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Adapting to climate change. Costs,benefits,and modelling approaches.

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SUMMARY As part of the research carried out under the Gemina Work Package 6.2.10, this paper provides a summary and a critical survey of the methodologies and results of the literature on the economics of adaptation. We divide the literature into two broad areas of research. First, we examine the studies that analyse adaptation from a bottom-up perspective. Second, we introduce the studies that examine adaptation using a top-down approach. The first group of studies investigates cost and benefits of sectoral adaptation strategies with a geographical detail that varies from country-level to global-level. The second group gathers two different streams of literature that share macro approaches, as opposed to the micro ones of the former group. It includes both theoretical works as well as the contributions based on Integrated Assessment Models (IAMs). IAMs have originally been created to study policies aimed at limiting global warming. Recently they have also been extended to include adaptation as an alternative policy option to mitigation. This latter development has raised new issues that represent new challenges for the research community. In particular, how to make use of the vast amount of information provided by the bottom-up literature and how to integrate it into global models is paramount. Important research gaps to be filled include the improvement of the quantitative assessment of cost and benefit of adaptation needs, especially in some sectors and in developing countries and the clarification of the aggregation procedure used for scaling up bottom-up data. In addition, uncertainty and irreversibility are very marginally tackled by adaptation studies. Finally, the role of adaptation in international climate change negotiations, which is presently growing in importance, remains largely unexplored.

Keywords: Adaptation, climate change, climate change policies

JEL: Q54, Q58

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List of Abbreviations

GHG	Greenhouse Gas
FAR	First Assessment Report
IPCC	Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework on Climate Change
AR4	4th Assesment Report
USD	United States Dollar
HHWS	Heat Health Warning Systems
ODA	Official Development Assistance
FDI	Foreign Direct Investment
GDI	Gross Domestic Investment
UNDP	United Nations Development Programme
NGOs	non-governmental organisations
EACC	The Economics of Adaptation to Climate Change
CES	Constant Elasticity of Substitution
OECD	Organisation for Economic Co-operation and Development
EUR	Euro
(PAGE)	Policy Analysis of Greenhouse Effect
FUND	
AD-DICE	
FEEM-RICE	
AD-RICE	
AD-FAIR	
AD-WITCH	
IAM	Integrated Assessment Models
DICE99	

1. Introduction

The Conferences of Bali 2007, Copenhagen 2009, and Cancun 2010 have witnessed the gained political consensus on the crucial role of adaptation. Operational rules and resources for adaptation funding were explicitly established, demonstrating the high political priority ascribed to the necessity of action on both mitigation and adaptation.

Adaptation to climate change is now widely acknowledged as a complementary response to greenhouse gas (GHG) mitigation. Mitigation, by limiting GHG emissions, aims at tackling the fundamental causes of climate change. In contrast, adaptation consists of deliberate actions undertaken to reduce the adverse impacts as well as to harness any beneficial opportunities resulting from climate change. A clear understanding of adaptation processes, autonomous or planned, along with a reliable quantification of their costs and benefits is fundamental for at least two reasons. The first reason is to assess the full cost of climate change. This is composed of three interdependent components: the cost of adaptation, the cost of mitigation, and residual climate damage. The second reason is to provide normative indications regarding efficient climate policy mixes. From a policy perspective, resources need to be allocated efficiently between different adaptation strategies on the one hand and between adaptation and mitigation strategies, on the other hand. This can only be done if costs and benefits of the different options are clearly determined.

The first appearance of adaptation in scientific assessments dates back to the First Assessment Report (FAR) of the Intergovernmental Panel on Climate Change (IPCC) published in 1991. However, mitigation received much greater attention than adaptation throughout the 1990s. Supporting adaptation was viewed as an implicit acceptance of climate change and as an excuse to avoid the necessary effort to address its fundamental causes, GHG emissions . Studying adaptation within a unifying analytical framework is also particularly complicated as it is multifaceted and its characteristics greatly vary across time and space (IPCC AR4 2007).

Although the definition of adaptation is very clear in principle, in practice it is difficult to distinguish between adaptation, development, and even mitigation strategies (EEA 2007).

The consensus on mitigation during the latest rounds of international negotiations implicitly requires complementary policy strategies. If it is true that Cancun made significant progress by bringing the essential elements of Copenhagen back into the UNFCCC framework, the feasibility of achieving the 2°C target remains uncertain. The 2009 Copenhagen Pledges iterated in Cancun 2010 have been estimated to lead to a temperature increase above pre-industrial levels, of approximately 2.5 °C 3.5°C by the end of the century (Parry 2009; Carraro and Massetti 2010). Such temperature increases, while potentially avoiding catastrophic and irreversible outcomes, would nevertheless expose natural and human systems to significant negative consequences (Solomon et al 2007; Parry et al 2007).

In light of this, economic analysis is asked to provide insights to policy makers on the cost and effectiveness of adaptation, the optimal resource allocation between adaptation and mitigation, their optimal timing, and their distributional implications. These tasks are challenging. It is important to recall the IPCC Fourth Assessment Report (AR4) published in 2007, which concluded that [p.737]: "… there is […] a need for research on the synergies and trade-offs between various adaptation measures, and between adaptation and other development priorities. […] Another key area where information is currently very limited is on the economic and social costs and benefits of adaptation measures".

Although necessary, studying adaptation and how it interacts with mitigation faces some major challenges. First, whereas mitigation brings global benefits, adaptation is by large implemented by local actors and its benefits are perceived at the scale of the impacted system, which is regional at best, but mostly local. The public good nature of global emissions reduction creates the incentive to free ride, which is one of the biggest impediments to reach large and sustainable international mitigation agreements. Differently, incentives to carry out adaptation are larger. The benefits of adaptation actions primarily benefit the acting community and therefore are appropriable. As a consequence, in the absence of international coordination, substantial mitigation actions are unlikely to occur. Instead, the excludability of adaptation benefits provides strong incentives to adapt, even unilaterally. Nevertheless, the "common but differentiated responsibility" principle raised by the Kyoto Protocol underlines the need for adaptation to be considered at a global level. In this sense, adaptation and mitigation are two strategies that work towards the solution of the global climate change problem. Further, from a methodological point of view, adaptation and mitigation have been studied with different tools, which only recently have been adjusted to study the two strategies simultaneously.

This paper proposes a summary and critical survey of methodologies and results of the growing literature on the economics of adaptation with particular focus on its interaction with mitigation. Due to the infancy of the topic, scientific contributions are sparse and the research found in grey literature is prominent. This is particularly evident in the quantification of the aggregate cost of adaptation and in the development of theoretical models to analyse the strategic role of adaptation. Because this review comes at a stage in which the literature on adaptation is rapidly growing, it is the pause of reflection on what has been done so far that offers indications on where future research should allocate more effort.

The remainder of the paper is structured as follows. Section 2 summarises the major findings from the bottom-up stream of literature. It investigates the cost and effectiveness of specific adaptation strategies with a geographical detail that varies from the country-level to the global-level. Section 3 surveys top-down studies that treat adaptation as an aggregate strategy or a group of strategies in Integrated Assessment Modelling frameworks. Theoretical models and results are presented first (Section 3.1) and numerical simulations follow (Section 3.2). Section 4 concludes.

2. On the costs and benefits of adaptation

A few existing studies have reviewed costs and benefits of adaptation in the main sectors impacted by climate change (Watkiss 2009; Parry et al 2007; EEA 2007; Agrawala and Fankhauser 2008; Callaway 2004). While not aiming to comprehensively review the relevant literature, as already done by those studies, this section summarises the most important results to illustrate the state of the art and its limitations for each sector of analysis.

Although the existing amount of information on adaptation costs and benefits is already vast, it is unevenly distributed across sectors and countries. Many studies address adaptation in sea-level rise or agriculture whereas there are only a few studies in sectors such as health and tourism. For some sectors information is mostly related to specific regions or activities. For example, in the case of energy, most studies relate to changes in energy demand resulting from warmer temperatures and are geographically limited to North America and Europe. Further, some sectors, such as agriculture, are more focused on the quantification of benefits from adaptation, whereas other sectors, such as health and tourism, are more focused on the costs.

2.1. Costs and benefits of adaptation to sea-level rise

Although climate change will have complex impacts on coastal zones that will exacerbate existing pressures, most studies on climate change and coastal zones have focused on sea-level rise. Adaptation in coastal zones can take a wide range of forms, including coastal protection as well as planned retreat, beach nourishment, flood-proofing, property insurance and changes in water management and agriculture.

A wide range of studies assess adaptation to sea-level rise using modelling techniques that seek to minimise the total costs of climate change, for instance the costs of protection and the residual (unprotected) damages. The benefits, which are the damages avoided as a result of protection, are a key component to computing optimal levels of protection. While in regions with extremely valuable assets total protection might be optimal, in other cases, the optimal strategy might be to invest in partial protection and accept a certain amount of residual damages. Table 1 summarises the results from the most recent studies in different regions at the global level. Such estimates are often limited, as they do not consider the progressive nature of adaptation. Infrastructure may be adapted over time to climate change instead of proactively building it. Estimates of costs and benefits of adaptation in this sector should also be considered relative to the time horizon. When the time horizon is large, the costs will be lower as they are distributed over time.

Table 1. Costs of coastal protection

Regions	Reference	Sea Level Rise Considered	Protection Level (% of coastline protected)	Protection costs (Billion USD)
WORLD	Nicholls (2007)[*]	8.9–9.1cm by 2030 (average); max 44.4–52.7cm by 2080	Not available (n/a)	4-10.6
	Tol (2002)	1m	89 %[8]	10.55
	Mendelsohn et al (2000)	0.5m	n/a	10 (1990 USD)
WESTERN EUROPE	Nicholls (2007)	8.9–9.1cm by 2030 (average); max 44.4–52.7cm by 2080	n/a	0.624-1.785
	Tol (2002)	1m	86 %	1.36
	Deke et al (2001)	1m	Total	1.76
	Bosello et al. (2007)	25cm (by 2050)	Total	11.2
NORTH AMERICA	Nicholls (2007)[*]	8.9–9.1cm by 2030 (average); max 44.4–52.7cm by 2080	n/a	0.88-2.02
	Tol (2002)	1m	86 %	0.83
	Deke et al (2001)	1m	Total	1.4
LATIN AMERICA	Nicholls (2007)[*]	8.9–9.1cm by 2030 (average); max 44.4–52.7cm by 2080	n/a	0.573-1.597
	Tol (2002)	1m	86 %	1.47
	Deke et al (2001)	1m	Total	0.12
AFRICA	Nicholls (2007)[*]	8.9–9.1cm by 2030 (average); max 44.4–52.7cm by 2080	n/a	0.528-1.319
	Tol (2002)	1m	80 %	0.92
SOUTH and SOUTH-EAST ASIA	Nicholls (2007)[*]	8.9–9.1cm by 2030 (average); max 44.4–52.7cm by 2080	n/a	0.801-2.181
	Tol (2002)	1m	93 %	3.05
PACIFIC	Nicholls (2007)[*]	8.9–9.1cm by 2030 (average); max 44.4–52.7cm by 2080	n/a	0.388-1.080
	Tol (2002)	1m	95 %	0.63

Source: Agrawala and Fankhauser, (2008)

In their studies, Agrawala and Fankhauser (2008) find that the optimal levels of coastal protection are quite high in most regions of the world. Exceptions include countries or regions where coastal land values might be low and therefore lower protection levels might be considered optimal. The annualised cost estimates for the achievement of such protection levels are typically relatively modest in normalised terms, frequently less than 0.1 % (or even 0.05 %) of GDP. However, adaptation costs may be high relative to the GDP of coastal areas, as it is not guaranteed that protection costs will be absorbed fully at the national level. There are also significant regional differences and the share of protection costs as a percentage of GDP might be higher for certain small island states.

