

European and Global Climate Change Projections

**Discussion of Climate Change Model
Outputs, Scenarios and Uncertainty in
the EC RTD ClimateCost Project**

Summary of Results from the ClimateCost
project, funded by the European
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Programme

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Key Messages



- 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, to make projections of future changes in temperature, 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).
- **Under a medium-high emission baseline (A1B)**, with no mitigation, the climate models considered in ClimateCost show that global average temperatures could rise by between 1.6°C and 2.3°C by 2041-2070, and 2.4°C and 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 across countries, for example, the Iberian Peninsula has a mean projected increase of up to 5°C by 2071-2100.

2.4°C to 3.4°C

rise in global temperature by the period 2071-2100 (A1B)¹

1.5°C

rise in global temperature with mitigation (E1)¹

Uncertainty

in the climate projections between emissions scenarios and climate models for Europe is considerable

¹These values are reported for a future average time period over 30 years, relative to a 1961-1990 baseline. They report the Ensembles Project results used in the ClimateCost project, not the full IPCC AR4 range.

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- 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 global temperatures are projected to increase by about 1.5°C by 2071-2100 compared with 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 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 the 1961-1990 baseline, irrespective of the emission pathway, highlighting the need for 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.

1. Introduction

The objective of the ClimateCost project is to advance the knowledge on the economics of climate change, focusing on three key areas: the impacts and economic costs of climate change (the costs of inaction), the costs and benefits of adaptation, and the costs and benefits of long-term targets and mitigation. The project has assessed the impacts and economic costs of climate change in Europe and globally. This included a bottom-up sectoral impact assessment for Europe, including adaptation, as well as a global economic modelling analysis with sector-based impact models and computable general equilibrium models.

To ensure that the assessment uses a consistent and harmonised approach, the project has used a common set of climate change scenarios and projections.

This technical policy briefing note² (TPBN) provides an overview of the global and European regional modelling projections used in the ClimateCost study. It includes the reasons for the choice of emissions scenarios and model projections, and the data sources used. It also provides an interpretation of the available information and the implications for the consideration of uncertainty in the project.

Key terms and definitions

A large number of technical terms are associated with climate change, several of which are used in this TPBN. The definition of key terms is outlined below, summarised from those presented in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (**AR4**) Glossary.

Emission scenario is a plausible representation of the future emissions (e.g. greenhouse gases (GHGs)), based on a coherent and internally consistent set of assumptions of driving forces (such as demographic and socio-economic development, technological

change). These include the IPCC Special Report on Emission Scenarios (**SRES**).

Concentration scenarios are derived from emission scenarios (above), are used as input to a climate model to compute climate projections.

Climate projections indicate the response of the climate system to emission or concentration scenarios and are based on simulations by climate models. Climate projections are distinguished from climate predictions to emphasise the fact that climate projections depend upon the emission/concentration scenarios used. These emission/concentration scenarios are based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised and are, therefore, subject to substantial uncertainty.

Climate change scenarios are plausible, but often simplified, representations of the future climate. They are the key input for the climate change impact models used in projects such as ClimateCost.

Climate models are numerical representations of the climate system and are based on physical, chemical, and biological properties, and interactions and feedback processes. They account for all or some of the known properties of the climate system and can be represented by models of varying complexity. Coupled atmosphere/ocean/sea-ice general circulation models, now more commonly referred to as global climate models (**GCMs**) provide a comprehensive representation of the climate system. More complex models include active chemistry and biology.

Downscaling is a method that derives local- to regional-scale (10 km to 100 km) information from larger-scale models or data analyses. There are two main methods: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses

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the output of regional climate models (RCMs) - the approach used in ClimateCost, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

Ensemble is a group of parallel model simulations used for climate projections. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model, but different initial conditions only characterise the uncertainty associated with internal climate variability, whereas multi-model ensembles, including simulations by several models, also include the impact of model differences.

2. Climate models and scenarios

Scenario-driven impact assessments – as undertaken in ClimateCost – require spatially and temporally detailed information on the projected climate in future years (e.g. in terms of temperature or precipitation changes). This information is produced by GCMs.

GCMs require information on future GHG and aerosol-particle emissions over time, information which is generated by socio-economic scenarios and models. The most widely used current estimates of future GHG emissions are those provided in the form of different scenarios in the IPCC SRES (Nakicenovic et al., 2000). These define a set of future self-consistent and harmonised socio-economic conditions and emission futures that, in turn, have been used to assess potential changes in climate through the use of global and European climate models. There is a wide range of future drivers and emissions paths associated with the scenarios and, thus, the degree of climate change varies considerably. This has a subsequent effect on impact and cost analyses.

The SRES scenarios were used in the IPCC AR4 (IPCC, 2007). However, none of these consider any mitigation scenarios. More recent work in Europe has developed some mitigation or stabilisation scenarios, notably as part of the ENSEMBLES project (van der Linden and Mitchell, 2009).

Finally, in 2010 a new family of scenarios was defined, the Representative Concentration Pathways or RCPs (Moss et al., 2010). The RCPs encompass mitigation and non-mitigation scenarios, and form the basis of new modelling work that is being undertaken for the IPCC Fifth Assessment Report.

2.1 The emission scenarios used in ClimateCost

The ClimateCost project has considered three alternative socio-economic scenarios, each of which leads to a different emissions profile. Thus, there are three sets of climate model projections of future climate change, each considering the results of a number of alternative climate model projections for each emissions scenario. The three emissions scenarios used by ClimateCost are summarised in the box.

ClimateCost emissions scenarios

It should be noted that when temperature increases are reported, **there are a number of alternative baseline periods that can be used.** Projections may be reported relative to pre-industrial, relative to the 1961-1990 baseline used in ClimateCost or relative to the period cited in the IPCC AR4 (1980-1999). In this summary, temperature changes are given with respect to the latter baseline period and for the full set of models considered in the IPCC AR4. Therefore, the ranges and numbers in this box differ somewhat from those reported elsewhere in this TPBN (which use a smaller set of models and a 1961-1990 baseline).

The first emission scenario considered is the SRES **A1B scenario.**

This is based on the SRES A1 storyline, which is a future world of rapid economic growth, new and more efficient technologies, and convergence between regions. The A1B scenario adopts a balance across all energy sources (fossil and renewable) for the technological change in the energy system. This scenario has been extensively used in recent European regional climate modelling studies, notably in the ENSEMBLES study.

The A1B scenario reflects a medium-to-high emission trajectory and leads to mid-range estimates of global average temperature change of around 3.4°C by 2100 (IPCC, 2007) relative to pre-industrial levels or 2.8°C for 2090-2099 compared with 1980-1999 (temperatures have increased by about 0.7°C between these two reference periods).

However, these central estimates are bounded by an uncertainty range of considerable size. The best estimate of 2.8°C (for 2080-2099, relative to 1980-1999) sits with a 'likely' range of 1.7°C to 4.4°C (as reported by the IPCC, 2007)³.

The second emission scenario is the **ENSEMBLES E1 scenario**.

The ENSEMBLES E1 scenario was constructed as a mitigation scenario aimed at achieving the EU's 2-degree goal (global warming relative to pre-industrial levels). The E1 scenario (van der Linden and Mitchell, 2009; Lowe et al., 2009; Roeckner et al., 2010) leads to long-term stabilisation at 450 ppm of carbon dioxide equivalent (CO₂e) (450 ppm stabilisation in the 21st century after a peak of 535 ppm in 2045). It is estimated to limit global warming to less than 2 degrees (compared with pre-industrial) with a high probability (though not with complete certainty).

