Executive Summary:

The ClimateCost project has advanced knowledge in three areas:

- The costs of inaction (the economic effects of climate change).
- Long-term targets and mitigation policies.
- The costs and benefits of adaptation.

The project has identified and developed consistent scenarios for climate change and socio-economic development, including mitigation scenarios.

Using these scenarios, the project has quantified in physical terms, and valued as economic costs, the effects of future climate change (the 'costs of inaction') under different scenarios for the EU and other major negotiator countries (China, India).

This work has included a detailed sectoral analysis, using bottom-up models for market and non-market sectors (coasts, health, ecosystems, energy, agriculture and infrastructure). The results show large economic costs from climate change in Europe. They also show strong distributional patterns in the levels of impacts between Member States. The use of different scenarios demonstrates that these economic costs are significantly lower under mitigation scenarios, but only after the year 2040, highlighting the need for adaptation and mitigation.

The analysis has also quantified and valued the costs and benefits of adaptation in Europe. The results show that adaptation is generally very effective at reducing impacts at low cost. However, the study has also considered the uncertainty in the climate models and how these affect economic costs and adaptation. The results highlight the need for robust and resilient adaptation strategies, which work within a framework of decision making under uncertainty.

The study has updated the literature on the bio-physical tipping extremes. The project has then undertaken a major case study to look at the economic costs of these types of major events, looking at extreme sea level rise. The analysis has assessed the impacts and economic costs of global high-end scenario by the end of the century, showing the large rise in people affected and economic costs. The study has also extended the consideration of the major effects to consider socially contingent extremes, i.e. large scale issues associated with conflict, migration, etc. The study has considered possible drivers, and overlaid state fragility and potential adverse climate change to highlight over 100 countries at risk of significant negative knock-on socio-political effects.

The project has reviewed endogenous technological change, built up a database of satellite R&D accounts, and incorporated this in a number of mitigation models. It has also reviewed and developed technological detail of new technologies and new components (agricultural sector, new abatement technologies, updated marginal abatement costs, non CO2 sinks) for a number of mitigation models used in EC policy analysis. These updated models were used in the recent EC 2050 Roadmap analysis.

The study has quantified the improvements in air quality from mitigation (co-benefits) for Europe, China and India, and assessed these in terms of physical and economic benefits. The results show very large co-benefits arise under mitigation scenarios, which lead to local and immediate benefits.

Finally, the study has also updated and developed a number of Computable General Equilibrium Models (CGEs) and Integrated Assessment Models (IAMs), including the development of the new PAGE09 model. These models have been used in a series of policy runs to look at various metrics in relation to the economic and wider economic costs of climate change, the social cost of carbon and the costs and benefits of mitigation.

The project findings have been written up and disseminated.

Project Context and Objectives:

There is increasing interest in the economics of climate change to:

- Provide important information on the costs of inaction (the economic effects of climate change);
- Assess the costs and benefits of adaptation;
- Inform the policy debate on long-term targets and mitigation policies.

Although relatively detailed and comprehensive research has been carried out in these areas, there are many gaps in the assessment of the full costs of climate change.The aim of the ClimateCost project has been to advance the knowledge across all of the three areas above, using detailed disaggregated, bottom-up approaches and top-down aggregated analysis.

The project has undertaken a number of work packages, with the following key research scientific and technical objectives:

1. To provide a comprehensive and consistent set of climate and socio-economic scenarios, with and without climate policy (i.e. including mitigation and going beyond the SRES), comparing different model outputs and including uncertainties. These provide the basis for subsequent analysis in later tasks.

2. To advance the knowledge on the economic costs of climate change (the costs of inaction) to provide a fuller coverage across different sectors using a dis-aggregated (bottom-up) approach that estimates both physical effects and monetary values, using the consistent and harmonised set of climate and socio-economic scenarios (from 1. above). This has included detailed assessment in Europe - as physical impacts and in monetary terms - but also analysis at the world level for many impacts. It has also included consideration of the costs and benefits of adaptation in Europe.

3. To expand the analysis of the costs of climate change to consider the potential for catastrophic events (major events and climate discontinuities) and major socially contingent effects. This will use scenario analysis, existing models, and undertake case study modelling in terms of physical effects and economic damages for a number of key case studies.

4. To update the mitigation (abatement) costs of GHG emission reductions, consistent with medium and long-term reduction targets / stabilisation goals for the mitigation scenarios (linked to the scenarios above). These will build on previous work undertaken, but will also include (induced) technological change and include non CO2 greenhouse gases (CH4 and N2O) and sinks and recent abatement technologies.

5. To quantify the ancillary air quality benefits of mitigation policies, using a spatially detailed dis-aggregated approach, with spatial analysis, to quantify in physical terms, and value as monetary benefits in Europe and major negotiator countries (China and India).

6. To use the information from tasks above to update a number of complementary models to assess the full costs of climate change. This will include the indirect economic effects associated with the costs of inaction using general equilibrium models to investigate whether the total effects of climate change are greater than implied by direct costs alone. It will also update and expand a number of integrated assessment models, to allow a much wider range of scenarios and policy analysis over much longer time-scales, to estimate marginal social costs, and to allow more in-depth consideration of uncertainty.

7. To bring this information together to provide information that is useful for policy makers, and to expand the analysis using integrated analysis. This will involve:

- To directly engage policy makers in the project to find out priorities and to ensure the research outputs are fit for purpose.
- To use the models to assess the full costs of climate change for the scenarios.
- To undertake policy analysis and summarise the project findings and to disseminate the project findings.

Project Results:

Background

There is increasing interest in the economics of climate change to:

- Provide important information on the costs of inaction (the economic effects of climate change);
- Assess the costs and benefits of adaptation;
- Inform the policy debate on long-term targets and mitigation policies.

Although relatively detailed and comprehensive research has been carried out in these areas, there are many gaps in the assessment of the full costs of climate change.

Against this background, the aim of the FP7 funded ClimateCost project has been to advance the knowledge in all of the three areas above, using detailed disaggregated, bottom-up approaches and top-down aggregated analysis.