Estimates of costs and benefits of adaptation in this sector heavily depend on the assumptions that are made, for instance, on protection costs, typically extrapolated from specific local projects, or endowment values. Darwin and Tol (2001) showed that uncertainties surrounding endowment values could lead to large differences in the estimates. Yohe et al (1996) and Yohe and Schlesinger (1998) showed how considering efficient markets would reduce adaptation costs.

Estimates of adaptation costs and benefits for coastal regions face a certain number of limitations. Studies are often limited to an inundation of coastal zones and wetlands and extreme scenarios of sea-level rise are rarely considered. Exceptions are Nicholls et al (2005), who examined the consequences of the collapse of the West Antarctic Ice Sheet, and Dasgupta et al (2007), who considered the costs of an extreme sea-level rise for developing countries. Most studies only focus on the direct protection costs to sea-level rise and do not consider the macroeconomic effects, such as increases in price level and shifts in the demand for capital resources. A limited number of studies have used computable general equilibrium models to assess the economy's wide impact of land loss and increased protection investment in coastal zones. The conclusion is that there might be very significant divergence between direct costs and welfare losses, as well as in the regional distribution of these costs (Darwin et al 2001; Deke et al 2001; Bosello et al 2007).

2.2. Costs and benefits of adaptation in agriculture

The agricultural sector has a long record of adapting to climate variability. Measures will be implemented spontaneously at the farm level through short-term production decisions including adjustments in planting dates, crop mixes, or in the intensity of input use such as fertiliser. Although farmers will spontaneously adapt, their decisions will be influenced by the economic environment including market conditions and public policies, particularly those stimulating research and development, diffusing information, providing institutional support and promoting efficient use of resources.

There is a wide range of literature on adaptation in the agricultural sector (Adams et al 1995; Seo and Mendelsohn 2008; Kurukulasuriya and Mendelsohn 2007; Wang et al 2009). The literature mostly focuses on benefits from adaptation. Salient studies include Reilly et al (1994) and Darwin et al (1995), which examined the climate change and adaptation impacts on world agriculture and economy, as well as a global assessment by Rosenzweig and Parry (1994), which reported the impacts and adaptation benefits in terms of increased cereal production and food security. Rather, Tan and Shibasaki (2003) use a GIS based crop model to compute global adaptation benefits. A general finding from these studies is that relatively modest adaptation measures can significantly offset declines in expected yields as a result of climate change.

There are also a large number of studies that assess the benefits of adaptation for different crops and regions. IPCC (2007) reviewed 69 studies on the impacts of climate change on crop yields. A key message from these studies is that while farm level adjustments yield significant benefits, such benefits do not occur equally in all regions. As tropical developing countries are, in many cases, expected to benefit less from low cost adaptations, benefits may be larger in developed countries than in developing ones.

The literature on the cost side of the adaptation equation for agriculture is almost entirely lacking, with the exception of the study by McCarl (2007). The study estimates that additional investments in research (e.g. in drought resistant seed varieties), agricultural extension, and physical capital (such as irrigation infrastructure) for agriculture, forestry and fisheries will be USD 14.23 billion per year by 2030. Strong assumptions on adaptation responses raise questions about the reliability of the results.

2.3. Costs and benefits of adaptation in the water sector

Water supply will be affected by changes in temperature and shifts in precipitation patterns. The impacts of climate change on precipitation are quite uncertain and will differ significantly across regions. These changes will affect many sectors, which depend on water supplies, including the drinking water supply, wastewater treatment, and agriculture. In addition, river water quality may also be affected due to lower stream flow and higher concentration of organic matter linked to more intense precipitation and erosion.

Adaptation in the water sector is inevitable and fundamental (Hurd et al 1999). It will require a combination of both supply side (e.g. building new storage capacity, prospecting and extracting ground water, rainwater harvesting, desalinisation, wastewater treatment) and demand side measures (e.g. recycling, changing usage patterns, greater use of water market). Because of the strong uncertainty in the future availability of water, big infrastructural investments may risk causing higher costs than benefits. In most cases, it would be better to wait until more accurate information is available before investing in infrastructure. While very limited, the literature on adaptation in the water sector covers a diversified set of impacts and adaptation measures (Table 2).

Table 2. Costs of adaptation of water resources

Study	Region/theme	Adaptation measures	Adaptation costs
Kirshen et al (2006)	Maintain water quality in the Assabet River (Boston, MA, USA)	• Extra treatment of wastewater • Establishment of wetlands • Infiltration basins to reduce non-point source inputs	Additional - USD 6.5-15.5 million in capital costs - USD 90.000-390.000 in annual operating costs
EEA (2007)	River flood management for River Rhine	• Flood defence	Over 21st century: - Costs: EUR 1.5 billion - Benefits: EUR 1.1-3.9 billion
Dore and Burton (2001)	Water utilities in Canada (availability of drinking water, capacity of treating wastewater)	• Building new treatment plans • Improved efficiency in actual plants • Retention tanks	Adaptation costs for Toronto could be as high as CAD 9,400 if extreme events are considered
Muller (2007)	Adaptation in urban water infrastructure in (Sub-Saharan) Africa	• Water infrastructure • Costs of new developments	• Climate change costs: USD 2-5 billion annually • Adaptation costs: - USD 1,050-2,640 million 1,050-2,650 million - USD 990-2,550 million
Vergara et al (2007)	Glacier retreat in the Andes causing water cycle disruption in glacier-dependent basins (Quito, Ecuador)	• Water infrastructure	Adaptation costs in net present value for the next 20 years: USD 100 million (30% increase in infrastructure in the absence of climate change)

Costs and benefits have been assessed for adaptation measures that offset the impacts of climate change on water availability, the reliability of water supplies, and water quality. In the US, Kirshen et al (2004) assessed the reliability of water supply in the Boston metropolitan region under climate change. Some estimates are also provided for adaptation costs related to water supplies in Canada. Dore and Burton (2001) examined adaptation costs in response to impacts of climate change on the availability of the drinking water supply and the capacity of treating wastewater. Muller (2007) estimated the costs of adapting urban water infrastructure in (Sub Saharan) Africa to climate change to be between USD 2 – 5 billion annually. There is also one study which examines the impacts of accelerated glacier retreat on water availability and the costs of adapting to it in the Andes (Vergara et al 2007).

Overall, the literature on adapting water supply and demand in response to the impacts of climate change is still too sparse and context specific to make a broad assessment of costs and benefits of adaptation. Nevertheless, some messages do emerge from this limited literature. For regions where precipitation is expected to increase, it is wastewater treatment that may become problematic and impose substantial costs in order to adapt public infrastructure. On the other hand, in regions where precipitation will decline or where water availability might decline on account of glacier retreat, investments in enhanced storage, as well as enhancing the efficiency of water allocation becomes highly valuable. However, drawbacks in terms of market access for the urban poor and related social impacts may need to be investigated. To ensure the drinking water supply, a diversification of supply sources through the interconnection of supply systems also proves to be beneficial. Maintaining river water quality may also be very costly for public authorities.

There is only one assessment of the costs of adaptation in water resources at the global level (Kirshen 2007). The method used in this study consists in comparing future projected water demands from different sectors to water supplies. The overall conclusion of this study assessment is that adaptation costs in the water sector will amount to a total of approximately USD 531 billion by 2050. However, the results are limited by the fact that these costs include adaptation responses not only to climate variations, but also to macroeconomic changes.

2.4. Costs and benefits of adaptation in the energy sector

Climate change is expected to impact the energy sector on the *demand* side as well as the *supply* side. Increasing temperatures will cause an increase in the *demand* for energy for cooling and a decrease in the demand for energy for heating. More extreme weather events may cause disruptions in the *supply* of energy and water scarcity may affect production especially in hydro-electric production.

The literature on adaptation costs in the energy sector is mostly limited to the costs associated with the changes in energy demand. Much of this literature is limited to the United States and the electricity sector. However, it is important to consider the effect that temperatures will have on the different types of fuels. As demonstrated by Mansur et al (2005), climate change will cause a shift in favour of electricity consumption since it is the primary source of cooling.

The literature in this sector includes both bottom-up and top-down analyses. Rosenthal et al (1995) used an engineering "bottom-up" model and found net benefits, that is a net reduction in energy consumption, of (1990) USD 5.3 billion, for the US economy under the assumption of a one degree temperature rise by 2010. Rather, Morrison and Mendelsohn (1999) used a top-down approach and examined the climate change impacts on US energy demand, disaggregating by sectors and fuel and energy types. The authors report net adaptation costs (for instance, increased energy expenditures) ranging from (1990) USD 1.93 billion to 12.79 billion for the 2060 horizon. The estimates of the net adaptation costs or benefits in energy demands are sensitive to the assumptions on the future evolution of building stocks. Morrison and Mendelsohn (1999) and Mendelsohn (2003) differentiated between different climate sensitive building characteristics. The studies conclude that considering the evolution in the cooling capacity of buildings significantly increases the cost of adaptation.

A few general conclusions can be drawn from the literature on the costs and benefits of adaptation in the energy sector. The majority of studies conclude that the adaptation costs of increased cooling will be greater than the benefits associated with reduced heating demands.

However, with the exception of Cartalis et al (2001), who provided estimates for the Southeast Mediterranean region, and of a few studies on a global basis (De Cian et al 2007; Tol 2002; 2002a; Bigano et al 2006; Petrick et al 2010), all assessments are specific to the US. Further, the studies are yet to systematically assess the effects of changes in climate variability and the role of market in adjusting prices to changes in energy demand.