The final emission scenario is the **RCP 8.5 scenario**.

This reflects a scenario with much higher emissions and, thus, a much greater degree of climate change. It is considered to be similar to the SRES A1FI scenario, which was a high fossil variation of the A1 family. The best estimate for A1FI is 4°C for 2090-2099, relative to 1980-1999, but with a likely range of between 2.4°C and 6.4°C.

Due to a lack of archived runs for A1FI and the fact that no runs had been performed with the new RCP8.5, the ClimateCost study commissioned a new, regional, RCP8.5 run. Therefore, the ClimateCost study has worked with the output for RCP8.5 from the community EC-Earth global model and this has been downscaled to Europe for ClimateCost at 25 km resolution using the HIRHAM5 RCM.

2.2 Background to the climate models considered

Climate change is global in nature and, therefore, the starting point for the assessment is the GCMs. These use the information on future GHG emissions from the socio-economic scenarios (discussed above) and project the future changes in a range of climate parameters.

However, assessment of climate change impacts requires climate data at a higher spatial resolution than can be provided by GCMs. An example is the river flood modelling assessment in ClimateCost, which requires more detailed information at the river catchment level. While several approaches exist for this downscaling, one of the main ways of obtaining such information is to use RCMs, which cover part of the globe (e.g. Europe). Such models provide a more realistic representation of topography and geography and, thus, potentially of smaller-scale features such as extreme precipitation events and storms (Christensen et al., 2007).

Both types of model are based on physical laws and processes, but the GCMs are represented on a horizontal grid with a typical grid point distance of between 150 km and 300 km (Meehl et al., 2007) and contain descriptions of atmosphere, ocean and sea ice, while the atmosphere-only RCMs use a grid of between about 25 km and 50 km. Moreover, the regional models are not run completely on their own, they require boundary conditions from GCMs and are, therefore, constrained by the ability of the GCMs to reliably simulate the large-scale circulation. When results from regional models are cited, they are based on a particular GCM-model simulation and associated boundary conditions.

A further key issue when using climate model output is the differences between alternative models – one of the main themes of this TPBN. It is current practice to consider a wide selection of model simulations, known as an ensemble. The aim of using an ensemble is to provide information on the uncertainties with the system, often represented using statistical information. There is a wide range of different types of ensembles. However, this TPBN refers to sets of alternative climate models for the same emission scenarios.

The ClimateCost project has used a combination of GCMs and RCMs. However, climate modelling is highly resource intensive. Consequently, the ClimateCost project has not undertaken new modelling (with one exception for a regional RCP8.5 scenario). Instead it has worked with existing

³ The IPCC defines 'likely' as greater than 66% probability.

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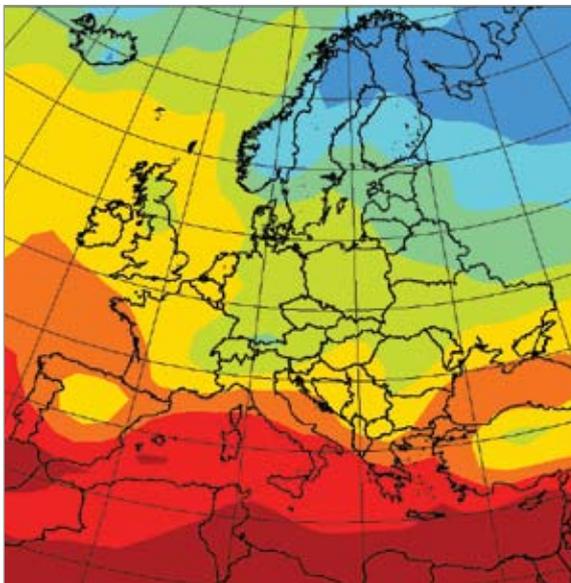
climate model data archives. This allows for a choice of models and projections, including ensemble outputs.

The specific archives of GCM and RCM output were obtained from the EC Framework Programme 6 ENSEMBLES project (van der Linden and Mitchell, 2009).

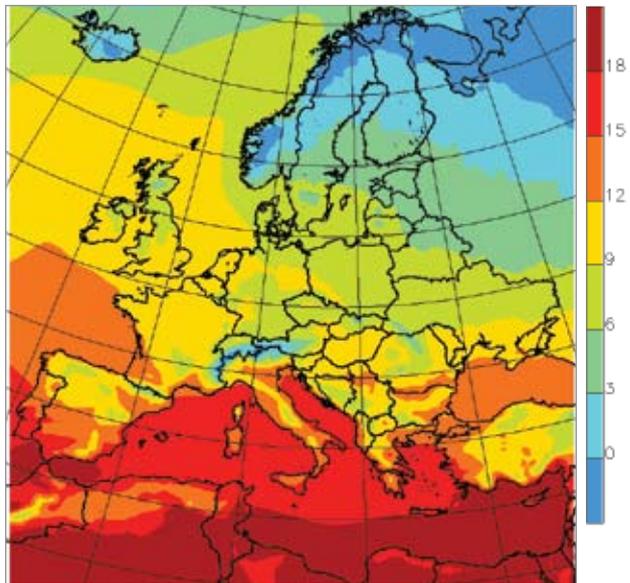
The difference between the spatial resolution for Europe for a GCM and RCM is illustrated in Figure 1. The top figure shows the summer temperature as simulated with a GCM

(left) and an RCM (right), respectively. The bottom figure shows how the two models project the change from the baseline. In both cases, the regional model – on the right – displays greater spatial detail. However, it should be noted that the climate change signal seems to have a larger spatial coherency than the actual absolute temperatures.

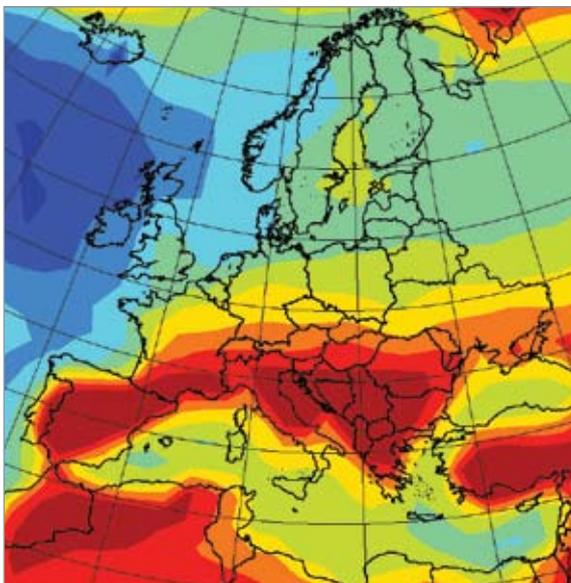
Figure 1. Comparison of the resolution of a GCM (left) and RCM (right). Top: Absolute values for the 1961-1990 baseline. Bottom: Change from 1961-1990 to 2070-2099 (bottom) for Europe in summer air temperature (°C) in the ECHAMr-r3 global simulation, and in one ENSEMBLES RCM simulation (KNMI) driven by this global simulation.