Study Objectives

The project has undertaken a number of work packages, with the following key research scientific and technical objectives. These were:

1. To provide a comprehensive and consistent set of climate and socio-economic scenarios, with and without climate policy (i.e. including mitigation and going beyond the SRES), comparing different model outputs and including uncertainties. These provide the basis for subsequent analysis in later tasks.

2. To advance the knowledge on the economic costs of climate change (the costs of inaction) to provide a fuller coverage across different sectors using a dis-aggregated (bottom-up) approach that estimates both physical effects and monetary values, using the consistent and harmonised set of climate and socio-economic scenarios (from 1. above). This has included detailed assessment in Europe - as physical impacts and in monetary terms - but also analysis at the world level for many impacts. It has also included consideration of the costs and benefits of adaptation in Europe.

3. To expand the analysis of the costs of climate change to consider the potential for catastrophic events (major events and climate discontinuities) and major socially contingent effects. This will use scenario analysis, existing models, and undertake case study modelling in terms of physical effects and economic damages for a number of key case studies.

4. To update the mitigation (abatement) costs of GHG emission reductions, consistent with medium and long-term reduction targets / stabilisation goals for the mitigation scenarios (linked to the scenarios above). These will build on previous work undertaken, but will also

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Scientific and Technical Results

1. Climate and Socio-Economic Scenarios

Analysis of the future impacts and economic costs of climate change requires climate models. These models require inputs of future greenhouse gas emissions based on modelled global socio-economic scenarios, in order to make projections of future changes in temperature and precipitation and other meteorological variables.

The ClimateCost project has considered three emissions scenarios, a medium-high non-mitigation baseline scenario (A1B), a mitigation scenario (E1), which stabilises global temperature change at about 2°C above pre-industrial levels, and a high emission scenario (RCP8.5). A summary of the projections is presented below.

Under a medium-high emission baseline (A1B), with no mitigation, the climate models considered in ClimateCost show that global average temperatures could rise by 1.6 to 2.3?C by 2041-2070 and 2.4 to 3.4?C by 2071-2100, relative to the modelled baseline period used in the project of 1961-1990. However, the models project much larger temperature increases for Europe in summer, and strong regional differences: for example, the Iberian Peninsula has a mean projected increase of up to or exceeding 5?C by 2071-2100.

The differences in the precipitation projections between the models are much greater and the distributional patterns across Europe are more pronounced than for temperature. Nonetheless, there are some robust patterns of change. There are wetter winters projected for Western and Northern Europe. By contrast, there are drier conditions projected all year for Southern Europe, where summer precipitation could be reduced by 50% by the end of the century. In other parts of Europe the changes are more uncertain, and the models even project differences in the direction of change (i.e. whether increases or decreases will occur).

Under an E1 stabilisation scenario, broadly equivalent to the EU 2 degrees global target, all changes are significantly reduced. Average temperatures are projected to increase by about 1.5?C by 2071-2100 globally compared to the 1961-1990 baseline. Furthermore, the stronger wetter signal in Northern Europe, and the drier summer signal in Southern Europe, are both considerably reduced. There are still major variations across different models. However, even under this mitigation scenario, the projections do not significantly diverge from the A1B scenario until after 2040. Therefore, summer temperatures in Europe are projected to increase by more than 2?C and possibly in excess of 3?C by 2071-2100, relative to the 1961-1990 baseline, even under this mitigation scenario, highlighting the need for both adaptation and mitigation.

The study has also considered the RCP8.5 "high" scenario. This reaches a global warming of about 3.5?C by 2071-2100 relative to the 1961-1990 baseline. The uncertainty cannot be estimated for this scenario, as only one simulation is available to the project.

It is highlighted that the E1 (mitigation) projections only diverge significantly from A1B after 2040, i.e. the differences only emerge in the latter part of the century. Mean global temperature is projected to increase by about 1?C by 2011-2040 relative to 1961-1990, irrespective of the emission pathway, highlighting the need for both adaptation and mitigation.

As has been found by other studies, projections of future climate change, particularly for precipitation, are uncertain. It is essential to recognise and to try to quantify this uncertainty, not to ignore it. In ClimateCost, this has been addressed with the use of multi-model analysis. This also leads to the need to plan robust strategies to prepare for uncertain futures, and not to use uncertainty as a reason for inaction.

The ClimateCost project also produced a new regional climate model run using output for RCP 8.5 from the community EC-Earth global model, downscaling this to Europe for ClimateCost at 25 km resolution with the HIRHAM5 RCM (Deliverable 1.3). The geographic pattern of climate change is quite similar to that observed for the less extreme A1B scenario, but the amplitude is larger, with an average warming exceeding all the 11 individual A1B simulations.

2. Impacts, Economic Costs and Adaptation

The project assessed the potential impacts and economic costs of climate change using bottom-up sectoral models, and the costs and benefits of adaptation in Europe. The results are summarised below.

Coastal Zones and Sea Level Rise

Coastal zones contain high population densities, significant economic activities and ecosystem services. These areas are already subject to coastal flooding, and climate change has the potential to pose increasing risks to these coastal zones in the future, though these changes need to be seen in the context of other socio-economic drivers. The ClimateCost study has assessed the potential impacts and economic costs of sea level rise, and the costs and benefits of adaptation, for Europe. The analysis has used the DIVA model, and considered both future climate and socio-economic change. As floods are probabilistic events, the results are presented as expected annual damage costs (undiscounted).

For Europe, the mid-range projections for a medium to high emissions scenario (A1B(I)) suggest 37cm of rise by the 2080s. Sea-levels will continue to rise into the 22nd century and beyond, and larger rises in sea level are possible, with rises of more than 1m being feasible by 2100. Under an E1 mitigation scenario, broadly consistent the EC's 2?C target, the rate of rise is reduced, with 26cm projected by the 2080s. Due to the thermal inertia of the ocean, the two scenarios do not become distinct until the 2050s.

Under a medium to high emission trajectory (A1B (I)), with no mitigation or adaptation, the study has estimated that 55,000 people could be flooded per year (mid estimate) by the 2050s (2041-2070) and potentially over 250,000 people per year by the 2080s (2071-2100). A further 438,000 people may need to move away from the coastal zone because of annual flooding.