2.5. Costs and benefits of adaptation in infrastructure

Infrastructure is a part of adaptation in many climate sensitive sectors ranging from water supply to energy. It is a high-valued asset, particularly vulnerable to climate change on account of its long lifetime over which climate change impacts will become progressively more pronounced. Adaptation costs for infrastructure could be interpreted either as the costs of infrastructural solutions that serve as adaptations, or as the costs of climate-proofing infrastructure itself to the progressive impacts of climate change.

Only very few studies exist which have attempted to provide more aggregate information. Dore and Burton (2001) quantified the cost two infrastructure-related adaptations in Canada: the replacement costs of the Canadian winter road network by “all weather roads” in response to rising temperatures; and the costs of investing in enhanced rainwater storage and wastewater treatment facilities. A more recent study examines the cost of adapting public infrastructure in Alaska to five impacts associated with climate change: permafrost melt, sea-level rise, accelerated coastal erosion, increased flooding, and increased fire risk (Larsen et al, 2007). In contrast to these two bottom-up studies, which aggregate micro level data, a third study uses a top-down approach to estimate the worldwide costs of adapting infrastructure (Satterthwaite 2007). The study estimates the worldwide costs of adapting infrastructure to be in the range of USD 7.8 - 130 billion by the year 2030. Finally, global estimates are calculated in the range of USD 4-41 billion per year by 2030 by the UNFCCC (2007) and of USD13 billion and USD 27.5 billion per year for the period between 2010 and 2050 by the World Bank (2010) for the driest and wettest scenarios respectively.

2.6. Costs and benefits of adaptation in the tourism sector

The tourism sector, particularly sensitive to climate and environmental conditions, will also be affected by climate change. The varied impacts of a changing climate are already influencing decision-making in the tourism sector (Simpson et al 2008). In general, outdoor recreation is increasing in the spring and fall, reducing the winter tourism seasons, and often changing tourist destination in summertime from warmer to cooler regions. Adaptation options for the tourism sector depend on the location and range from snowmaking in mountain areas to water recycling in dry areas or cyclone-proof building design in areas subject to extreme events.

Although concerns of negative impacts of climate change on the tourism sector regard many areas, in particular small island states or the Caribbean, studies have mainly focused on mountain areas regarding winter tourism and the ski industry. Agrawala (2007) and Bigano et al (2008) assessed adaptation measures and some of the costs provided for technological adaptations in the winter tourism industry. Until now, technological adaptations appear to be the main types of adaptation strategies adopted by tourism stakeholders in the European Alps.

While some adaptation strategies, such as the protection of glaciers with white sheets, can be relatively cheap (cost of EUR 3/m^2), other strategies, such as extending ski areas to high elevations and artificial snowmaking, can be expensive. For example, Mathis et al (2003), carried out a survey of projected ski area developments in Switzerland and found that the high mountain extensions would cost between EUR 25-30 million. In France, for the 2003-04 winters, investment costs for snowmaking material reached EUR 60 million. However, the investment in new snowmaking equipment rarely represents the development of completely new installations but an extension to or improvement in current equipment. Functioning costs for that same season in France reached EUR 9.4 million. Different figures are available regarding the production of one cubic metre of snow. For example, the costs are estimated to be EUR 1-5 by the Association of Austrian Cableways and EUR 3-5 by CIPRA (2004). Thus, the relationship between costs and benefits is still unclear.

The costs and benefits of such adaptations are also highly dependent on the time horizon considered and the level of comprehensiveness of the studies. These adaptations are not necessarily sustainable in the long-term and may generate negative externalities. For example, glacier skiing may be unsustainable, as glaciers may soon be disappearing. Other adaptations, such as the installation of ski transportation facilities, the implantation of artificial snow pumps and increase in artificial snowmaking, are likely to have detrimental environmental impacts which have not been considered in the cost-benefit studies.

2.7. Costs and benefits of adaptation in health

Weather and climate influence human health through direct effects of extreme events such as heat-waves, floods and storms. I Indirect effects on the distribution and transmission intensity of infectious diseases, and on the availability of freshwater and food (Campbell-Lendrum and Woodruff 2007) also influence human health. In particular, there is a broad consensus that climate change will increase the costs arising from diseases, such as malaria and diarrhoea, and that the increases will be the largest in the developing world (Markandya and Chiabai 2009). In this context, development and adaptive capacity are fundamental as they may lower the costs of implementation of adaptation programmes such as vaccination schemes.

Many studies have estimated the implications of climate change on public health, on the costs and benefits of delivering health services, and on the possible adaptation strategies that can be implemented in the health sector (WHO 2005; WHO 2006). Some studies have also attempted to estimate the economy-wide impacts of climate change on the health sector (Bosello et al 2006; Watkiss et al 2007). Nevertheless, specific information on adaptation costs and benefits in this sector is still scarce. Although there are several studies that focus on the health costs of climate-related diseases, only a few focus specifically on the diseases induced by climate change. Van Rensburg and Blignaut (2002) estimated the additional health care costs due to an increase in the incidence of malaria induced by climate change in Southern Africa. Markandya and Chiabai (2009) evaluated the cost-effectiveness of different health adaptation programmes.

The study by Ebi (2008) provides global estimates of adaptation costs to climate change in the health sector. It estimates direct adaptation costs in a bottom-up approach by investigating treatment costs of additional number of cases limited to diarrhoeal diseases, malnutrition and malaria. Globally, the study estimates these costs to amount to a total of USD 4-5 billion by 2030, primarily in developing countries. More recently, the UNFCCC (2007) estimated an overall cost of USD 5 billion per year to be spent on health by 2030, while the World Bank (2010) estimated USD 2 billion per year between 2010 and 2050. These studies mostly focus on diseases and do not consider other adaptation costs, such as a new infrastructure that will be particularly needed in developing countries. An exception is Ebi et al (2004) who considered the Heat Health Warning Systems (HHWS) adopted in Philadelphia (US) in 1995.

In general the literature in this sector is still very limited because of the difficulties involved in estimating the climate change specific costs. Assessing the component of investments in public health infrastructure that might be needed to address climate change as opposed to those required on account of social and demographic trends is not straightforward. Further, the boundary between what constitutes climate change impacts and what might be an adaptation is not entirely clear in the case of public health. Specifically, the costs of treatment of climate sensitive diseases could equally be included under the impacts of climate change and under costs of adaptation. What assumptions are made would therefore critically affect the final estimates of adaptation costs and benefits.

2.8. Global estimates of adaptation costs

After a long period of total absence of empirical estimates of the global costs of adaptation across sectors, there have been a number of assessments that confronted this issue in recent years. Global adaptation cost assessments can be divided into two generations mostly based on different methodologies for the calculation of adaptation costs (Fankhauser 2010). Results from the main studies are illustrated in Figure 1.

In the first generation based on the work initiated by the World Bank as part of the "Investment Framework for Clean Energy and Development" (2007), adaptation costs are calculated on the basis of current climate sensitive investments. The costs of climate-proofing future capital investments are then calculated using a mark-up factor. The investments considered were Official Development Assistance (ODA) and concessional finance, Foreign Direct Investment (FDI) and Gross Domestic Investment (GDI). The World Bank study was then updated by the Stern Review (2006), which follows the same methodology but uses different mark up values.

The adaptation cost numbers in the World Bank Investment Framework also served as primary inputs for the assessments by Oxfam (2007) and the UNDP (2007). The Oxfam assessment adds three elements: scaled-up costs of community level projects by Non-Governmental Organisations (NGOs); scaled-up costs of immediate adaptation needs of developing country governments; and considerations of adaptation costs which are excluded from the World Bank study. Contrary to previous studies that look at current adaptation costs, UNDP assesses annual investments required for adaptation for 2015.

The first generation estimates strongly rely on the chosen mark ups and result in a large range of estimates, which stresses their lack of reliability. Furthermore, although usually referred to as global estimates, they only considered developing countries. The methodology on which they are based does not allow for the possibility to distinguish between sectors and to calculate adaptation costs needed in the longer-run. These shortcomings have motivated the change in methodology of the second-generation studies.

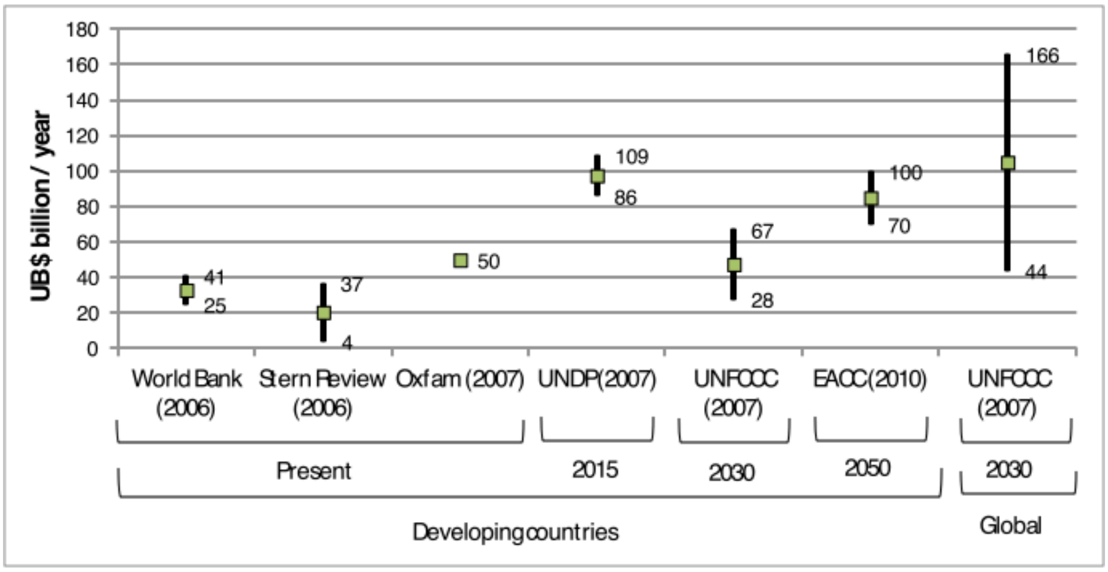
The second set of works was initiated by the UNFCCC as part of its "Analysis of Existing and Planned Investment and Financial Flows Relevant to the Development of Effective and Appropriate International Response to Climate Change" (2007). The UNFCCC estimates examined investments and financial flows for adaptation to climate change for the year 2030 in five sectors: agriculture, forestry and fisheries; water supply; human health; coastal zones; and infrastructure.