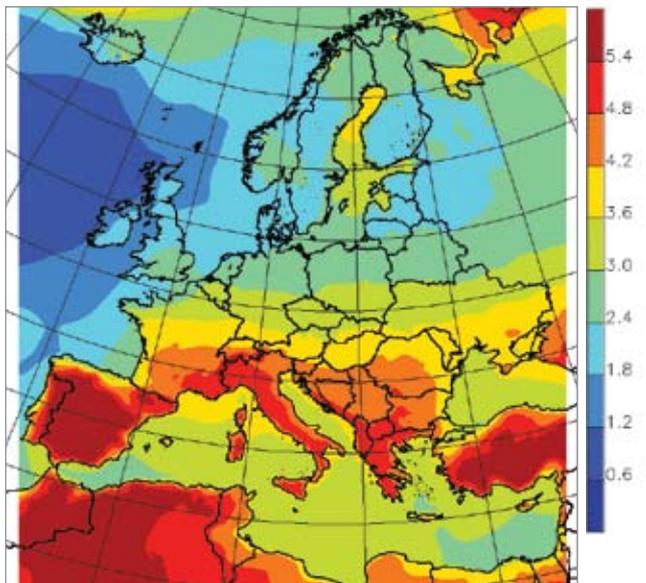
Global Climate Model Resolution.
Simulated summer temperature (1961-1990)



Regional Climate Model Resolution.
Simulated summer temperature (1961-1990)



Global Climate Model Resolution.
Summer temperature change (1961-1999 to 2070-2099)



Regional Climate Model Resolution.
Summer temperature change (1961-1999 to 2070-2099)

These climate models provide extensive data with a high degree of temporal and spatial detail. This allows comparison with a modelled baseline period to investigate future climate change. However, the natural inter-annual variability of weather/climate, which is simulated by the models, necessitates the consideration of aggregated future time periods; climate modelling is about extracting statistical properties from simulations and comparing these.

In ClimateCost, the following time-slices have been considered.

The years 1961-1990 represent the 'baseline' climate period.

Three future time-slices are also considered:

- 2011 - 2040 (the 'near future' period).
- 2041 - 2070 (the 'mid future' period).
- 2071 - 2100 (the 'far future' period).

It should be noted that the period 1961 - 1990 is used as the baseline in ClimateCost (though it is stressed that temperatures are now considerably warmer than this). This is important in interpreting the subsequent impact results. The total observed global temperature increase from 1850 - 1899 (which can be considered as pre-industrial) to 2001 - 2005 (close to present day) is 0.76°C (IPCC, 2007). Warming has accelerated over the most recent decades. The observed rate of global temperature increase over the

last 25 years (to 2005) is 0.18°C per decade compared with 0.07°C over the last 100 years (IPCC, 2007).

This leads to an important caveat - care must be taken when comparing temperature projections between studies and models. It is necessary to be explicit about the baseline period (i.e. whether changes are relative to pre-industrial, 1961 - 1990 (as used in ClimateCost) or 1980 - 1999 (as used in IPCC AR4)).

In ClimateCost, the analysis is presented relative to the baseline period of 1961 - 1990. To illustrate this, the changes in the GCMs reported in this TPBN are shown below – showing the increase relative to the period 1871 - 1900 and from the baseline period (1961 - 1990), both to the later time period of 2071 - 2100. The final column shows the changes from a 1991 - 2010 baseline and thus provides an indication of the simulated warming between the 1961 - 1990 ClimateCost baseline period and now: this is around 0.4°C for the globe and 0.7°C for Europe.

Reporting climate model results involves key issues of 'uncertainty'. The term uncertainty is often used very generally and can be interpreted in different ways. The key issues associated with uncertainty, and climate models and outputs are described in the box below. In this TPBN, uncertainty is primarily associated with climate model outputs (i.e. scenario and structural uncertainty).

Table 1. Temperature changes for global and European regions, by scenario, season and baseline.

Region	Scenario	Season	Baseline		
			Change from 1871-1900* to 2071-2100	Change from 1961-1990 to 2071-2100	Change from 1991-2010 to 2071-2100
Reference scenario (A1B)					
Global	A1B	Winter (DJF)	3.4	3.0	2.6
Global	A1B	Summer (JJA)	3.1	2.7	2.3
Europe	A1B	Winter (DJF)	4.1	3.6	2.9
Europe	A1B	Summer (JJA)	3.8	3.5	3.0
Mitigation scenario (E1)					
Global	E1	Winter (DJF)	1.8	1.5	1.0
Global	E1	Summer (JJA)	1.7	1.4	1.0
Europe	E1	Winter (DJF)	2.6	2.2	1.4
Europe	E1	Summer (JJA)	2.4	2.2	1.4

*This is the earliest 30-year period available from the climate models and is used here to provide an approximation of the pre-industrial baseline.

The concept of uncertainty in climate modelling

The IPCC AR4 Glossary defines uncertainty as 'an expression of the degree to which a value (e.g. the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Therefore, uncertainty can be represented by quantitative measures, for example, a range of values calculated by various models or by qualitative statements (e.g. reflecting the judgement of a team of experts)'.

In this TPBN, uncertainty is used to describe all aspects of our lack of knowledge of the future climate. This uncertainty can be divided into several, conceptually very different, parts.

One unknowable determinant of future climate is the timeline of future anthropogenic emissions of various gases. This uncertainty can only be treated by doing simulations with several storylines and comparing them, as has been done in the present report.

The second relates to the fact that the climate system is inherently chaotic and, therefore, predictability is inherently limited. Even the slightest perturbation or lack of knowledge of an initial state of the system will grow. Climate research is about weather statistics and not about prediction - prediction is the attempt to produce an estimate of the actual evolution of the climate of the future. Since the chaotic behaviour of the climate system includes variations of annual and even decadal timescale, even the statistical properties of some 30-year period in the future would only be predictable with a limited accuracy, given a perfect model and a perfect knowledge of future GHG concentrations. The best result that would be achievable with a perfect model and infinite computer resources would be a probability distribution of climatic changes, according to which society could make adaptation plans. Thus, in ClimateCost, 'climate projections' (see box on 'Key terms and definitions') is used rather than 'climate predictions'.

In reality, climate models are based on simplified mathematical characterisations of the climate

system and do not all give exactly the same results. Furthermore, only a limited number of simulations can be performed. The uncertainty of climate projections is normally split into the following parts:

- Scenario uncertainty - the uncertainty due to the inherent lack of knowledge about future forcing.
- Structural uncertainty - this is the effect of imperfect modelling. This can be estimated by using several different models, global and regional. This is done systematically in the IPCC work and also in ClimateCost. The structural uncertainty can be split into an uncertainty in climate sensitivity (i.e. how much the global temperature changes for a given forcing), and a pattern of uncertainty about the exact regional and seasonal changes associated with climate change of a given strength.
- Statistical uncertainty - the effect of climate variability on annual and decadal scales. The statistical uncertainty arises from the fact that the climate system has variations on many timescales. Traditionally, at least 30 years have been considered necessary to assess climatic parameters with any confidence – hence the use of the 30-year time-slices in ClimateCost; some variability stills remains even for periods of this length. The statistical uncertainty can be quantified by running intra-model ensembles (i.e. several simulations with the same model).

In general, the confidence in a given model result is a question of signal-to-noise ratio (as well as model reliability): the result of a forcing can be hidden in the statistical uncertainty. Therefore, it is easier to identify and estimate larger climate change signals arising from large forcings or from projections further into the future (i.e. in the period after 2050) than it is to look at short-term climate change. Results from numerical climate models looking only a few decades into the future may not exhibit statistically significant climate change.