This flooding - along with other impacts of sea level rise such as erosion - leads to large economic costs. The impacts in Europe are estimated at up to ?11 billion/year for the 2050s (mid estimate), rising to ?25 billion/year by the 2080s from the combined effects of climate and socio-economic change (current prices, with no discounting). These costs include costs based on GDP, salinisation, costs of moving and land loss. Additional unquantified costs will occur due to ecosystem losses, and possible knock-on effects of damage on supply chains.

These impacts have a strong distributional pattern. Countries in north-west Europe have the greatest potential damages and costs, although many of these countries are the most prepared for climate change in the European Union.

In addition, sea level rise will affect coastal ecosystems. Wetlands act as natural flood barriers, feeding grounds, food and recreational values. The analysis has estimated that by the 2080s, over 35% of EU wetlands could be lost unless protective measures are undertaken. Where hard defences are also present, coastal squeeze could result.

It is stressed that there is a wide range of uncertainty around these mid estimates, reflecting the underlying uncertainty in the sea level response to a given emissions scenario and temperature outcome. As an example, while the mid estimate of the number of people flooded

in the 2080s is 250,000, and estimated damage costs of ?25 billion/year, the response range varies between 121,000 and 425,000 people flooded, and damage costs of ?19 billion/year to ?37 billion/year. This uncertainty needs to be considered tin formulating adaptation strategies.

Under higher emission scenarios, there is a growing risk of extreme sea level rise, with a scenario in excess of 1 metre by 2100. The study has estimated the potential damage costs from such a scenario, and estimated this would increase the damage costs for the EU to ?156 billion/year (undiscounted) by the 2080s - six times higher than for the A1B scenario.

Under a stabilisation scenario broadly equivalent to the EU 2?C target, these impacts are significantly reduced, with the number of people flooded reduced by two thirds, and the economic costs are significantly reduced. Under this scenario, the estimated annual number of people flooded falls to 180,000 people per year and the damage costs fall to ?17 billion/year (mid estimates) by the 2080s for Europe. This mitigation scenario reduces the chance of major sea level rise but this has not been quantified, an additional factor in the relative costs and benefits between the A1B and E1 (stabilisation) scenario.

The study has also assessed the costs and benefits of adaptation. Hard (dike building) and soft (beach nourishment) adaptation greatly reduces damage cost, with a cost of ?1.6 billion per year in the 2050s (EU, current prices, undiscounted), with a benefit to cost ratio of 6:1 (A1B(I) Mid scenario). The benefit to cost ratios increase throughout the 21st century. However, hard defences need ongoing maintenance to operate efficiently and to keep risk at an acceptable level. As the stock of dikes grows throughout the 21st century, so annual maintenance costs approach or exceed annual incremental costs if we adapt via dikes.

It is highlighted that the costs of adaptation vary significantly with the level of future climate change, the level of acceptable risk protection, and the framework of analysis (risks protection versus economic efficiency). Other adaptation options not used in the model may be more costly, but effective in reducing flood risk. Sea-level rise should be anticipated and planned for in adaptation policies.

The climate and socio-economic uncertainty makes a large difference to the actual adaptation response at a country level. The need to recognize and work with uncertainty - as part of integrated and sustainable policies - requires an iterative and flexible approach. Climate change is only one aspect of coastal management policy in the EU, and adaptation to climate change needs to be positioned within a broader integrated coastal zone management policy framework

Mitigating for climate change by reducing the rate of sea-level rise is likely to decrease wetland loss, those at risk from flooding, damage costs and subsequent adaptation costs. Mitigation as opposed to hard adaptation benefits the natural environment as habitats and ecosystems are allowed a greater time to respond to a changing environment and climate.

These results reinforce the message that the most appropriate response to sea-level rise for coastal areas is a combination of adaptation to deal with the inevitable rise, and mitigation to limit the long-term rise to a manageable level. More detailed, local-scale assessments are required to assess and reduce risk to vulnerable areas, including adaptation plans.

Similar work has been undertaken for China and India. This shows much higher numbers, particularly for China, where the number of people at risk from flooding increases

exponentially to over 16 million people per year in the 2080s, with estimated damage costs of €140 billion/year.

Agriculture

The agricultural analysis has considered the effects of climate change on productivity at the global scale for the A1B and E1 scenario. The assessment considered a large number of climate model outputs, which showed significant variations between model outputs.

Much lower impacts were revealed under the E1 scenario. The analysis also extended to look at the benefits of adaptation, considering a range of adaptation scenarios. This included scenarios that optimised for water requirements and fertilisers and both. The effects of these policies in reducing impacts is clear by considering the effect of adaptation.

The analysis of adaptation on water demand (irrigation) increases was assessed and reported. Finally, the results were entered in a global trade model to look at the results in terms of regional land productivity changes, GDP, imports, prices, and manufacture and services exports under climate change.

River Floods

Floods already cause major economic costs in Europe. Climate change could increase the magnitude and frequency of these events, leading to higher costs. However, these events need to be seen in the context of other socio-economic drivers.

The ClimateCost study has assessed the potential impacts of climate change on river flood damage in Europe, and the costs and benefits of adaptation. The analysis used the LISFLOOD model, and considered future climate and socio-economic change. As floods are probabilistic events, the results are presented as expected annual damage (EAD) costs (undiscounted). It should be noted that the damages reported here only include direct physical losses and could, therefore, be conservative.

The study first assessed the number of people potentially affected by river flooding in the EU27. The expected annual people (EAP) flooded in the baseline climate period (1961-1990) was estimated at around 167,000/year.

The economic damages from flooding of the residential and other sectors were then assessed. The EAD in the baseline climate period (with current socio-economic conditions) is estimated at around €5.5 billion in the EU27. The analysis then looked at the increase in the number of people and the EAD from future climate change, considering three future time periods (averaged in thirty year periods), for a medium-high emission and mitigation scenario.

Under a medium-high emission baseline (A1B), with no mitigation or adaptation, the projected mean expected number of people affected by flooding annually is 300,000 by the

2050s (the years 2041-2070), rising to 360,000 by the 2080s (2071-2100) in the EU27. This includes the combined effects of socio-economic change (future population) and climate change.