Recently, the World Bank has undertaken a comprehensive study of global adaptation costs in the project "The Economics of Adaptation to Climate Change" (EACC). The study takes a similar approach to the UNFCCC but considers more details on infrastructure as well as general equilibrium effects. The drawback of the study is that adaptation is overestimated because it is assumed to lead back to pre-climate change welfare levels.

Although there is a fundamental input in the formulation of adaptation in global climate-economy models, estimates of adaptation costs and benefits show serious limitations. Sector specific studies are still limited in sectoral and geographical coverage. Thus, scaling up to global levels may be biased where information is only related to particular case studies. The role of the assumptions undertaken in the aggregation for the final results is underlined by

Watkiss (2011). Global estimates are also subject to limitations and the low state of knowledge is evident in the wide range of global adaptation costs estimates. Nevertheless, there is a growing understanding of how the literature could be improved, which is mostly by furthering country and sector case studies and research on adaptation under uncertainty.

Figure 1: Global adaptation costs estimates



3. Top-down approaches

Given its local-specific and project-specific nature, the research on adaptation strategies has been mostly conducted with the bottom-up or micro approaches reviewed in the previous section. Although this methodology can provide information about the economic performance, viability and side effects of specific adaptation projects or types, it lacks the broader perspective on their interactions with other economic activities and policies, primarily mitigation. A major difficulty in doing so relates to the necessity of reconciling the global nature of mitigation, typically studied with international macroeconomic models and implemented through large-scale tax-quota schemes with the micro, often site-specific, nature of adaptation. This raises problems of data, timing, and modelling consistency. A very recent, but growing literature has addressed these issues, using macroeconomic approaches. Adaptation is modelled as an aggregate strategy that is fostered by some form of planned spending and that directly reduces climate change damages. Adaptation is then compared to cost-benefit or cost-effectiveness exercises with mitigation and residual damages. The studies using this approach can be further grouped into theoretical contributions that identify the conditions for specific results to hold and applied numerical works, which instead give some quantitative indications. Below we review the two streams of literature.

3.1. Theoretical models

There is little theoretical work on adaptation and contributions come mainly from the grey literature. Nevertheless, it is a promising and rapidly expanding field. It can be broadly classified into three main different research areas: the first aims to define the nature of the relationship between mitigation and adaptation; the second describes the optimal mix between mitigation and adaptation; and the third investigates the potential role of adaptation in international environmental negotiations.

The relationship of adaptation with mitigation

Within the first stream, the literature tries to determine whether mitigation and adaptation are substitutes. For instance, a reduction in the cost of one increases its use and decreases that of the other, or complements, that when one strategy increases so does the marginal productivity of the other. Ingham et al (2005) used a linear programming framework to find that under standard conditions mitigation and adaptation are substitutes. This result is robust to the introduction of uncertainty and holds in partial and general equilibrium as well as in a static and dynamic setting. Mitigation and adaptation can be complements in the unlikely occurrence that mitigation decreases the marginal adaptation costs. This, for instance, may arise in the presence of catastrophic events when mitigation, as a means to reduce the risk of the catastrophe, also aids in the occurrence of adaptation. Yohe and Strzepeck (2004, 2007) obtained a very similar outcome. However, the authors highlight that, with reference to the irreversibility of climate change, complementarity between adaptation and mitigation should be the rule and not the exception.

Lecoq and Shalizi (2007) also used linear programming to demonstrate the substitutability between mitigation, and both anticipatory and reactive adaptation. Based on this finding, they argue that adaptation and mitigation should be jointly determined in international climate negotiations. They also demonstrate that the introduction of uncertainty on the amount and geographical distribution of environmental damages tends to increase cost effectiveness of mitigation, which has a global scope, compared to adaptation, which instead is location-specific. By the same token, uncertainty favours reactive compared to anticipatory adaptation when the two are substitutes.

The optimal mix between adaptation and mitigation

Addressing the optimal mix between mitigation and adaptation, Kane and Shogren (2000) used economic theory of endogenous risk to replicate a result that is a standard outcome in the absence of uncertainty: when adaptation and mitigation are substitutes they are used until their expected marginal benefits and costs are equated[2]. Corner solutions (adaptation or mitigation only outcomes) are also discussed as theoretical possibilities[3], but unlikely in practice. The analysis of agents' responses to increased climate change risk is more complex. It depends upon two effects: a direct effect of risk on the marginal productivity of a strategy and an indirect one determined both by the risk impacts on the other strategy and by the relationship between the two strategies. For example, the indirect effect amplifies the direct effect if the

[2] Tulkens and van Steenberghe (2009) formally iterated this result more recently.
[3] If for instance an international mitigation agreement is not signed, making agents aware of the practical ineffectiveness of (unilateral) mitigation action or if, conversely, climate regime is so strict to eliminate the necessity to adapt to any climate change damage.

marginal productivity of one strategy increases and the two strategies are complements or if marginal productivity decreases and the strategies are substitutes.

Buob and Stephan found partly similar results (2011). They investigate the problem in a non-cooperative game-theoretical setting finding that it is possible to find adaptation-only and mitigation-only equilibria when the two are perfect substitutes. The strategy that exhibits the lower discounted marginal costs will prevail. This reflects the fact that if there are two almost equally effective ways to improve a region's environmental quality, the decision to mitigate or to adapt in the end depends on intertemporal cost-effectiveness. On the contrary, when the strategies are complements, an equilibrium in which all regions invest in mitigation and adaptation from the outset can exist.

Bréchet et al (2010) builds on a Solow Swan growth set-up endowing a central planner with the possibility to decide how much to invest in mitigation ad adaptation. In their comparative static analysis they show that the ratio between adaptation and mitigation depends crucially on the stage of development of the economy. In richer, developed and more productive economic systems it is worth investing in adaptation whereas in developing, poorer, weakly efficient economies, opportunity cost of adaptation can be too high inducing zero adaptation. Differently from adaptation, some level of mitigation is always optimal. The consequence is a bell-shaped behaviour of the adaptation-mitigation ratio. Before a given development level is reached no adaptation is undertaken and only mitigation takes place. With economic growth, adaptation increases to a maximum level after which adaptation investment starts to decline. This is driven by the specific modelling of adaptation: it is a cumulative stock with declining marginal productivity. Therefore, when almost full protection is reached, the value of additional adaptation investment is so little that it is preferable to invest in productive capital.

The role of adaptation in international environmental negotiations

The different incentive structure that characterises mitigation and adaptation raises the question of whether a climate negotiation linking the two strategies can be more successful at either enlarging participation, especially by developing countries, or increasing the overall mitigation effort compared to an agreement addressing mitigation only. Barrett (2008) noted that enforceability and adequate incentives can be better provided in a fragmented rather than in a global "Kyoto-like" regime. In a fragmented regime, separate agreements both for different greenhouse gas emissions and sectors can be concluded. In this "portfolio of agreements" adaptation can play an important role as, differently from mitigation, it is strongly needed by Developing Countries, its benefits are almost fully appropriable, and it is sector specific. In a seminal paper Barrett (2010) developed a non-cooperative game theoretical set-up and demonstrates that adaptation enlarges participation. However, enlargement occurs because adaptation decreases the need to mitigate thus pushing the environmental effectiveness of the mitigation agreement closer to a non-cooperative effort. In conclusion, adaptation enhances participation by emptying the agreement of its mitigation content.

Buob and Stephan (2008) also used non-cooperative game theory for their analysis. Their conclusion is also pessimistic. When mitigation and adaptation are complements, developed countries can effectively increase developing countries abatement effort as well as global abatement by financing adaptation in developing countries. However, when welfare increases in donor countries, it decreases in receiving countries. This happens because the adaptation funding shifts the burden of abatement from developed to developing countries and the subsequent additional abatement costs result to be typically higher than the adaptation aids. Consequently, developing countries will not be willing to accept such an agreement. In general, investigation in this field is at an early stage and conclusions are not consolidated yet. Moreover, the theoretical literature can only describe what could happen when mitigation and adaptation are substitutes or complements or clarify under which conditions the two are substitutes or complements. Accordingly, specific conclusions and policy advice depend crucially on different empirical cases, as in reality both substitutability and complementarity can be observed (Klein et al 2007).

3.2. Numerical models

The applied studies have been conducted mostly with Integrated Assessment Models (IAMs). IAMs represent the complex cause-effect relationships between climate change, economic growth, and policy options. The development of IAMs started in the early 90s as multidisciplinary efforts integrating climate, environmental and economic expertises. Since then they have become a common and consolidated tool for the assessment of climate change mitigation policies. In response to the raising political interest, the potential of IAMs in addressing the policy aspects of climate change dynamics has recently been exploited to also include adaptation into the numerical integrated assessment frameworks. Because of the vast uncertainty that affects both adaptation costs and benefits and the simplifying and often subjectivity assumptions made for calibrating global models, quantitative insights should be taken with a grain of salt.

3.2.1. Methodology

The merit of being the first attempt to include adaptation in an Integrated Assessment Model goes to the Policy Analysis of Greenhouse Effect (PAGE) model (Hope 1993; Plambeck et al 1997). In PAGE, a maximum rate of change (slope parameter) and a maximum absolute change (plateau parameter) in global temperature are assumed to be sustainable without considerable damages. Adaptation can operate in three ways. It can increase the slope of the tolerable temperature profile, its plateau, or it can reduce the adverse impacts of climate change when temperature exceeds the tolerable threshold. The default adaptation strategy is very effective because benefits are assumed to be large. Impact reduction through adaptation ranges between 90% in the OECD to 50% in other regions. Globally, adaptation can achieve a damage reduction of roughly USD 35 trillion at the cost of USD 3 trillion, within the period 2000-2200 using a 3% discount rate. With these assumptions, PAGE justifies aggressive adaptation policies, implicitly decreasing the appeal of mitigation. In all its versions (Hope 1993, 2006, 2009; Plambeck et al 1997), the PAGE model treats adaptation as exogenous or scenario variable decided at the outset. As a consequence, the model cannot endogenously determine the optimal characteristics of a mitigation and adaptation policy portfolio.

A step in this direction is provided by the FUND model (Tol 2007). Adaptation is an explicit policy decision variable, but only to contrast sea-level rise consequences. Coastal protection is a continuous decision variable that is optimally chosen on the basis of a cost-benefit criterion based on Fankhauser (1994). The costs and benefits of coastal protection are efficiently balanced in different scenarios with and without mitigation. Insights on adaptation dynamics are then derived. Coastal protection entails mostly large infrastructural projects (e.g. building dikes) and therefore the form of adaptation represented here is anticipatory or proactive in nature.