Regional and seasonal climate change signals are normally associated with larger structural and statistical uncertainties. However, in some cases, such changes can be more robust and meaningful than grand-total averages (e.g. in the case of precipitation where the global average is constructed from areas with increasing precipitation as well as areas with decreasing precipitation).

3 Temperature projections

This section presents the outputs from the climate models used in ClimateCost. It starts with the GCM analysis of global average temperatures. It then considers the GCM output values for Europe. Finally, it assesses the RCM output for Europe.

3.1 GCM results: Global average temperature

The GCM data for the A1B and E1 emissions scenarios used in ClimateCost were downloaded from the archives of the ENSEMBLES project (van der Linden and Mitchell, 2009). This allowed consideration of a large number of models, including:

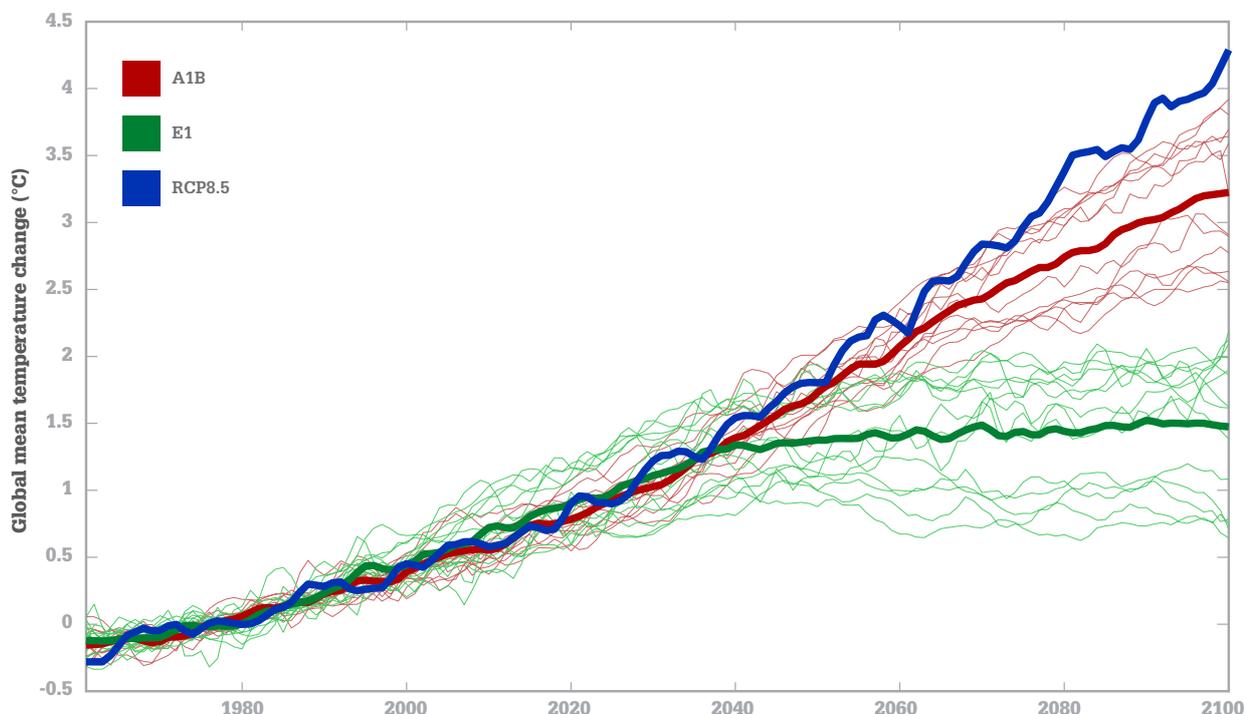
- 12 A1B runs, based on eight different GCMs⁴.
- 14 E1 runs, based on eight different GCMs⁴.

In addition, one GCM simulation has been completed recently for the high emission RCP8.5 scenario at the Danish Meteorological Institute⁵ and this was made available to the ClimateCost project. This simulation has also been included in the study.

Each individual simulation samples possible, plausible, climate time series in a different way, so it is of value to do several simulations (an intra-model ensemble) with one global model. Some of the ENSEMBLES project models were run two or three times. Thus, the datasets reflect inter-model uncertainty (eight different models are available) and intra-model uncertainty (multiple runs are available for some individual models).

The global average temperature projections from the models – over the next century – are shown in Figure 2, for the A1B (red) and E1 (green) scenarios, with the ensemble mean values in bold, but also all models shown. Figure 2 shows the evolution of temperature since 1961, with the warming plotted relative to the 1961-1990 baseline. It should be

Figure 2. Projected change in global mean temperature (°C) with respect to the 1961-1990 baseline for the A1B (red) and E1 (green) emissions scenarios. Results from the ENSEMBLES project GCM runs. Blue line shows the EC-Earth RCP8.5 model run, thin lines show individual models, and thick red and green lines show ensemble mean.



Note ENSEMBLES does not reflect the full uncertainty captured through the full international model community. Hence, Figure 2 does not cover the same likely range as reported in the IPCC AR4.

⁴For the A1B runs, this comprised eight different coupled atmosphere-ocean GCMs. For the E1 runs, this comprised eight different coupled earth-system models. Note that the A1B set is a subset of the GCMs contributing to the CMIP3 multi-model ensemble produced in advance of the IPCC AR4. The E1 models are based on the earlier GCMs, but incorporate additional processes and model components such as, in some cases, carbon cycle models.

⁵This used the EC-Earth coupled earth-system model.

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noted that this only includes the ENSEMBLES model runs, it does not include the full IPCC AR4 ensemble of models. Thus, the range is lower than the likely range (i.e. > 66% probability) reported in IPCC AR4. Figure 2 also includes one run with the EC-Earth global model for the RCP8.5 scenario (blue line).

Figure 2 leads to the following key messages:

- The results show higher values in the A1B scenario (red, bold line), with an ensemble mean value of a 2.9°C increase for 2071-2100 relative to the 1961-1990 baseline. This compares to a 1.5°C increase for the E1 scenario (green, bold line) relative to the same baseline period. The one RCP8.5 run (in blue) shows an increase of 3.5°C by 2071-2100.
- None of the scenarios shows a significant divergence until after around 2040. This is because these early changes are already 'locked-in' to the climate system as a result of historical emissions. They cannot be altered by any mitigation action. Therefore, these changes are a key issue for early adaptation.
- All the models show robust increases in warming, but the range around the ensemble mean is large and increases in later time periods. Even for this selection of model runs, which does not encompass the full range