The EAD for the A1B scenario is estimated at €20 billion by the 2020s (2011-2040), €46 billion by the 2050s (2041-2070) and €98 billion by the 2080s (2071-2100) (mean ensemble results, current values, undiscounted) in the EU27. However, a large part of this is due to socio-economic change (population and economic growth). The marginal effect of climate change (alone) is estimated at €9 billion/year by the 2020s, €19 billion/year by the 2050s and €50 billion/year by the 2080s. Analysis at the country level shows high climate-related costs in the UK, Ireland, Italy, the Netherlands and Belgium.

There is a very wide range around these central (mean) estimates, representing the range of results from different climate models. The study considered 12 alternative climate outputs (GCM-RCM combinations). These reveal that the potential costs vary by a factor of two (higher or lower). These differences are even more significant at the country level, with some models even reporting differences in the effects of climate change (i.e. some models project relative reductions in future flood risk from climate change for some areas). This highlights the need to consider this variability (uncertainty) in formulating adaptation strategies.

Under an E1 stabilisation scenario, broadly equivalent to the EU 2 degrees target, the EAD is estimated to all to €15 billion by the 2020s, €42 billion by the 2050s and €68 billion by the 2080s in the EU27 (current values, undiscounted). The marginal impact of climate change alone (i.e. with socio-economic change not included) is estimated at €5 billion/year by the 2020s, €20 billion/year by the 2050s and €30 billion/year by the 2080s - significantly lower than for A1B estimates above, especially towards the end of this century. However, this analysis is built around a limited number of E1 (climate data sets, mostly focused on one climate model. Therefore, the lower damages under the stabilisation scenario are more likely to be related to the climate model choice rather than to the effect of mitigation.

The study also assessed the costs and benefits of adaptation. The analysis first assessed the benefits of maintaining 1 in 100-year levels of flood protection across Europe in future time periods, set against the increases under the A1B scenario. The benefits of these minimum protection levels (i.e. the reduction in damage costs) is estimated at €8 billion/year by the 2020s, €19 billion/year by the 2050s and €50 billion/year by the 2080s for the results (mean ensemble, EU27, climate and socio-economic change current values, undiscounted). It should be noted that the benefits vary with the climate variability, so there is a significant range around these values. There are also significant residual damages in later years under these minimum protection levels, and this suggests higher protection levels would be justified.

The analysis then assessed the costs of achieving these protection levels. This has transferred information from detailed protection studies to derive indicative costs of adaptation at the European scale. The costs to maintain minimum protection levels are estimated at €1.7 billion/year by the 2020s, €3.4 billion/year by the 2050s and €7.9 billion/year by the 2080s for the EU (mean ensemble, A1B, undiscounted). It should be noted that the costs of adaptation vary significantly with the level of future climate change, the level of acceptable risk protection and the framework of analysis (risks protection versus economic efficiency).

The socio-economic uncertainty and climate-model variability make a large difference to the actual adaptation response at a country level. The need to recognise and work with uncertainty - as part of integrated and sustainable policies - requires an iterative and flexible approach.

A number of implications arise from the analysis, the most important of which is to start including these issues in policy across Europe

Health

There are a large number of potential impacts on health that could arise from climate change, directly or indirectly, including heat related mortality and morbidity, food-, water- or vector-borne disease, air pollution, deaths/injuries and wider well-being from flooding, though there are also some potential benefits. There are also risks to public health systems and infrastructure. There are regional differences across Europe and inequalities across groups for all of these impacts.

The ClimateCost study has assessed the potential impacts and economic costs of health impacts in Europe. This has considered future climate and socio-economic change. The latter is important in taking into account age specific changes in population, particularly Europe's aging population.

The association between daily temperature and mortality has been well described in many populations, and temperature-mortality relationships can be used to estimate the impacts of future climate change. The estimates were assessed for the A1B medium high and the E1 mitigation scenario, with and without autonomous acclimatization.

The results show that heat-related mortality in Europe is project to increase in all regions. The majority of climate change attributable heat deaths are projected to occur in the elderly, and in Southern Europe. By 2050s, following annual impacts on years of life lost are projected (assuming no acclimatization) (ensemble mean): Eastern Europe 7369; Southern Europe 19384; Northern Europe 3980 and Western Europe 13430. The total years of life lost is estimated at 44163/year. This increases to an estimated 63050 by the 2080s. In both cases, autonomous acclimatisation reduces the impacts significantly, to 21882 (2050s) and 19745 per year (2080s). The number of deaths by country is shown below for the 2050s.

The impacts are lower under the E1 mitigation scenario. Total estimated years of life lost are estimated at 37487 (for the 2050s) and 36928 (2080s) per year, and even lower under this scenario with autonomous acclimatisation included at 15967 (for the 2050s) and 7384 (2080s) per year

The economic costs of these heat effects has been estimated using two alternative metrics for valuation, the Value of a Life Year Lost (VOLY) and Value of a Statistical Life (VSL). For the first of these, the welfare cost using VOLY metrics is estimated to be €2.8bn/year in the 2050s for EU25 (A1B, no adaptation) rising to €4.0bn/year in the 2080s. These fall to €2.4 and €2.3bn/year respectively under an E1 scenario. If autonomous acclimatisation is

included, the estimates fall significantly, to €1.4/year (2050s) and €1.3bn/year (2080s) under an A1B scenario, and to €1.0/year (2050s) and €0.4bn/year (2080s) under an A1B scenario. However, the numbers are 30 - 50 times higher when the VSL metric is used rather than when life-years and VOLYs are used. For example, under the A1B scenario, the economic costs rise to €102bn/year (2050s) and €146 bn/year (2080s).

Salmonellosis is a leading cause of food borne illness in European region and has an established sensitivity to ambient temperature. The study has applied the existing epidemiological study information to estimate the future impacts of climate change. The results show that under the A1B scenario, climate change is estimated to cause an additional 8702 cases of salmonellosis in EU25 if the incidence remains at current levels, but 5848 cases if a baseline decline in incidence is assumed.