Further developments are provided by a group of models - FEEM-RICE (Bosello 2010), AD-DICE (De Bruin, Dellink and Tol 2009; Agrawala et al 2010), AD-RICE (Bruin, Dellink and Agrawala 2009; Agrawala et al 2010), AD-FAIR (Hof et al 2009), AD-WITCH (Bosello, Carraro and De Cian 2010, 2010a; Agrawala et al 2010), and Ada-BaHaMa (Bahn, Chesney and Gheyssens 2010) – presenting strong methodological similarities.

All share an intertemporal utility maximisation growth modelling core with climate dynamics inspired by the RICE-DICE model family (Nordhaus 1994, 1996, 2000). They integrate an economic module where a single world or multiple regional social planners choose between current consumption, investment in productive capital, and emissions reduction with a damage component. This is represented by global or regional damage functions that depend on the temperature increase compared to 1900 levels. Nordhaus and Boyer (2000) still remain the main reference for the parameterisation of regional damages in nearly all these models[4]. In DICE/RICE, adaptation is also included in the damage function as a cost. However, it is neither disentangled from residual damages, nor represented as a decision variable. The effort made by the studies mentioned goes in one or both of these directions.

Bosello (2010) introduces anticipatory adaptation as a stock of defensive capital that is accrued over time by a periodical endogenous investment. He uses the FEEM-RICE model, an enriched version of the Nordhaus and Yang (1996)'s RICE96 model, allowing for endogenous technical progress. Adaptation investment reduces climate change damage, but must compete with investment in R&D, physical capital and mitigation expenditure in the planner's utility maximisation problem. Bosello (2010) however, treats planned adaptation costs as not included in the original RICE damage function. Although calibrated to replicate available information, they are added to that damage. This decision was motivated by the author with the practical difficulty and subjectivity involved in singling out "optimal" adaptation patterns from the RICE damage function, given the large uncertainty on adaptation costs and residual damages.

Separating adaptation costs from the residual damage component in the Nordhaus damage function is the approach used by Bahn et al (2010), De Bruin, Dellink and Tol (2009), De Bruin, Dellink and Agrawala (2009), Hof et al (2009), Bosello, Carraro, and De Cian (2010), and Agrawala et al (2010). This means that the baseline damages of these studies that made adaptation explicit coincide with the original damages of RICE or DICE, in which adaptation was left implicit.

Bahn et al (2010) developed a model in the spirit of DICE, but with stock adaptation and distinguishing two macro sectors: the fossil-fuel-based economy and the carbon-free or clean economy. This feature allows exploring the effect of stock adaptation on the accumulation

[4] Updated estimations of regional climate change damages are contained in RICE-2007, however these are not yet publicly available.

of clean capital. The adaptation module is calibrated on DICE2007[5] and AD-DICE, but the resulting damages are slightly more conservative compared to AD-DICE, especially for a large increase in greenhouse gas concentrations.

De Bruin, Dellink and Tol (2009) developed the AD-DICE model, building upon the damages of DICE99, (Nordhaus and Boyer 2000). In AD-DICE adaptation is reactive; it is a flow variable that needs to be adjusted period-by-period as it does not address future damage. This approach has also been implemented in a regionalised version of the model, AD-RICE, based on RICE, and in the updated global version, DICE2007 (De Bruin, Dellink and Agrawala 2009). Hof at al (2009) re-propose the same methodology to model adaptation in the regional model FAIR, used to analyse the effectiveness of international financing of adaptation costs using the revenue from emission trading.

Bosello, Carraro, and De Cian (2010, 2010a) and Agrawala et al (2010) proposed further improvements. They represent adaptation not as a single choice variable, but as a portfolio of alternative policy responses in a nested Constant Elasticity of Substitution (CES) functions. The two studies represent anticipatory and reactive adaptation as imperfect substitutes, capturing the stock and flow nature of these different strategies. In addition, Bosello, Carraro, and De Cian, (2010) allowed for endogenous improvements in the effectiveness of reactive adaptation by investing in dedicated R&D[6]. In Agrawala et al (2010) a dedicated investment can be addressed to develop adaptive capacity, before further allocating resources between reactive and anticipatory measures.

3.2.2. Main results

When analysing the results of different modelling exercises, it is important to distinguish between cost-benefit and cost-effective analyses. The former aims at determining

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[5] http://nordhaus.econ.yale.edu/dice_mss_091107_public.pdf.

[6] Innovation is especially important in sectors such as agriculture and health, where the discovery of new crops and vaccines is crucial to reduce vulnerability to climate change.

the first-best balance between adaptation and mitigation, given the respective costs and benefits. The latter approach aims at identifying the least-cost combination of adaptation and mitigation consistent with a given policy target, independently on the optimality of the policy objective. Despite the variety of approaches used to represent adaptation in IAMs, modelling results agree on a number of findings, summarised below.

The strategic complementarity between adaptation and mitigation

The literature described in Section 3.1 emphasises the strategic complementarity of mitigation and adaptation. As both strategies reduce climate change damages, applied works replicate the first-best outcome according to which two instruments cannot perform worse than one. Welfare is indeed higher when both options are available (de Bruin, Dellink and Tol 2009; de Bruin, Dellink and Agrawala 2009; Bosello, Carraro and De Cian 2010, Bahn et al 2010). But it also increases when adaptation is added to pre-existing CO_2 stabilisation policies thus in cost-effectiveness environments (Agrawala et al 2010; Hof et al 2009, Bosello, Carraro and De Cian 2010a). Table 3 summarises the gains from using a combination of adaptation and mitigation according to the studies quoted.

Table 3. Effects of mitigation and adaptation singularly or jointly implemented on economic/welfare performances

	Adaptation	Mitigation	Adaptation & Mitigation
Studies proposing a cost-benefit approach			
Bosello, Carraro and De Cian (2010) Discounted consumption (2004-2100) (Percentage change compared to no policy)	0.49%	1.18%	1.23%
Bosello, Carraro and De Cian (2010) Discounted Gross World Product (2004-2100) (Percentage change compared to no policy)	1.26%	0.98%	1.27%
Bahn et al (2010) Gross World Product (GWP) (Percentage change compared to optimal case, annual average)	From less than -0.2% before 2055 up to -3% in 2100	From -0.03% before 2085 to -0.2% after 2085	0%
de Bruin, Dellink and Agrawala (2009) (Utility index, 100=optimal case)	99.8	99.7	100
de Bruin, Dellink and Agrawala (2009) Net Present Value per capita GDP (Millions USD)	2.30	2.39	2.40

Bosello (2010) **Discounted consumption in 2100** **(Percentage change compared to mitigation only)**	n.a.-	0%	0.3%
Studies proposing a cost-effectiveness approach			
Hof et al (2009) **Total climate change costs in 2100** **for different stabilization targets of** **temperature above pre-industrial levels** **(share of Gross World Product)**	3%	2°C: 2.8% 2.5°C: 3% 3°C: 3.6%	2°C: 2.2% 2.5°C: 2.3% 3°C: 2.4%
Agrawala et al (2010) **Total climate change costs in 2100** **in the presence of a 550 ppme stabilization target** **(share of Gross World Product)**	AD-WITCH:2.4% AD-DICE: 2.9%	AD-WITCH: 2.6% AD-DICE: 3.1%	AD-WITCH: 2% AD-DICE: 2.5%

Source: Our adaptation from the studies quoted

Interestingly, in cost-benefit studies adaptation appears the most favoured option, usually absorbing the majority of resources and providing the higher contribution to damage reduction (Bosello 2008; de Bruin, Dellink and Agrawala 2009; Bosello, Carraro and De Cian 2010), although this result is sensitive to the chosen discount rate (see the discussion on discounting below).

In Bosello (2008), adaptation contribution to damage reduction increases from 80% in 2040 to 94% in 2100. In de Bruin, Dellink and Agrawala (2009) while short-run adaptation can reduce USD 132 billion of the annual residual damage, mitigation can reduce USD 78 billion. Bosello, Carraro and De Cian (2010) showed that optimal adaptation alone could reduce residual damages to 55% in 2100 whereas optimal mitigation alone would lower damage to 20%.

This outcome is driven by the absence in the models cited of the risk of abrupt changes and low-probability, catastrophic irreversibility (Lenton et al 2008). If included, these would likely increase the role of mitigation. Indeed, by reducing GHG emissions mitigation lowers the probability that a bad state of nature occurs. On the contrary, adaptation can only reduce the severity of a bad state if it does occur (Settle et al 2007). This is in fact at the basis of the currently proposed precautionary mitigation policies within the EU and the international context. In light of this, Bosello, Carraro and De Cian (2010) suggested that mitigation should be defined independently on adaptation as a precautionary device to avoid catastrophic climatic outcomes. Adaptation could then be tailored to address the residual damage not accommodated by mitigation.

The trade off between adaptation and mitigation

The strategic complementarity between mitigation and adaptation also implies an economic trade-off stressed by both cost-effective and cost-benefit approaches. Because resources are scarce, increasing those invested in one implies that less are available for the other (Agrawala et al 2010; Hof et al 2009). But in addition, more adaptation implies less damage to mitigate and *vice versa* (applied models replicate what noted by Fankhauser (2010), namely that more adaptation decreases the marginal benefit of mitigation).

In a cost-benefits framework, Bahn et al (2010), discussed how the trade-off depends of the attributes of the two policy options. Very effective adaptation, by shielding the economy from climate change damages, can delay the transition towards a cleaner economy, leading to very high GHG concentrations at the end of the century. Bosello (2008) showed how adding adaptation reduces optimal abatement rates significantly, by 5% in 2000 and 80% in 2100 compared to the mitigation only case. De Bruin, Dellink and Agrawala (2009) showed that adaptation reduces the benefit-cost ratio of mitigation. De Bruin, Dellink and Tol (2009) and Bosello, Carraro and De Cian (2010) highlighted the asymmetry that characterises the trade-off. Although mitigation crowds out adaptation and *vice versa*, the latter effect is notably stronger than the former. Indeed, mitigation lowers only slightly climate related damages in the short-medium term. Therefore, it does little to decrease the need to adapt, particularly during the first decades.

The presence of aggressive mitigation policies to reach a given CO_2 or temperature stabilisation target is a push to reduce adaptation[7]. Agrawala et al (2010) compared the crowding-out on adaptation of a 550 ppm mitigation policy in the AD-DICE and AD-WITCH model. Adaptation expenditure net present value is reduced from about 0.26% to 0.15% and from about 0.2% to 0.1% of GWP, respectively. In Hof et al (2009) mitigation lowers baseline adaptation costs in 2100 from 1% to 0.4% in the case of a 3°C target, and to approximately 0.1% in the case of a 2°C target. However, adaptation efforts remain far from negligible particularly in developing countries (see below).