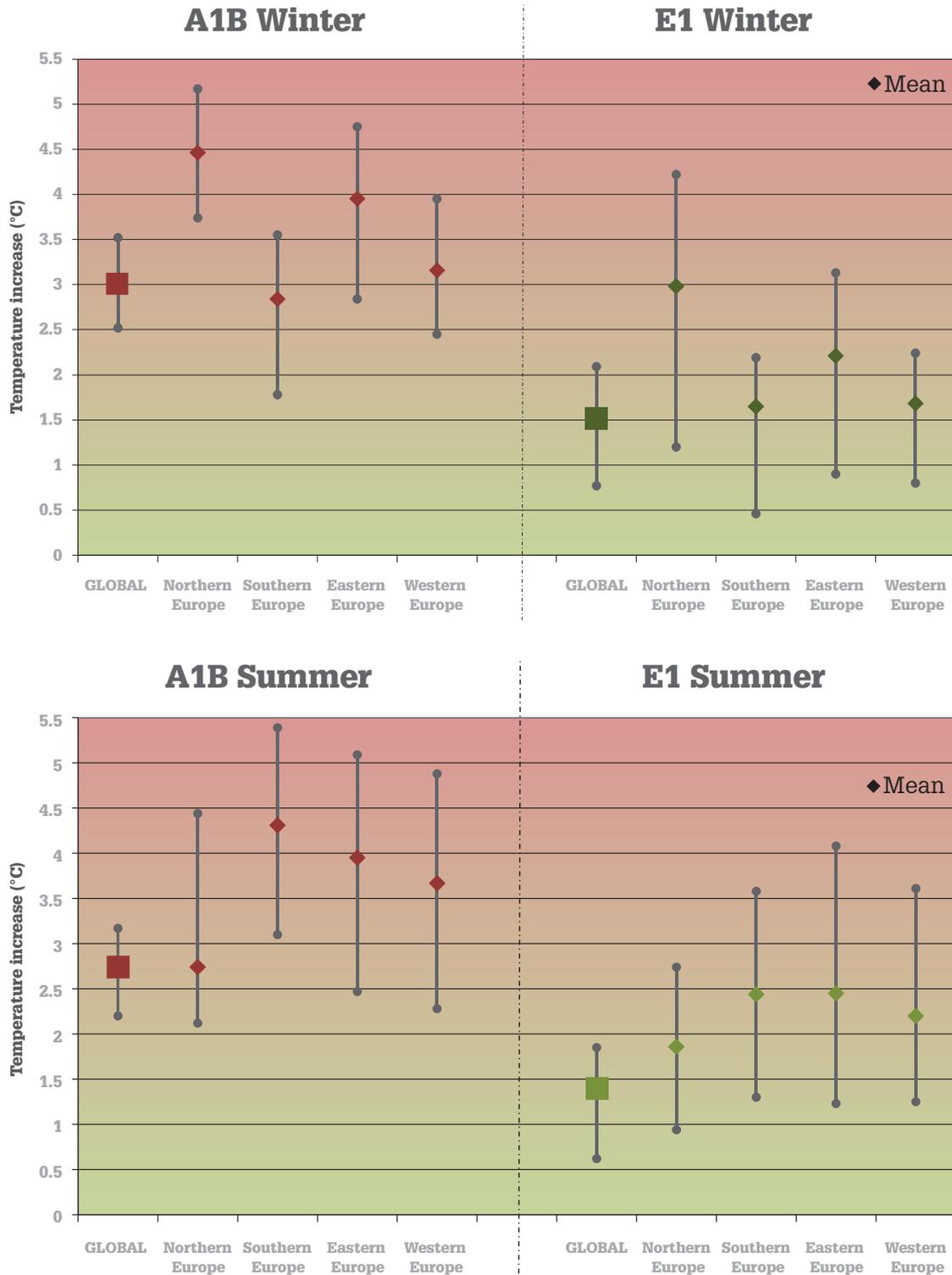
of available model runs, the range of outcomes for A1B is between 2.4 and 3.4°C by 2071-2100, relative to the 1961-1990 baseline. For the E1 scenario, the available simulations indicate a range of 0.7°C – 2.0°C for 2071-2100, relative to the baseline period. This reflects the importance of natural variability and the influence of model structural uncertainty. It is also highlighted that with some models, the E1 scenario exceeds the 2 degrees global target (from pre-industrial).

3.2 GCM results for Europe

This section considers the GCM results for Europe, split into four aggregated regions of Northern, Southern, Eastern and Western Europe. The countries included in each of these regions are outlined in the Annex

The European results are plotted in Figure 3. These show the change in the period 2071-2100, relative to the 1961-1990 baseline, for the A1B and E1 (mitigation) scenarios for winter (December, January and February at the top) and summer (June, July and August at the bottom). The global values are also included for comparison. The figure shows the mean results, and the low and high range, from the ensemble of model runs.

Figure 3. Projected change in global and European regions for mean temperature (°C) 2071-2100, compared with the 1961-1990 baseline, for the A1B and E1 emissions scenarios (winter and summer), showing ensemble minimum, maximum (black dots) and mean (squares/diamonds) results. The data, and the key to which countries are in which regions, are available in the Appendix.



It should be noted that in interpreting these data, ENSEMBLES does not reflect the full uncertainty captured through the full international model community.

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The first immediate conclusion from these graphs is that the average mean temperature change in Europe is different from the global mean temperature change. It also varies considerably with season. This, in itself, is extremely important in the policy context: the discussion of limiting global average temperature change to 2°C (from pre-industrial), will not mean that changes in Europe are also limited to this level of change.

A number of other key messages can be drawn from Figure 3:

- The change in **summer temperature** (bottom) is much higher for Europe, when compared with the global average, especially for Southern Europe under the A1B scenario, with potentially more than 4°C or even 5°C of change by 2071-2100 compared with the baseline period. The change in winter temperature (top) for both scenarios is relatively similar between Europe and the global average, except for the larger changes in Northern Europe. Under the E1 scenario, temperature increases are substantially smaller than those under A1B. The regional and seasonal differences are similar to A1B, but with a smaller amplitude. Nonetheless, summer warming is projected to be considerably higher in Europe under this mitigation scenario than the global average, in excess of 2°C and possibly even in excess of 3°C of change projected by 2071-2100, relative to the baseline period.
- There is a considerable spread in absolute regional values of change among the models, independent of scenario. However, the regional and seasonal patterns of change are robust.

This highlights the importance of considering regionally specific data.

The average temperature change in Europe is different from the global average. Importantly, it is noticeably higher in summer, especially in Southern Europe.