The economic costs of these additional food borne illnesses has been estimated. The welfare costs, in monetary terms, for the 2050s are estimated at €45 million/year for the EU for the A1B scenario under current baseline assumptions, falling to €30 million/year if a baseline decline in incidence is assumed.

Coastal flooding is associated with direct health impacts (injury and fatality). The health study has the and storm surge With climate change but no adaptation of sea defences, the number of deaths from coastal flooding is projected to increase over time in all regions. The greatest absolute impacts are seen Western and Northern Europe, with median estimates for the 2080s in Western Europe of ~400 deaths annually under A1B (~20 times the number seen at baseline) and a total of ~600 deaths for Europe. The estimated economic costs of these impacts have been monetised. The estimated welfare costs associated with premature mortality are €700 million/year for the EU by the 2080s under the A1B scenario.

These fall significantly under a mitigation scenario to ~180 under E1 for Europe in the 2080s (~6 times baseline), equivalent to €200 million/year. Similarly, matching the output from WP2A, coastal adaptation is extremely effective in reducing down coastal flooding deaths, reducing the impacts above down to around 10 deaths per year in the 2080s (equivalent to around €10 million/year).

Finally, there are well-established physiological limits for an active individual. When the external temperature is raised, an individual must either slow down productivity (or stop working) or, if heat exposure continues, the individual will eventually become ill from heat exhaustion and other heat conditions. Climate change is likely to cause negative impacts on labour productivity in some regions. In Eastern Europe under the A1B scenario, mean losses of 0.5% arise, and impacts are even high in Southern Europe, with a mean of 0.9% of productivity lost. These impacts are significantly reduced under the E1 mitigation scenario, falling from 0.5 to 0.1% for Eastern Europe and from 0.9 to 0.4% for Southern Europe.

The study has estimated the monetary totals for the labour productivity losses. The results show that in the 2080s, under the A1B scenario, the effects on climate change on labour productivity are equivalent to around 750 million Euro/year, though these fall to around 300 million Euro if it assumed the workforce moves towards less intense occupations over time. These impacts are significantly reduced under the E1 scenario, to around 150 million Euro/year (2080s, baseline).

Energy

Temperature is already a major driver of energy demand in Europe for the domestic and service sectors, driving winter heating and summer cooling.

Climate change will have positive and negative effects on these demand levels, reducing winter heating demand but increasing summer cooling demand. However, these changes need to be seen in the context of other socio-economic drivers and future energy and mitigation scenarios. Climate change may also have other effects on energy supply technologies, notably on hydro electricity generation, but also potentially on other supply technologies.

The ClimateCost study has assessed the potential impacts and economic costs of climate change on energy supply and demand in Europe. The analysis used the POLES model, and considered future climate and socio-economic change, as well as future climate change. This takes account of energy growth, but also mitigation policy and the effects on the energy mix

The study has first assessed the increase in cooling demand in Europe from climate change for two scenarios. A medium-high emission scenario (A1B) and a low emission (mitigation scenario, E1) that is consistent with the 2 degrees stabilisation target. The POLES simulations for the A1B and E1 scenarios, incorporating climate change, show reduced demand, of -9 % by 2050 to -22% by 2100 for the A1B scenario and from -6 to -9% for E1 scenarios. The results in the service sector are more important in absolute figures, but similar in relative terms. There are also large differences by region of Europe (and country) with the largest reductions in Western Europe.

When considered in economic terms, the reduction in heating demand is estimated at a reduction of $ 140 billion in the EU27 by 2100 under the A1B scenario in heating expenditures, corresponding to around -0.17% of projected EU27 GDP in 2100.

The study has also assessed the increase in cooling demand in Europe. Under the A1B scenario EU27 electricity use for space cooling is projected to increase by around 3% a year during the century. With climate change, the analysis estimates an increase from 22% to 127% for the 2050s and from 1.2 to 3 times for the 2100s for A1B scenarios with climate change for the domestic sector. For E1 scenarios this increase varies from 15% to 130% for the 2050s, and from -6 to 3 times for the 2100s. In the service sector, warming would increase cooling energy demand in average by 82% for the 2050s and 2 times for the 2100s for A1B scenarios with climate change compared to the baseline; and by 55% for the 2050s, 62% for the 2100s for E1 scenarios with climate change. There is a strong distributional effect across Europe, with much higher levels in Southern Europe.

The costs of additional electricity consumption for air conditioning in residential and service sector are estimated rise to around $ 130 billion in EU27 by 2100 under the A1B scenario (corresponding to 0.16% of projected EU27 GDP). Note that this cost includes only the energy costs - it is necessary to add the investment costs for new air conditioners. Therefore, the new capacity of air conditioners added each year, at an average cost of 250 $/kw, is used

to calculate the average investment cost of new air conditioners. Costs are lower in E1 scenario. The total cost approaches $104 billion representing 0.12% of the projected European GDP.

Overall, warmer conditions lead to a reduction of $ 140 billion in the EU27 in heating expenditures corresponding to around -0.17% of projected EU27 GDP in 2100. The costs of additional electricity consumption for air conditioning arise to around $ 130 billion in EU27 in the end of the period (corresponding to 0.16% of projected EU27 GDP). However, the cost of investment costs for new air conditioners is added to this, estimated at $23 billion. Corresponding costs are lower in E1 scenario. Total cost approaches $120 billion representing 0.14% of the projected GDP

The study has also considered energy supply effects. Hydropower plants are affected by climate change. The impacts of climate change on hydro generation vary strongly according to the climate models, due to the fact that different models predict very different levels of precipitation change. The A1B scenario results show a decrease of European hydro generation due to climate change of around -3% in 2050 and -8% in 2100, compared to the case without climate change. The impacts are lower for E1 scenario at respectively around -2 and -3%.

The values vary according to the region. Results indicate decreasing discharge volumes for southern and east-central Europe, by more than 20% in some countries, whilst the projected rises in discharge volumes for northern European countries may at times exceed 20%. Note that this analysis does not take annual variability into account.

In addition, higher temperatures affect power plant cooling influence efficiency. This effect has been considered in POLES. The efficiency decrease was derived and implemented for all types of thermal power plants (nuclear and fossil). The results estimate that thermal and nuclear power generation could be constrained respectively 2-3% and 4-5% per year, which would mean less 150 TWh per year due to changes in CDD in A1B scenarios.