The optimal timing of adaptation and mitigation

Another issue discussed by the literature is the optimal timing of adaptation and mitigation particularly when used as a combined strategy. Adaptation expenditure closely follows the dynamics of climate change damage, which in most models is a gently increasing, convex function. Therefore it becomes important after the first decades of the century. Mitigation on the contrary is optimally implemented in early periods. These different dynamics are due to the intertermporal distribution of costs and benefits of either strategy. The time gap between costs and benefits of mitigation is much longer compared to adaptation because greenhouse gases live in the atmosphere for decades to centuries and because the turnover of energy infrastructure is slow. This implies that mitigation costs are to be anticipated compared to adaptation expenditure, which is more rapidly effective. In addition, from the welfare maximiser's point of view it is not worthwhile reducing consumption by investing in adaptation when damage is low. This result has been highlighted both in cost-benefit (Bosello 2008; Bosello, Carraro and De Cian 2010, 2010a; Bahn et al 2010) and cost-effectiveness (Hof et al 2009; Agrawala et al 2010).

[7] According to Tol (2007) this may actually have adverse effects as a lower level of adaptation and may in turn lead to more net climate change damage.

Differences among studies emerge comparing the time effects of mitigation and adaptation. In de Bruin, Dellink, and Tol (2009) and de Bruin, Dellink, and Agrawala (2009), adaptation is the main climate change cost reducer until 2100, whereas mitigation prevails afterwards. In Bosello (2008), Bosello, Carraro and De Cian (2010, 2010a), Bahn et al (2010) the reverse happens.

The longer time inertia of mitigation also explains why it is more sensitive than adaptation to subjective assumptions in policy decision-making, such as the discount rate. A lower discount rate favours policy responses with long-term benefits because agents become more far-sighted. All studies suggest that a lower discount rate increases the relative contribution of mitigation to damage reduction. However, some further qualifications can be made. When adaptation is modelled as a flow variable, mitigation substitutes adaptation (de Bruin, Dellink, and Tol 2009; de Bruin, Dellink, and Agrawala, 2009). When adaptation is a stock and its benefits are also partly delayed compared to costs, both mitigation and adaptation increase, but mitigation is used more intensively in relative terms (Bosello 2008; Bahn et al 2010; Bosello, Carraro and De Cian 2010, 2010a). The choice of discounting also affects the composition of the adaptation portfolio. A lower pure rate of time preference makes the agents more likely to invest in stock adaptation and in building adaptive capacity that offer delayed benefits (Agrawala et al 2010).

Damages and uncertainty

By the same token, higher damages increase both adaptation and mitigation, however the relative importance of the two strategies changes depending on the manner in which adaptation is modelled. When adaptation is a stock, the relative share of damage reduction due to adaptation increases (Bosello 2008; Bosello, Carraro and De Cian 2010, 2010a), whereas in models with flow adaptation (de Bruin, Dellink and Tol 2009; de Bruin, Dellink and Agrawala 2009) higher damages increase the effectiveness of mitigation. Bosello (2008) showed that the tendency to prefer (stock) adaptation when damages are high is strengthened by the presence of growth-enhancing endogenous technical change.

Uncertainty about future damages or climate sensitivity could also tilt the balance towards mitigation. Incorporating uncertainty into IAMs featuring both adaptation and mitigation is at a very early stage and to our knowledge only Felgenhauer and de Bruin (2009) have investigated this. The authors analyse the effect of uncertain climate outcomes, in terms of a probability distribution over five possible values of climate sensitivity (CS), in a two-stage model with learning. In the pre-learning period, uncertainty in future CS leads to a lower emphasis on both mitigation and adaptation as compared to the certain case. The comparison of the certain and uncertain optimal strategy under low and high climate sensitivity shows that climate sensitivity increases mitigation relatively more than adaptation and even more under uncertainty.

The regional dimension of adaptation

Regional analysis is still at very early stage, mostly because of the uncertainty on climate change damages at the regional/local level. However the higher vulnerability of developing countries is a consolidated fact (IPCC AR 4). As a consequence, all studies agree that adaptation expenditures will also be concentrated in developing countries. Depending on the scenarios and models' assumptions, their expected adaptation expenditure can be between two to four times larger than that of developed countries. It also sharply increases in the second half of the century, driven by growing climate change damages. In 2050 it could amount to USD 78 billion, in 2065 it will be above USD 500 billion and peak above USD 2 trillion by the end of the century (Bosello, Carraro and De Cian 2010).

Bosello, Carraro and De Cian (2010) and Agrawala et al (2010) highlighted the variation in the composition of the adaptation bundle across regions. I In non-OECD countries, the weight of reactive and anticipatory measures is rather balanced while in OECD countries proactive measures represent 88% of total adaptation expenditure. Note that, although anticipatory adaptation in non-OECD countries represents only 43% of total adaptation expenditure (cumulative and undiscounted), it amounts to USD 25 trillion, as opposed to USD 12 trillion in OECD countries. In general this literature emphasises the role of anticipatory adaptation. This, however, can be very difficult in practice either because of the difficulty to anticipate damages at the local level, or because of the institutional and technological capacity needed. Agrawala et al (2010) pointed at the role of capacity building in developing countries, which should be the prioritised form of adaptation until mid century, attracting half of the adaptation funds. Once a sufficient level of adaptive capacity is built up, investments in adaptation actions (as opposed to building adaptive capacity) will dominate the strategy mix in non-OECD countries as well.

Larger adaptation needs and the lack of innovative capacity in developing countries create a mismatch between where adaptation can be carried out and where it is mostly needed. This suggests a specific direction for international cooperation on adaptation. Bosello, Carraro and De Cian (2010), estimated that the transfer required to equalise the ratio of total adaptation expenditure over GDP across regions would amount to an annuity of USD 470 billion from OECD to non-OECD countries.

Hof et al (2009) computed the share of adaptation needs in developing countries that could be financed by a 2% levy on Clean Development Mechanism (CDM) and emission trading. Even for very stringent mitigation targets and for high reduction targets for developed countries, this share would be at most 40% in 2040. The amount would increase roughly linearly starting from almost zero in 2015 to USD 22 billion in 2040, yielding a rough estimate of about USD 250 billion[8] in to developing countries.

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[8] Our own calculations based on Figure 7 of the paper.

4. Conclusions

About a decade ago, Tol et al (1998) called attention to the scarce research on adaptation. They identified a list of shortcomings, including the simplified treatment of adaptation, without distinctions between reactive, anticipatory, and autonomous adaptation, the scarce attention paid to the distributional implications and to the costs of adaptation during the transition towards equilibrium GHG concentrations. Ten years later, according to the 2007 IPCC AR4 the situation was not very different. Moreover, that report, supported by EEA (2007) and Stern (2006) continued to stress the lack of quantitative information on adaptation costs and benefits. To some extent, the recent research activity addressed all these issues.

First, efforts have been made to organise the existing amount of information on adaptation costs and benefits, which is sparse, but already relatively large. What emerged is its uneven distribution across sectors and countries. While in some fields like sea-level rise or agriculture many studies are available, but only a few tackle sectors such as health and tourism. There is also a clear regional bias: developed countries, primarily the US or the EU, are rather information abundant, whereas data on developing countries are extremely scarce. Further, it is not always possible to find information both on cost and benefits of adaptation. For example, in sectors such as agriculture research is more focused on the quantification of benefits, whereas in other sectors, such as health and tourism, the focus is on the costs. Global adaptation cost assessments have been also produced scaling up sector specific studies. Although first attempts were useful, these studies suffer from the above-mentioned low state of knowledge which is evident in the wide range of global adaptation costs estimates they produce. These studies, however, highlight that climate change is already imposing non-negligible adaptation costs, mainly to developing countries and that these are expected to increase sharply by the middle of the century.

Although partial and incomplete, this data has been used by a still narrow, but rapidly expanding literature, to calibrate and build adaptation costs and benefit functions into Integrated Assessment Models. The ultimate goal is to empirically address the optimal mix between mitigation and adaptation, its dynamics, and regional distribution. Even though quantitative insights should be handled with care, some reliability can be placed on a number of qualitative findings which are robust across models and scenarios. Mitigation and adaptation are strategic complements and the use of two instruments to contrast climate change is welfare improving compared to using only one. Research also agrees that, because mitigation has a delayed effect, it should be anticipated. In contrast, adaptation can be put in place just slightly before or when the damage effectively materialises. Studies emphasise the functional complementarity of the two strategies that, coupled with limited resources, originates a trade-off: mitigation crowds out adaptation and vice versa. The crowding out of mitigation on adaptation is weaker however, especially in early stages. This is exactly because mitigation, deploying its effects in the future, initially leaves almost unaffected climatic damages and the need to adapt. Even in the presence of mitigation policies, adaptation needs to remain substantial and concentrated in developing countries. This raises the issue of supporting adaptation in poorer regions by developed countries. Modelling exercises stress that the size of adaptation funding currently debated in an international context may still be insufficient to meet adaptation needs of developing countries in the next future.

Parallel to empirical research, a theoretical literature has investigated similar issues, e.g. the nature of the relationship between mitigation and adaptation, the optimal mix between mitigation and adaptation, and the potential role of adaptation in international environmental negotiations. In general, investigation in this field is however just at the beginning and conclusions are far from consolidated.

Notwithstanding the progress made by the recent literature, the following research gaps can be identified. The quantitative assessment of cost and benefit of adaptation needs to be greatly improved especially for some domains and for developing countries. A major challenge here is also the consistent scaling up of bottom-up data to provide reliable information on top-down research. Uncertainty and irreversibility are very marginally tackled by adaptation studies. Finally, the role of adaptation in international climate change negotiations, which is presently growing in importance, remains largely unexplored.

5. References

Adams Richard M., Ronald A. Fleming, Ching-Chang Chang, Bruce A. McCarl and Cynthia Rosenzweig (1995) “A reassessment of the economic-effects of global climate-change on US agriculture”. Climatic Change 30(2), 147–167.

Agrawala Shardul (ed.) (2007) “Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management”, OECD, Paris

Agrawala Shardul, Francesco Bosello, Carlo Carraro, Enrica De Cian, Elisa Lanzi, Kelly De Bruin, Robert Dellink (2010) “PLAN or REACT? Analysis of adaptation costs and benefits Using Integrated Assessment Models”, OECD Environment Working Papers, No. 23, OECD Publishing.