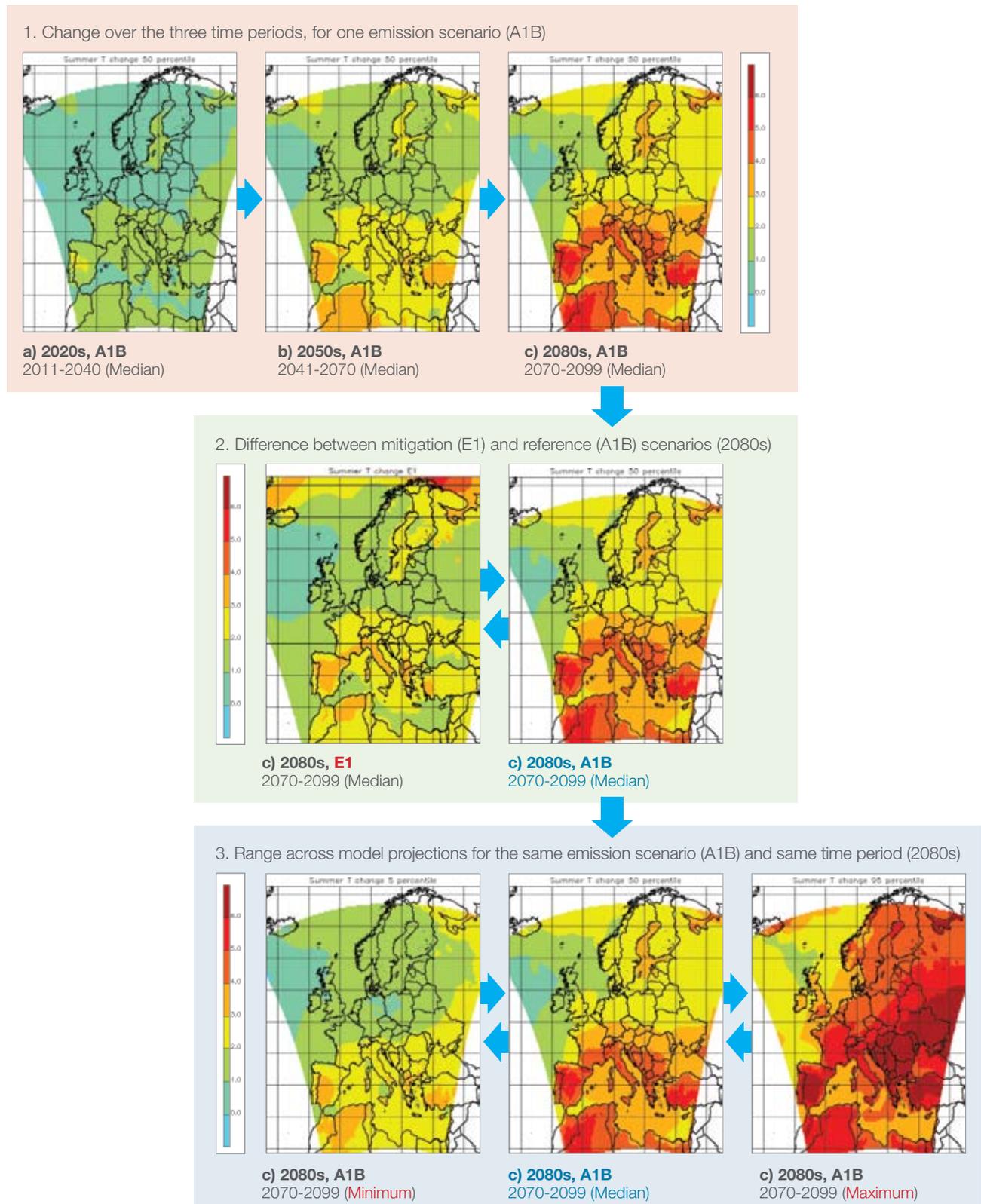
3.3 RCM results: Temperature results for Europe

The ClimateCost study has also used RCM results. The results from these models largely mirror the GCM results for Europe above, but provide a more spatially detailed distribution of change across Europe and have been used to also provide mapped outputs that show country-level changes.

The model output is taken from 11 different regional model simulations at 25 km grid resolution covering the period 1961-2099 produced in the EC RTD FP6 project ENSEMBLES (van der Linden and Mitchell, 2009). These simulations downscale different GCMs for the A1B scenario. There are also now four regionally downscaled simulations for the E1 scenario, which were undertaken after the ENSEMBLES project at a resolution of around 50 km.

For the A1B scenario runs, the 11 RCM projections were analysed. The E1 projections were also assessed, though this included a much smaller number of model runs. A selection of model statistics, reflecting central, low and high model results are presented below. These are used to illustrate key points at a higher spatial resolution than is possible using GCMs.

Figure 4. Change in **surface air temperature** (°C) for summer (June, July and August) in 11 RCM simulations from the ENSEMBLES archive, showing trends 1) over time for the median A1B change from 1961-1990 for 2011-2040, 2041-2070 and 2070-2099, 2) for different scenarios with the A1B and E1 median scenarios for 2070-2099 and 3) the range across the alternative model projections for the same time period and emissions scenario (the central panel shows the central, the left the lowest and the right the highest of the models considered, all for the period 2070-2099 A1B).



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Figure 4 reinforces a number of key results above, with high spatial resolution⁶.

At the top of Figure 4, series 1) the **Change over the three time periods**, shows the increasing temperature signal across the three time-slices considered, 2011-2040, 2041-2070 and 2071-2100, for a single emission scenario (A1B). The red colour scale shows the strong increase in relative temperature over time.

It also demonstrates the strongly inhomogeneous pattern of change across Europe. Substantial warming is expected in all areas for all models. However, the largest changes projected are for land areas of Southern Europe, in particular over the Iberian Peninsula. The absolute magnitude of the warming for these models with the SRES A1B scenario varies across Europe by a factor of around two. Even in the short term, there are potentially large increases in summer warming in Southern Europe.

In the middle of Figure 4, series 2) the **'Difference between the reference and mitigation scenarios'**, the relative change for two alternative scenarios (A1B and E1), are shown for the time period 2071-2100. These reveal that there are important end-of-century differences between the A1B and E1 scenarios, noting these only really start to diverge in the period 2041-2070 (not shown above). Indeed, the projections for the E1 2080s can be seen to be similar – both in magnitude and in spatial distribution - to the projections for A1B for the 2050s⁷.

The bottom of Figure 4, series 3) the **'Range across the model projections'**, shows the low – central – high changes across the 11 models for the A1B scenario in the final time period (2071-2100), showing the large uncertainty range with respect to the magnitude of change.

It should be noted that even though regional simulations at a high spatial resolution should improve the realism of the simulated climate, RCM simulations still have biases compared to the actual observed climate. Therefore, some impact assessment models that are heavily calibrated towards the observed climate need to correct for model bias before input. Bias correction was, for example, used in the ClimateCost flood risk assessment, TPBN3.

4 Precipitation projections

This section presents the precipitation outputs from the climate models used in ClimateCost. It starts with the analysis of global average results, considers the GCM output values for Europe and, finally, assesses the RCM output for Europe.

Precipitation involves more complex local processes than temperature. In this regard, the greater levels of disaggregation in the RCMs potentially provide important information for impact and economic analysis. However, in general, precipitation is less well simulated than temperature and projections are less robust than those for temperature.