The total supply side analysis implies annual European energy costs could be $ 95 billion higher in 2100, representing 0.12% of the European projected GDP.

The study has also looked at the potential for low and very low efficiency houses, a planned adaptation response to additional cooling demand.

Ecosystems

The ClimateCost study has used the Lund-Potsdam-Jena (LPJ) Dynamic Global Vegetation Model, simulating the dynamics of natural and managed vegetation grouped into plant functional types.

To assess the impacts of climate change on forestry a linkage between the Global Forest Model (G4M) and the partial equilibrium land use model GLOBIOM was established. This enables the analysis to model forestry and alternative land use and to quantify the economic impacts of global forest management.

The analysis has run this framework for Europe and globally. The results obtained for this report are largely in line with the existing literature. Up to 2040, accumulated carbon is higher for the E1 scenario if strong CO2 fertilization effects are assumed. Afterwards the carbon content is lower for the woodland biomes. This result is due to the E1 scenario being characterised by an initially stronger warming than the A1B scenario. In later years, carbon fertilization effects become more dominant and leads to higher vegetation carbon accumulation for the A1B scenario. Concerning the uncertainty between climate models, the standard deviation of simulated vegetation carbon for different climate models for A1B has been found to be rather low in comparison to mean vegetation carbon, but also to be growing over time.

One of the key findings is that biomes will shift further northwards/to higher altitudes. This leads to a replacement of productive forest ecosystems by lower productive shrublands and to a change in the structure of the landscape.

As a result, carbon storage in southern and Central Europe will likely decrease, while it will increase in regions presently covered by taiga vegetation. The effects in terms of reductions in carbon storage are shown below. These effects have also been monetised using values for the social cost of carbon (linking with WP7).

These changes will also have an effect on ecosystems. The variability of vegetation cover between years will likely increase, leading to less stable habitats for various species.

Dependent on the impact of carbon fertilization, losses of vegetation carbon are expected to increase (due to higher absolute vegetation carbon with fertilization) or stay relatively constant (due to relatively constant absolute vegetation carbon without fertilization)

A similar analysis has also been undertaken at the global level. Again, this shows large biome shifts are detectable, with boreal trees shifting further towards the poles and to higher elevations and shrublands expanding in their area. World-wide a decrease in highly productive evergreen trees can be found which are replaced by summer-green trees (boreal and temperature climate) or rain-green trees (tropical climate).

Results for the impact analysis for the forestry sector in Europe and a selection of climate change scenarios are also presented. These show a strong climate feedback on forest growth and biomass accumulation that can be mitigated through species change. However, species change needs time to become effective. Moreover, such adaptation strategies might conflict with mitigation measures in the forestry sector such as biomass maximization.

3. Major Events

There are emerging concerns that much of the economic literature on the impacts of climate change does not adequately cover catastrophic events from climate change - though this also reflects the underlying state of scientific knowledge on these aspects.

These include two types of events. First the major climate 'tipping points' (catastrophic events, also referred to as major climate discontinuities or irreversibilities), as identified by

Lenton et al (2008). These include, for example, irreversible collapse of the West Antarctic or Greenland ice sheets and resulting sea level rise. Second, so called socially contingent effects, where multiple stresses come together and lead to large-scale human societal changes, i.e. with regional conflict, poverty or famine, migration, etc. A key policy question here is whether these effects make globally significant differences in the cost of climate change impacts.

The ClimateCost study has updated the literature on the bio-physical tipping extremes. Tipping elements in the Earth system include some that could have serious consequences within 100 years, reporting on the melting of the Greenland and West Antarctic ice caps and the Hindu-Kush-Himalaya-Tibetan glaciers; changes in the Atlantic thermohaline circulation and El Nino/Southern Oscillation (ENSO); drought in the Amazon; and shifts in the Indian summer monsoon and rainfall in southwestern North America.

The study has also reviewed the information on socially contingent extremes. The study has considered a large number of the possible drivers, and overlaid state fragility and potential adverse climate change to highlight over 100 countries at risk of significant negative knock-on socio-political effects. Of these countries, over half do not have institutions capable of sustaining the strain of climate change, leading to political instability. A case study of South Asia illustrates the many security, conflict and physical impacts of climate change could contribute to a socially contingent tipping point. South Asia is a major concern given the instability of the Indian monsoon and potential drought risk that would limit agricultural adaptation options.

The project has also progressed a major case study to look at the impacts and economic costs of major sea level rise. The population occupying coastal zones subject to inundation (including storm surges) for a high-end scenario of SLR by the end of the century is nearly double the population affected middle-range scenarios. By the 2080s, nearly 25 million people per year could be affected. The vast majority of the population at-risk is from low and middle income countries. People choosing to live outside at-risk coastal regions, referred to here as SLR-induced migration, reaches a cumulative total of over 250 million people by the 2080s (from 1990).

The cost of this high-end sea level rise (not including the cost of adaptation) rises to Euro 900 billion per year globally in the 2080s. This is four times greater than a moderate scenario, indicating the extreme outcomes that are possible in the future.

Furthermore, some scoping work has been undertaken looking at major sea level rise by considering future possible exposure. Over 600 million people currently live in the low elevation coastal zone, i.e. less than 10m elevation, that is hydrologically connected to the sea. Economic activity in this at-risk region has been mapped in the ClimateCost study at over $2,000 trillion GDP. Not surprisingly, Asia and the Asia-Pacific account for the majority of the population-at-risk and a third of the global GDP at-risk. Europe and North America (including Mexico) stand out as having the highest economic risks. In comparison, Africa is much less exposed to sea level rise as a whole. However, individual countries with high exposure are found in every region.

Finally, the study concludes that complex problems as tipping elements and extreme outcomes can only be addressed through multiple lines of evidence. The ClimateCost project

explored a full range, from qualitative narratives and case studies, to integrated assessment models and formal models of behavior based on actor-network approaches. Clearly, extreme outcomes are not marginal effects of climate change; and traditional economic frameworks struggle to capture these effects; adaptive management will require significant departures from 'business as usual' scenarios.