Agrawala Shardul and Samuel Fankhauser (2008) “Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments”, OECD, Paris.

Agrawala Shardul, Arnoldo Matus Kramer, Guillaume Prudent-Richard, Marcus Sainsbury (2010) “Incorporating Climate Change Impacts and Adaptation in Environmental Impact Assessments: Opportunities and Challenges”, OECD Environment Working Papers No. 24, p. 38.

Bahn Olivier, Marc Chesney, Jonathan Gheyssens (2010) “The Effect of Adaptation Measures on the Adoption of Clean Technologies” paper presented at the WCERE Congress, Montréal, 2010. Viewed on December 22, 2010

Barrett Scott (2008) “A Portfolio System of Climate Treaties,” Discussion Paper 08-13. The Harvard Project on International Climate Change Agreements, http://www.webmeets.com/files/papers/WCERE/2010/793/Bahn-WCERE2010.pdf

Barrett Scott (2008) “Dikes v. Windmills: Climate Treaties and Adaptation”, paper presented at the workshop “The Environment, Technology and Uncertainty” of the Ragnar Frisch Centre for Economic Research, Oslo http://www.frisch.uio.no/renergi/Barrett.pdf

Bigano Andrea, Francesco Bosello, Roberto Roson and Richard S.J. Tol (2008) "Economy-wide impacts of climate change: a joint analysis for sea level rise and tourism," *Mitigation and Adaptation Strategies for Global Change*, Springer, Vol. 13: No.8, pp. 765-791.

Bosello Francesco, Carlo Carraro, Enrica De Cian (2010) “Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage”, *Climate Change Economics*: Vol.1: No. 2, pp 1-22.

Bosello Francesco, Carlo Carraro, Enrica De Cian (2010a) “Market- and Policy-driven adaptation” in Bjorn Lomborg (ed) *Smart Solutions to Climate Change*, Chapter 6, Cambridge University Press.

Bosello Francesco (2008) “Adaptation, Mitigation and Green R&D to Combat Global Climate Change. Insights From an Empirical Integrated Assessment Exercise,” CMCC Research Paper No.20.

Bosello Francesco, Roberto Roson and Richard S. J. Tol (2007) “Economywide estimates of the implications of climate change: Sea level rise”. *Environmental and Resource Economics* Vol: 37, pp. 549571.

Bosello Francesco, Roberto Roson and Rrichard S. J. Tol (2006) Economy-wide estimates of the implications of climate change: human health, *Ecological Economics* 58: 579-591.

Bréchet Thierry, Natali Hritonenko and Yuri Yatsenko (2010) "Adaptation and mitigation in long-term climate policies", CORE Discussion Papers No. 65, Université catholique de Louvain, Center for Operations Research and Econometrics (CORE).

Buob Seraina and Gunter Stephan (2008) "Global climate change and the funding of adaptation", Bern University Discussion Papers 08-04.

Buob Seraina and Gunter Stephan (2011) "To mitigate or to adapt: How to confront global climate change", *European Journal of Political Economy*, 27: 1-16.

Callaway John M. Callaway (2004) "Adaptation Benefits and Costs: Are they Important in the Global Policy Picture and How Can We Estimate Them?", *Global Environmental Change* 14: 273–282.

Carraro Carlo and Emanuele Massetti (2010) "Two good news from Copenhagen?" viewed on 15 January 2010 at http://www.voxeu.org/index.php?q=node/4490.

Campbell-Lendrum Diarmid and Rosalie Woodruff (2007) "Climate change: Quantifying the health impact at national and local levels", *Environmental burden of disease series*, No. 14.

Cartalis Costas, Angeliki Synodinou, Margaritis Proedrou, Aris Tsangrassoulis and Matheos Santamouris (2001), "Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region", *Energy Conversion and Management,* Vol. 42: No. 14, pp. 1647-1656.

CIPRA (2004) "Kunstliche Beschneiung im Alpenraum – ein Hintergrundbericht", www.alpmedia.net.

Cline William R. (1992) *Global Warming: The Economic Stakes,* Institute for International Economics, Washington D.C.

Darwin Roy F., Marinos Tsigas, Jan Lewandrowski, and Anton Raneses (1995) "World Agriculture and Climate Change: Economic Adaptations", Agricultural Economic Report No. (AER703) 100 pp.

Darwin Roy F. and Richard S. J. Tol (2001) "Estimates of the economic effects of sea level rise". *Environmental and Resource Economics* Vol 19, pp.113129.

Dasgupta Susmita, Benoit Laplante, Craig Meisner, David Wheeler and Jianping Yan (2007) "The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis", World Bank Policy Research Working Paper 4136.

de Bruin Kelly C., Rob B. Dellink and Richard S.J. Tol (2009) "AD-DICE: An Implementation of Adaptation in the DICE Model," *Climatic Change*: Vol.95, pp 63–81.

de Bruin Kelly C., Rob B. and Shardul Agrawala (2009) "Economic aspects of adaptation to climate change: integrated assessment modelling of adaptation costs and benefits," OECD Environment Working Paper, No. 6.

De Cian Enrica, Elisa Lanzi, Roberto Roson (2007) "The Impact of Temperature Change on Energy Demand: A Dynamic Panel Analysis", FEEM Working Paper No. 46.

Deke Oliver, Kurt Georg Hooss, Christiane Kasten, Gernot Klepper and Katrin Springer (2001) "Economic Impact of Climate Change: Simulations with a Regionalized ClimateEconomy Model". Kiel Working Paper 1065. Kiel Institute of World Economics.

Dore Mohammed H.I. and Ian Burton (2001) "The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions Social Infrastructure", Climate Change Laboratory, Brook University, St. Catherines, Ontario.

Ebi Kristie L. (2008) "Adaptation costs for climate change-related cases of diarrheal disease, malnutrition, and malaria in 2030". *Globalization and Health*: 4.

Ebi Kristie L., Thomas J. Teisberg, Laurence S. Kalkstein, Lawrence Robinson and Rodney F. Weiher (2004) "Heat Watch/Warning Systems Save Lives: Estimated Costs and Benefits for Philadelphia 1995-1998", *Bulletin of the American Meteorological Society*, 85(8): pp. 1067-1073.

European Environment Agency (EEA) (2007) "Climate Change: The Cost of Inaction and the Cost of Adaptation", EEA Technical Report, No. 13/2007.

European Environment Agency (EEA) (2007) "Climate Change: The Cost of Inaction and the Cost of Adaptation", EEA Technical Report, No. 13/2007.

Fankhauser Samuel (1994) "Protection vs. retreat—the economic costs of sea level rise," *Environmental Planning A*: Vol.27: No.2, pp 299–319.

Fankhauser Samuel (2010) "The costs of adaptation", *Wiley Interdisciplinary Reviews: Climate Change*, Vol. 1: No. 1, pp 23–30.

Hope Chris, John Anderson, and Paul Wenman (1993) "Policy Analysis of the Greenhouse effect: an Application of the PAGE model," *Energy Policy*: Vol. 21: No. 3, pp 327-338.

Hope Chris (2006) "The marginal impact of CO2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern", *The Integrated Assessment Journal*: Vol. 6: No. 1, pp 19–56.

Hope Chris (2009) "The costs and benefits of adaptation", in *Assessing the costs of adaptation to climate change: A review of the UNFCCC and other recent estimates*: pp. 100-110. IIED London.

Hof Andries F., Kelly C. de Bruin, Rob B. Dellink, Michel G.J. den Elzen, Detlef P. van Vuuren (2009) "The effect of different mitigation strategies on international financing of adaptation", *Environmental Science and Policy*, Vol. 12: pp 832–843.

Hurd Brian, Neil Leafy, Russell Jones, and Joel Smith (1999) "Relative regional vulnerability of water resources to climate change". *Journal of the American Water Resources Association*, 35(6): 1399-1409.

Ingham Alan, Jie Ma, Alistair M. Ulph (2005) "Can Adaptation and Mitigation be Complements?", Working Paper No. 79, Tyndall Centre for Climate Change Research.

IPCC (Intergovernmental Panel for Climate Change) (2007), "Climate Change 2007: The Physical Science Basis", Working Group I Contribution to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, "Chapter 10: Global Climate Projections", Cambridge University Press, Cambridge.

Kane Sally and Jason F. Shogren (2000) "Linking Adaptation and Mitigation in Climate Change Policy", *Climatic Change*: Vol. 45: No 1, pp 75-102.

Kirshen Paul (2007) "Adaptation options and cost in water supply: A report to the UNFCCC Secretariat Financial and Technical Support Division" (http://unfccc.int/cooperation_and_support/financial_mechanism/financial_mechanism_gef/items/4054.php)

Klein, Robert, S. Huq, F. Denton, Tom Downing, Richard Richels, J.B. Robinson, Ferenc Toth (2007) "Inter-relationships between adaptation and mitigation", *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Martin L. Parry, Osvaldo.F. Canziani, Jean Palutikof, Paul van der Linden and Clair Hanson, Eds., Cambridge University Press, Cambridge, UK, 745-777.

Kurukulasuriya Pradeep and Robert O. Mendelsohn (2007) "Crop Selection: Adapting to Climage Change in Africa", World Bank Policy Research Working Paper No. 4307.

Larsen Peter H., Scott Goldsmithb, Orson Smithc, Meghan L. Wilsonb, Ken Strzepekd, Paul Chinowskyd, and Ben Saylorb (2008) "Estimating future costs for Alaska public infrastructure at risk from climate change", *Global Environmental Change,* Vol. 18, No. 3, pp. 442-457.

Lecoq Frank and Zmarak Shalizi (2007) "Balancing Expenditures on Mitigation and Adaptation to Climate Change: An Explorations of Issues Relevant for Developing Countries", World Bank Policy Research Working Paper 4299.

Lenton Timothy M., Hermann Held, Elmar Kriegler, Jim W. Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans Joachim Schellnhuber (2008) "Tipping elements in the Earth's climate system", PNAS: Vol: 105: No. 6. www.pnas.org_cgi_doi_10.1073_pnas.0705414105

Mansur, Erin T., Mendelsohn, Robert O. and Morrison, Wendy (2005) "A Discrete-Continuous Choice Model of Climate Change Impacts on Energy", Yale SOM Working Paper No. ES-43.

Markandya Anil and Aline Chiabai (2009) "Valuing Climate Change Impacts on Human Health: Empirical Evidence from the Literature". *International Journal of Environmental Research and Public Health*. 6(2): pp. 759-786.