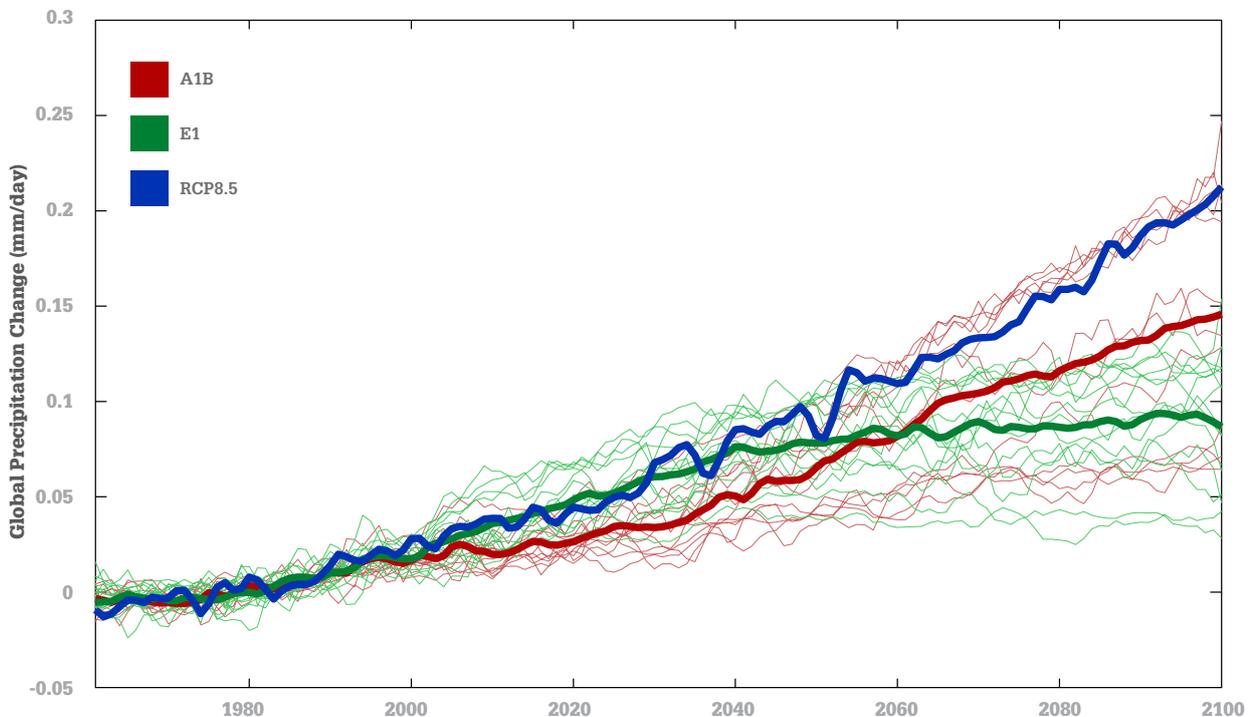
4.1 GCM results: Global average precipitation

The figure below reports the changes in global mean precipitation over the next century for the A1B (red), E1 (green) and RCP8.5 (blue) scenarios. The ensemble values are plotted in bold, alongside the individual model outputs. The figure shows the evolution of precipitation since 1961, plotted relative to the 1961-1990 baseline.

⁶ It is stressed that the 11 available regional runs used do not cover the full uncertainty range of global model forcing, since only a subset of the 12 ENSEMBLES GCM runs are used (and these are themselves a subset of the full international modelling community range).

⁷ Note that the E1 simulations depicted here are from regional models and, therefore, do not show exactly the same results as the global results shown above.

Figure 5. Projected change in global mean precipitation (mm per day) with respect to the 1961-1990 baseline for the A1B (red) and E1 (green) emissions scenarios. Thin lines show individual models, thick red and green lines show ensemble mean and the blue line shows the EC-Earth RCP8.5 model run.



Note that ENSEMBLES does not reflect the full uncertainty captured through the full international model community.

A number of key points are to be noted from Figure 5:

- At the global level, there is an increase in precipitation over time because more water vapour can be contained in the atmosphere, generally intensifying the hydrological cycle. Consistent with this, the ensemble mean results show higher values in the A1B scenario, with increases for 2071-2100 of 0.13 mm per day compared to 0.09 mm per day for E1, both relative to the 1961-1990 baseline (mean values). For the one RCP8.5 run, the 2071-2100 increase is 0.18 mm per day.
- The range around the ensemble mean is very large and increases in later time periods. Unlike temperature, the A1B and E1 scenarios still overlap at the end of the 21st century.

In the case of precipitation, the ensemble-mean increase for E1 is actually greater than that for A1B until around 2060. This is due to the fact that aerosol emissions are reduced more quickly in E1 than they are in A1B. Since aerosol particles in the atmosphere exert a negative forcing by reflecting sunlight, there is a slightly larger climate change in the E1 scenario until around 2040 than that in the A1B scenario.

However, the **global mean values are of relatively little use in indicating changes for Europe** because changes for particular regions and seasons can be considerably larger and more meaningful than global averages where the global average consists of positive and negative changes.

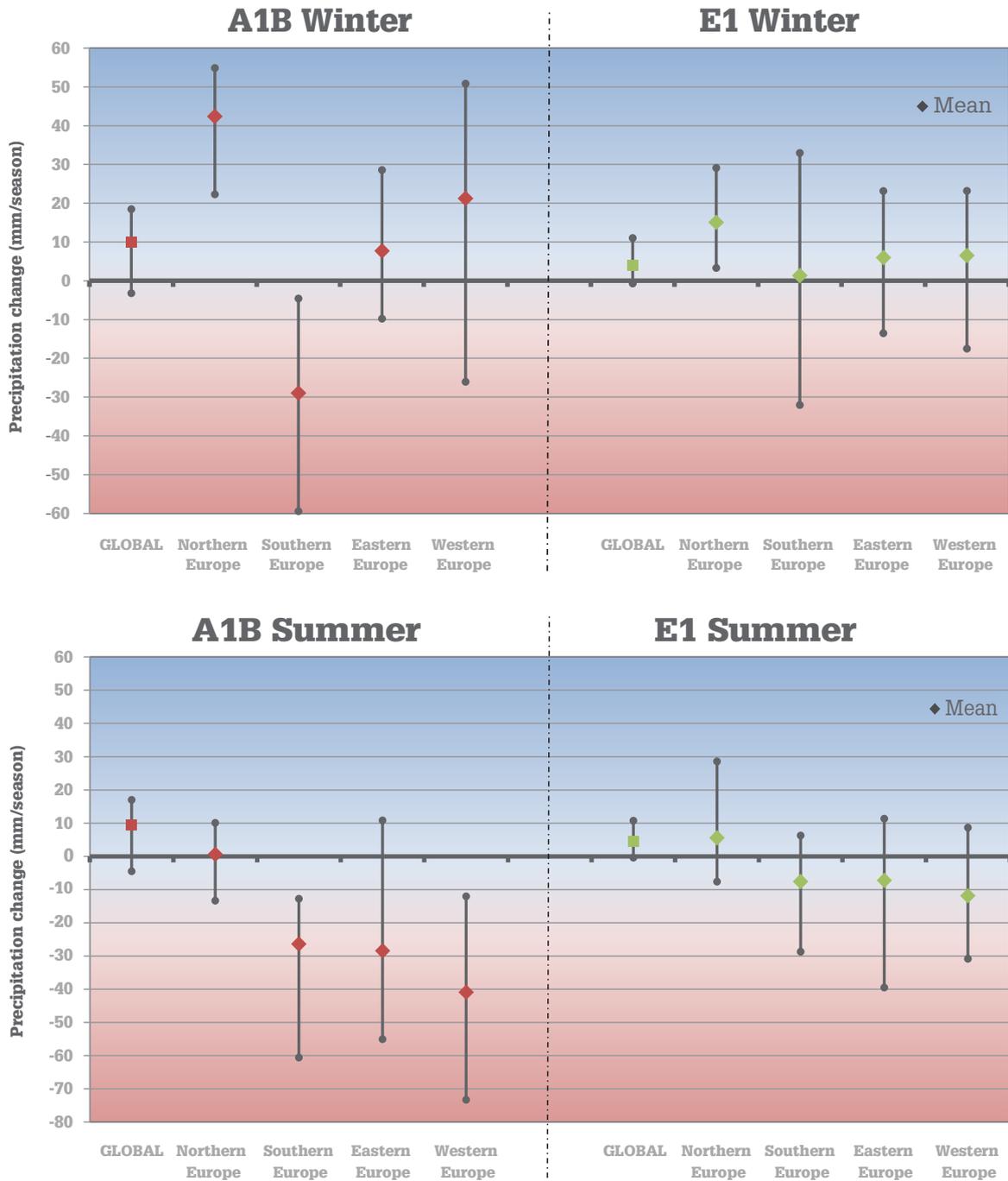
4.2 GCM results for Europe

This section considers the GCM results for Europe, split into four aggregated regions of Northern, Southern, Eastern and Western Europe. The countries included in each of these regions are outlined in the Appendix.