4. Mitigation

The project reviewed endogenous technological change and R&D accounts and incorporated these in a number of mitigation models. It reviewed and developed technological detail of new technologies in the POLES model. It also developed a number of components in the GEM-E3 model, including the improved modelling of the agriculture sector (including mitigation options) and a review of marginal abatement cost of GHG at EU and World level.

The project successfully built a database (OECD information) on satellite R&D accounts with geographical coverage and sectoral disaggregation and incorporated in the PACE model and in GEM-E3.

It also included an update with new technological detail in the POLES model to consider new technologies and updated the GEM-E3 model, including the improved modelling of the agriculture sector (including mitigation options) and an update of marginal abatement cost of GHG at EU and World level.

The updated models were used to provide the modelling analysis in the EC Roadmap for moving to a competitive low carbon economy in 2050 (CEC, 2011) and the information underpinning the Impact Assessment (CEC, 2011b).

5. Ancillary Air Quality Co-Benefits of Mitigation

The reduction of greenhouse gas emissions (mitigation) often leads to associated reductions in air pollution emissions. This leads in turn to air quality benefits, and improved health and environmental quality. When expressed in monetary terms, these benefits offset a substantial proportion of mitigation costs. Furthermore, whilst the full benefit of GHG reductions resulting climate action are only experienced by future generations, and tend to be global in nature, the ancillary benefits of climate policy are experienced immediately by the current generation and occur locally, e.g. in Europe.

ClimateCost has assessed the air quality co-benefits from mitigation using a spatially disaggregated bottom-up approach that considers short -term (2020s) and longer term benefits (2050s), considering two policy scenarios, a current policy baseline and a 2°C climate Mitigation scenario. It has assessed these benefits in terms of physical impacts and monetary benefits, for Europe, China and India using a bottom-up detailed approach. This uses detailed air quality modelling using the GAINS Model.

The results show climate mitigation measures are more effective in reducing oxides of sulphur and nitrogen, while emissions of particulate matter are reduced to a smaller extent. Decarbonisation of the global energy system by 2050 results in SO2 and NOx emissions lower by two-thirds. The corresponding reduction in the emissions of PM2.5 is estimated at about 30% relative to the Baseline and is particularly sensitive to the assumptions on projected biomass combustion.

The health impacts of the associated reduced air pollution in Europe, China and India is very large, in terms of loss of life expectancy related to the exposure from anthropogenic emissions of PM2.5, as well as in terms of premature mortality due to ground-level ozone. For example in China, current ambient concentrations of PM2.5 are responsible for 38 months-losses in the average life expectancy. In 2050, the global GHG-mitigating strategies reduce this indicator in China by 16 months. In addition, decrease of ozone concentrations in the three regions as estimated for the climate Mitigation scenario in 2050 might save nearly 80,000 cases of premature death per year. Similarly significant are reductions of impacts on ecosystems due to acidification and eutrophication.

The major contributions to these health benefits in Europe of reduced air pollution arise from 885,000 fewer life years lost, 36,000 fewer new cases of chronic bronchitis, 21,000 fewer hospital admissions and in total around 150 million fewer person days of restricted activity, respiratory medication use and lower respiratory symptoms.

When expressed in monetary values, the co-benefits are estimated to be very large. Results demonstrate that the co-benefits to health of the Mitigation Scenario are likely to be substantial across the EU27, with a best estimate of 72billion per year by 2050.

Expenditures on air pollution control under the global climate mitigation regime are reduced in 2050 by 250 billion when compared to the Baseline scenario. Under the GAINS cost assumptions the largest potential for cost savings is reported for the transport sector, followed by savings in the power generation sector. Around one third of financial co-benefits estimated world-wide in this study by 2050 are allocated to China, while an annual cost saving of 35 billion is estimated for the EU member countries if the current air pollution legislation and climate policies are adopted in parallel.

The work on air quality co-benefits in ClimateCost was reported in the EC Roadmap for moving to a competitive low carbon economy in 2050 and the underlying impact assessment (CEC, 2011). This cited the GAINS model results co funded by the project on the benefits of GHG emission reductions through to 2050, and the environmental and economic benefits. The work is reported in the main communication, and also in section 5.2.14 of the Impact Assessment (co-benefits in terms of air pollution) - see earlier section for details.

The benefits in India and China have also been estimated and are even larger. In China, health benefits of mitigation are estimated at 29 000 years of life per year, equivalent to 595 to 2400 billion a year by 2050. For India, the benefits are even larger, at 44,000 years of life per year, equivalent to 409 to 3658 billion a year.

6. Model Development

The project updated a number of General Circulation Models (GCMs) and Integrated Assessment Models (IAM), with significant activities brought forward on these tasks.

This has included a major re-development of the PAGE model, the tool used to estimate economic costs in the Stern Review, producing the PAG09 model. The PAGE (09) integrated assessment model was successfully developed, completed, peer reviewed. The technical papers for the model and the first results run have been accepted in academic journals.

It has also included major developments and new modules to the existing FUND model. New developments to the FUND model were completed, including a storm module, non-CO2 GHG, work on equity (inequity aversion), sensitivity of functions and deep uncertainty. These updates were published in academic papers.

Work progressed on the development of the GEM-E3 and IECS-WITCH models, investigating the potential for linking the models to the output from WP2.

7. Policy Runs

The ClimateCost project has run a number of computable general equilibrium and integrated assessment models, looking at a number of relevant policy metrics.

The GEM-E3 model used the sectoral impact results from WP2 and assessed within a CGE framework. The results reported at that the EU would undergo a GDP loss of around 0.1% by the 2020s, which grows significantly in the 2050s and 2080s, to 0.4 and 0.8%, respectively. The largest GDP losses would occur in the Southern Europe region, attaining a loss of 2.3% by the 2080s.

