies or globalization. Since current economic models represent marginal economic changes and are not able to reproduce structural shifts in the economic system, these thresholds effects are difficult to predict and their consequences are difficult to assess.

We know that coping with climate change (from extreme events to changes in average conditions) will require the mobilization of additional resources for natural disaster reconstruction, infrastructure retrofitting and development, and economic diversification. Where these resources are available, climate change impacts will be much smaller than where additional resources cannot be found. But the fact that resources are available is not sufficient. These resources will have to be mobilized to cope with climate change. Current experience with risk management and infrastructure investment shows that even where financial resources are available, there are huge problems in dealing with extreme weather events or infrastructure under-investment. These problems can be driven by scarcities in human capital, decision routines, technical inertia, or institutional and cultural constraints. Economic models that assume an optimal allocation of resources cannot take into account these constraints and simply disregard this aspect of the climate change problem. In so doing, they may well be disregarding the main issue for climate change adaptation.

Limiting climate change is the best way to reduce these uncertainties and their associated costs.

But how does this translate into a cost-benefit analysis, in the absence of a fully-fledged monetary assessment of damages? The only way out, as pointed out very early by Manne and Richels and stressed by the Second Assessment Report of the IPCC (1995) is to reframe the cost-benefit analysis in the context of a sequential decision-making process, with progressive learning and reorientation of the initial course of action. This type of approach (Ha-Duong et al., 1998; Ambrosi et al, 2003) tries to balance the costs of premature aggressive mitigation action against the risks of its delay. Their main lesson is the importance of the asymmetry between, on the one hand, the relatively low costs of loosening a carbon constraint in view of new and more optimistic information and, on the other hand, the high costs of strengthening mitigation policies if they had been too lax to achieve the initial emissions goal or if new information shows that dangerous impacts will likely occur at concentration levels lower than previously thought (e.g., Ambrosi et al., 2003; Hourcade et al., 2009).[11]

Considering the high level of uncertainty surrounding the impact of a large global warming, this approach leads to favoring ambitious climate policies over the short term. In an additional analysis, Dumas and Hourcade show what type of beliefs and probability priors about growth, mitigation costs, and the absolute level and shape of the damage curve justify a 2°C target, for

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[11] These impacts may then last for centuries and millenniums. For some impacts, like the Greenland ice sheet or biodiversity, the consequences may even be irreversible over longer timescales.

various values of the discount rate. They show that this target is justified under most sets of beliefs that recognize the possibility of nonlinearity in the link between temperature increase and climate change damages. They show also that the current “window of opportunity” to limit warming to 2°C will only last about twenty years. Beyond that, if the damages triggered by, say, a 3°C warming prove to be significant, we will enter the domain of irrecoverable regret.

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