Mathis Priska, Dominik Siegrist, and Rico Kessler (2003) "Neue Skigebiete in der Schweiz? Planungsstand und Finanzierung von touristischen Neuerschliessungen unter besonderer Berucksichtigung der Kantoner", Berne.

McCarl Bruce A. (2007) "Adaptation options for agriculture, forestry and fisheries: A report to the UNFCCC Secretariat Financial and Technical Support Division" (http://unfccc.int/cooperation_and_support/financial_mechanism/financial_mechanism_gef/items/4054.php).

Mendelsohn Robert O., Wendy Morrison, Michael E. Schlesinger and Natalia G. Andronova (2000) “Countryspecific market impacts of climate change”. *Climatic Change* Vol 45, pp. 553569.

Mendelsohn Robert O. (2003) “The Impact of Climate Change on Energy Expenditures in California”, in C. Thomas and R. Howard (eds.), *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy*, Appendix XI, Sacramento, CA, p. 35.

Morrison Wendy N. and Robert O. Mendelsohn (1999) “The Impact of Global Warming on US Energy Expenditures”, in R. Mendelsohn and J. Neumann (eds.), *The Impact of Climate Change on the United States Economy*, Cambridge University Press, Cambridge, pp. 209-236.

Muller Mike (2007) “Adapting to Climate Change: Water Management for Urban Resilience”, *Environment and Urbanization,* Vol. 19:No.1, pp. 99-112.

Nicholls Robert J. (2007) “Adaptation options for coastal areas and infrastructure, an analysis for 2030. A report to the UNFCCC Secretariat Financial and Technical Support Division” (http://unfccc.int/cooperation_and_support/financial_mechanism/financial_mechanism_gef/items/4054.php).

Nicholls Robert J., Richard S.J. Tol and Athanasios T. Vafeidis (2005) “Global Estimates of the Impact of a Collapse of the West Antarctic Ice Sheet: An Application of FUND”, Working Paper FNU78.

Nordhaus William D. (1994) “Managing the Global Commons: The Economics of the Greenhouse Effect”. MIT Press, Cambridge, MA.

Nordhaus William D. and Zili Yang (1996) “A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies”, *American Economic Review*: Vol. 86; No. 4, pp 741-765.

Nordhaus William D., and Boyer Joseph (2000) *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA.

Oxfam (2007) “Adapting to Climate Change. What is Needed in Poor Countries and Who Should Pay?” Oxfam Briefing Paper 104.

Parry Martin (2009) “Closing the loop between mitigation, impacts and adaptation,” Climatic Change: Vol. 96: pp 23–27.

Parry Martin, Osvaldo Canziani, Jean Palutikof, Paul van der Linden, Clair Hanson (eds.) (2007) “Climate Change 2007. Impacts, Adaptation and Vulnerability”. Contribution of Working Group II to the Fourth Assessment Report on Climate Change. Cambridge University Press.

Parry Martin, Nigel Arnell, Pam Berry, David Dodman, Samuel Fankhauser, Chris Hope, Sari Kovats, Robert Nicholls, David Sattherwaite, Richard Tiffin, Tim Wheeler (2009) “Assessing the costs of adaptation to climate change: A critique of the UNFCCC estimates”, IIED.

Petrick Sebastian, Katrin Rehdanz and Richard S.J. Tol (2010) "The Impact of Temperature Changes on Residential Energy Consumption." Kiel Working Paper No. 1618.

Plambeck Erica L., Hope Chris, Anderson John (1997) “The PAGE95 model: integrating the science and economics of climate change”, *Energy Economics:* Vol.19:No.1, pp. 77–101.

Reilly John, Neil Hohmann and Sally Kane (1994) “Climate change and agricultural trade: Who benefits, who loses?”, *Global Environmental Change*, Vol. 4:No. 1, pp. 24-36.

Rosenthal Donald H., Howard K. Gruenspecht and Emily A. Moran (1995) “effects of global warming on energy use for space heating and cooling in the United States”, *Energy Journal*, Vol. 16:No.2, pp. 77-96.

Rosenzweig Cynthia and Martin L. Parry (1994) “Potential Impact of Climate Change on World Food Supply”, *Nature*, Vol. 367, pp. 133-138.

Settle Chad, Jason F. Shogren, Sally Kane (2007) “Assessing mitigation-adaptation scenarios for reducing catastrophic climate risk”, *Climatic Change*: Vol: 83: pp 443–456. DOI 10.1007/s10584-007-9260-5.

Satterthwaite David (2007) “Adaptation Options for Infrastructure in Developing Countries”, A Report to the UNFCCC Financial and Technical Support Division (Bonn, Germany: UNFCCC, 2007).

Seo S. Niggol and Robert O. Mendelsohn (2008) “A Ricardian analysis of the impact of climate change on South American farms”. *Chilean Journal of Agricultural Resuorces*, 68(1), 69–79.

Simpson, M.C., Gössling, S., Scott, D., Hall, C.M. and Gladin, E. (2008) “Climate Change Adaptation and Mitigation in the Tourism Sector: Frameworks, Tools and Practices”. UNEP, University of Oxford, UNWTO, WMO: Paris, France.

Solomon Susan, Dahe Qin, Martin Manning, Richard B. Alley, Terje Berntsen, Nathaniel L. Bindoff, Zhenlin Chen, Amnat Chidthaisong, Jonathan M. Gregory, GabrielC. Hegerl, Martin Heimann, Bruce Hewitson, Brain J. Hoskins, Fortunate Joos, Jean Jouzel, Vladimir Kattsov, Ulrike Lohmann, Taroh Matsuno, Mario Molina, Neville Nicholls, Jonathan Overpeck, Graciela Raga, Venkatachalam Ramaswamy, Jiawen Ren, Matilde Rusticucci, Richard Somerville, Thomas F. Stocker, Ronald J. Stouffer, Penny Whetton, Richard A. Wood and David Wratt (2007) “Technical Summary”. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stern Nicholas, (2006) “The Economics of Climate Change”. The Stern Review. Cambridge University Press, Cambridge UK.

Tan Guoxin and Ryosuke Shibasaki (2003) “Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration”, *Ecological Modeling*, Vol. 168:No.3, pp. 357-370.

Tol Richard S.J. (2002) “Estimates of the damage costs of climate change. Part 1: Benchmark Estimates”. *Environmental and Resource Economics* 21 (1): 4773.

Tol Richard S.J. (2002) “Estimates of the damage costs of climate change. Part II. Dynamic Estimates”. *Environmental and Resource Economics* 21 (2): 135160.

Tol Richard S.J. (2007) “The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of FUND”, *Mitigation and Adaptation Strategies for Global Change*: Vol.12: pp 741–753. DOI 10.1007/s11027-007-9097-2

Tol Richard S.J. and Samuel Fankhauser (1998) “On the representation of impact in integrated assessment models of climate change”, *Environmental Modeling and Assessment*: Vol: 3, pp 63-74.

Tulkens Henry and Vincent van Steenberghe (2009) “Mitigation, adaptation, suffering” : In search of the right mix in the face of climate change," CORE Discussion Papers No. 054, Université catholique de Louvain, Center for Operations Research and Econometrics (CORE).

UNDP (2007). *Human Development Report* 2007/08. Palgrave McMillan, New York.

UNFCCC (United Nations Framework Convention on Climate Change) (2007), “Investment and Financial Flows to Address Climate Change”. Background paper on analysis of existing and planned investment and financial flows relevant to the development of effective and appropriate international response to climate change.

van Rensburg Janse J.J. and James Nelson Blignaut (2002) “The Economic Impact of an Increasing Health Risk due to Global Warming”. In Proceedings of the Forum for Economics and Environment Conference, Cape Town, South Africa.

Vergara Walter, Alejandro M. Deeb, Adriana M. Valencia, Raymond S. Bradley, Bernard Francou, Alonso Zarzar, Alfred Grünwaldt and Seraphine M. Haeussling (2007) “Economic Impacts of Rapid Glacier Retreat in the Andes”, EOS, TRANSACTIONS AMERICAN GEOPHYSICAL UNION, VOL. 88, NO. 25, P. 261.

Yohe Gary W. and Kenneth Strzepeck (2004) “Climate change and water resources assessment in South Asia: Addressing uncertainties”, in Mizra MMQ (ed) Climate change and water resources in South Asia. Taylor and Francis, The Netherlands.

Yohe Gary W. and Kenneth Strzepeck (2007) “Adaptation and mitigation as complementary tools for reducing the risk of climate impacts”, *Mitigation and Adaptation Strategies for Global Change*: Vol. 12: pp 727-739, DOI 10.1007/s11027-007-9096-3.

Yohe Gary W. and Michael E. Schlesinger (1998) “Sea-Level Change: The Expected Economic Cost of Protection or Abandonment in the United States”, *Climatic Change*, Vol. 38, pp. 447-472.

Yohe Gary W., Hadi Dowlatabadi, Jason West, Richard Warrick, Richard Klein, Richard S. J. Tol, Samuel Fankhauser, Baruch Fischhoff (1996) “The Economic Costs of Sea Level Rise”, *Climatic Change*, Vol. 32, pp. 387-410.

Wang Jinxia, Robert O. Mendelsohn, Ariel Dinarc, Jikun Huang, Scott Rozelle and Lijuan Zhang (2009) “The Impact of Climate Change on China’s Agriculture”, *Agricultural Economics*, 40: 323-337.

Watkiss Paul, Lisa Horrocks, Stephen Pye, Alison Searl and Alistair Hunt (2007). "Projection of economic impacts of climate change in sectors of Europe based on Bottom up Analysis (PESETA)". Human Health. Summary for Policy Makers. Report to JRC / IPTS.

Watkiss Paul (2009) "Potential Costs and Benefits of Adaptation Options: a Review of Existing Literature", Technical Paper, United Framework Convention on Climate Change, FCCC/TP/2009/2/Rev. 1.

Watkiss Paul (2011) "Aggregate economic measures of climate change damages: explaining the differences and implications", *Wiley Interdisciplinary Reviews: Climate Change*, Volume 2, Issue 3, pp. 356–372.

WHO (2005) "Preventing Disease through Healthy Environments: Towards an Estimate of the Environmental Burden of Disease". World Health Organisation, Geneva.

WHO (2006) "World Health Organisation Malaria report 2008", WHO/HTM/GMP/2008.1, World Health Organisation, Geneva.

World Bank (2007) "PPI in Developing Countries in 2006". Results from the PPI Project Database, Washington DC, November.

World Bank (2010) "Economics of Adaptation to Climate Change: Synthesis Report", The International Bank for Reconstruction and Development/The World Bank.

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