The ICES model has used the impact information from WP2 and integrated this within a global CGE model. The results indicate that a temperature increase of 1.9°C compared to pre-industrial levels in 2050 could lead to global GDP losses of about 0.5% compared to a hypothetical scenario where no climate change is assumed to occur and there is no planned adaptation. The most vulnerable countries are the less developed regions, such as South Asia, South-East Asia, North Africa and Sub-Saharan Africa and in all these regions, the most exposed sector is agriculture (without adaptation). The model analysis also found that the general equilibrium estimates tend to be lower, in absolute terms, than the bottom-up, partial equilibrium estimates. The difference is to be attributed to the effect of market-driven adaptation. Using the relationships from this analysis in the WITCH model allows estimation of SCC and overall costs and benefits of mitigation. The global social cost of carbon (SCC) in 2020 estimated assuming full and immediate cooperation ranges between 65 (PRTP 3%) and 347 (PRTP 0.1%) US$2005/tC. However, in cost-benefit terms a very stringent (e.g. 2°C target) stabilizations is not justified.

The PAGE09 model was run to estimate the social cost of CO2 from the PAGE09 model. This provided major new results, with the mean SCCO2 for emissions in 2009 under the A1B scenario estimates at about $100 per tonne of CO2, with a 5% to 95% range of about $10 to

$270. This is significantly higher than the PAGE02 runs and many other literature estimates. The reasons for this increase is explained through the use of updated information on impacts and major events, moving the analysis to a more recent base year, and improved analysis in the model. A comparison of the A1B and E1 runs shows that the strict mitigation target can be justified, i.e. the benefits exceed the costs. A further analysis was also undertaken to look at the influences on the SCC (New insights from the PAGE09 model), which included analysis of discount rate and equity weights, as well as other factors. Finally, the model was run to look at the policy question of how high should climate change taxes be? This analysis highlights the model would justify high policy taxes, and it discusses the contradiction with current policy situation in the US. The work has been written up in three academic papers, which have all been submitted (one is already published).

The FUND model was used to estimate the social cost of carbon under different assumptions of discount rate and equity, and also to look at (Regional and Sectoral Estimates of the Social Cost of Carbon in FUND). The work reports the strong importance of the pure rate of time preference (within the discount rate) on the results: for a 3% rate, the SCC is $1.33/tC; it is $30.3/tC for 1%; and $186/tC for 0.1%. Global equity weights increase the global social cost of carbon by a factor of 3.0 to 4.5, depending on the discount rate. The regional breakdown showed that China, Western Europe and the United States have the highest share of harmful impacts, with the order depending on the discount rate. The most important sectors in terms of impacts are agriculture and increased energy use for cooling.

The FUND analysis also looked at the SCC over time (The Time Evolution of the Social Cost of Carbon: An Application of FUND). This found that the social cost of carbon increases by 1.3% to 3.9% per year, with a central estimate of 2.2%. However, the rate of increase depends on a range of factors, including the pure rate of time preference, the rate of risk aversion, equity weighting, the socio-economic and emission scenarios, the climate sensitivity, dynamic vulnerability, and the curvature of the impact functions.

Potential Impact:

The final results and potential impacts are summarised below.

The project has provided a more complete, updated assessment of cost of mitigation, impacts and economic costs of climate change, and the costs and benefits of adaptation. The potential impact of the project will be primarily through the outputs and results (especially the briefing papers), which will be highly relevant for European Commission climate policy, as well as for Member States. Indeed, the results have already been included in policy discussion and deliberations.

First, in relation to European adaptation, the project has provided results that are of high relevance to Commission Services in relation to the priorities and action identified in the Adaptation White Paper (Adapting to climate change: Towards a European framework for action. COM(2009) 147/4), particularly under the proposed EU action area 3.1, 'developing the knowledge base'. This includes:

- ClimateCost provided information on European impacts and economic costs and adaptation of relevance for action (3.1) for the Impacts, vulnerability and adaptation clearing house.
- ClimateCost provided information relevant for action (3.1) 'assess the cost and benefit of adaptation options by 2011'. It also provides useful information for the subsequent adaptation policy (and supporting impact assessment) in 2012.
- ClimateCost provided information of relevance for EU proposals under (4) instruments - financing in response to the action to 'estimate adaptation costs for relevant policy areas so that they can be taken into account in future financial decisions'.

Information from ClimateCost has already been included in the draft Adaptation Clearing House and used in policy deliberations during 2011 on the discussion on the consideration of adaptation in future budget negotiations and in the early work for the new Adaptation Strategy. It is also anticipated the results will feature heavily in the consideration of the costs and benefit discussion around this strategy during 2012.

Second, in relation to long-term targets and justification for mitigation, the study has provided final results and available models that are of high relevance for the Commission and others, in relation to the short- and long-term GHG emission reduction targets and stabilisation. This includes:

- Information on the cost of inaction for Europe under future scenarios (work package 2). Some of this work was used in the EC impact assessment for the Roadmap for moving to a competitive low carbon economy in 2050.
- Information on the economic consequences of tipping elements, with case study analysis for major sea level rise (work package 3)
- An updated suite of models with major improvements that are used in European Commission mitigation cost and economic analysis (POLES, GEM-E3) plus new

runs with these models which will provide potential information for supporting future impact assessment. These updates models were used to provide the modelling analysis in the EC Roadmap for moving to a competitive low carbon economy in 2050.

- Estimates of the economic co-benefits of mitigation for Europe, as well as China and India, which will be valuable for discussions within Europe as well as international negotiation discussion (work package 5). The modelling work (GAINS), which was part funded by the ClimateCost project, was cited in the EC Roadmap analysis for moving to a competitive low carbon economy in 2050.
- An updated suite of CGM and IAM models (WP6) for use in policy analysis. The PAGE09 results were presented and provided to the European Commission for consideration in the Roadmap analysis.
- Analysis of the costs of climate change and the social cost of carbon from the updated integrated assessment models (PAGE09, FUND and Witch), the availability and dissemination of the PAGE09 model for research groups, and the costs and benefits of mitigation policy from the suite of IAM and CGM runs, which will be of relevance for discussions within Europe as well as international negotiation discussion (work package 7). They have already been used in several applications, including US EPA/DOE review work, as well as in a number of country or regional specific studies.

The information from the study is also relevant for other organisations (European Environment Agency) and Member states.

The details of activities and expected outputs is included in the attached pdf. The outputs and results were disseminated through meetings, as well as study brochures and briefing notes. The results of the project also provide valuable research

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