Figure 6 shows the mean change in precipitation in mm/season for winter (December, January and February at the top) and summer (June, July and August at the bottom) in 2071-2100 compared with the 1961-1990 baseline. The ensemble mean and range (minimum and maximum) are shown for each set of scenario runs, A1B and E1, comparing the global and European regional results. The figure shows the mean results, and the low and high range from the ensemble of model runs.

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Figure 6. Projected change in global and European regions for mean precipitation (mm/season) 2071-2100 compared with the 1961-1990 baseline for the A1B and E1 emissions scenarios for winter (December, January and February at the top) and summer (June, July and August at the bottom) showing the range (black dots) and mean ensemble (squares/diamonds) results. The data, and the key to which countries are in which regions, are available in the Appendix.



Note that in interpreting these data, ENSEMBLES does not reflect the full uncertainty captured through the full international model community.

Figure 6 reveals very large differences between the global and European values. A number of key issues are highlighted below:

- Global and European changes differ substantially across the projections, even **in terms of the direction of change**. The results also show major differences in precipitation change within Europe (i.e. between Southern and Western Europe in winter).
- The results show the likely **increase** in precipitation in Northern and Western Europe in winter, particularly under the A1B scenario (top left). However, there is a **decrease** in precipitation in winter for Southern Europe, though the change is of uncertain sign or close to zero under the E1 scenario.

The results show a strong drying trend for the A1B and E1 scenarios in summer in Southern, Eastern and Western Europe (bottom), although less markedly for the E1 projections.

4.3 RCM results: Precipitation results for Europe

The ClimateCost study has also used RCM results. These are particularly valuable for the changes in precipitation as they provide more spatial detail of change across Europe. The RCM results have been used to provide mapped outputs that show country level changes.

As above, ClimateCost used RCM projections for Europe for A1B and E1 (from ENSEMBLES).

For the A1B scenario runs, the 11 RCM projections were analysed. The E1 projections were also assessed, though this included a much smaller number of model runs. A selection of model statistics, reflecting central, low and high model results are presented in Figure 7. These are used to illustrate key points at a higher spatial resolution than is possible for GCMs.

Figure 7 also shows results for relative change in summer precipitation. The results confirm the general conclusions based on the GCMs, but provide much greater information on the spatial distribution of changes, which are particularly important in the case of precipitation.

At the top of Figure 7, series 1) the '**Change over the three time periods**', the relative precipitation signal can be seen for 2011-2040, 2041-2070 and 2071-2100 – with the red colour scale indicating a decrease and the green an increase in seasonal precipitation. There are strong differences in the precipitation changes over time for Europe with an

The projections of rainfall show large differences by season across Europe. Nonetheless, there are some robust patterns of change, with wetter winters for Northern Europe and drier summers for Southern Europe.

increasing amplitude through the three time periods. There is also a strong spatial pattern of change across Europe, which is similar in all periods. The regional variation of GCM results reported in Figure 6 is revealed to be a clear north-south gradient.

The projections show substantial drying in Southern Europe. Summer precipitation could well be reduced to half the current value in Southern Europe by the end of the century, according to the ENSEMBLES simulations.

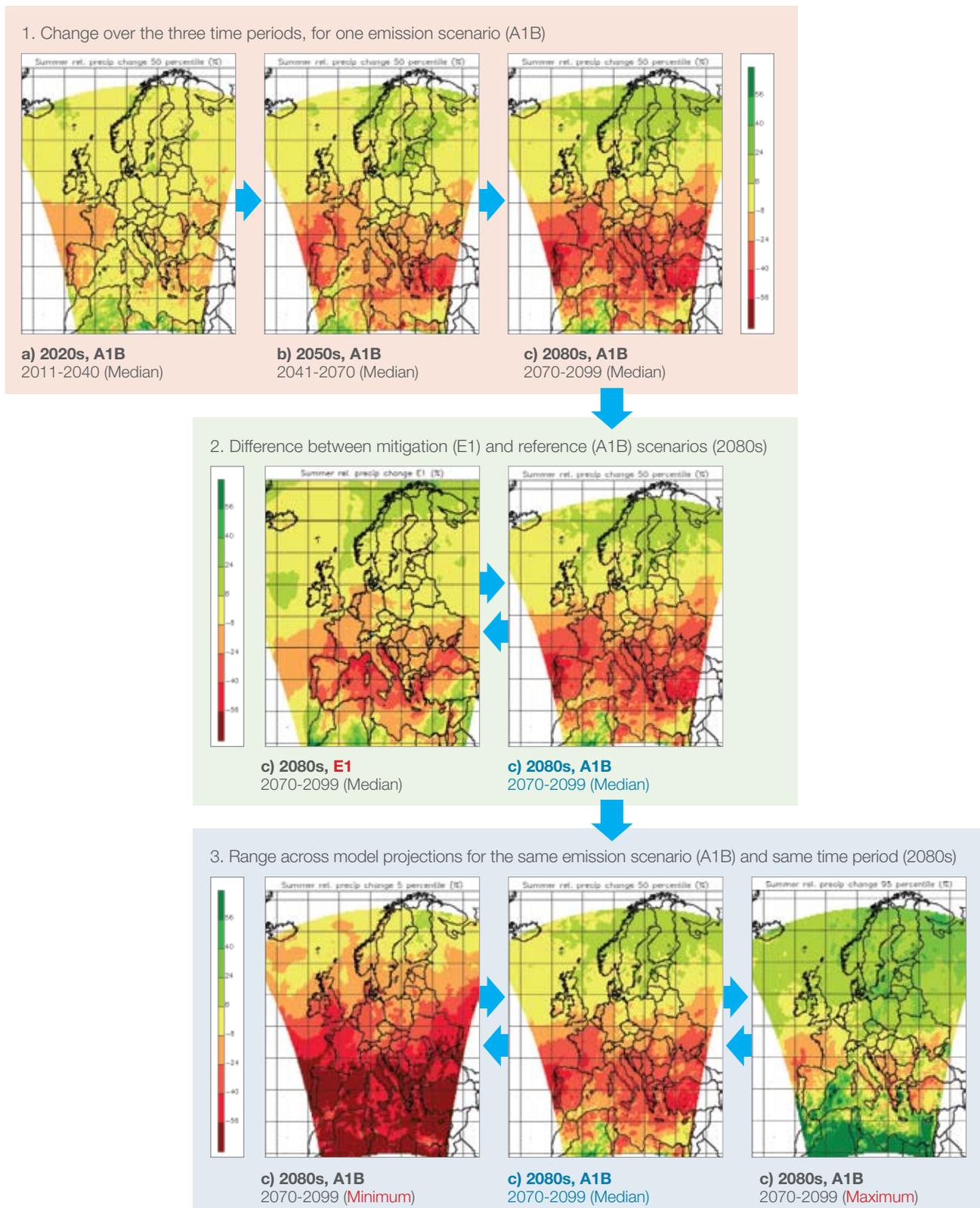
In the middle of the figure, series 2) the '**Difference between the reference and mitigation scenario**', the relative change for two alternative scenarios (i.e. A1B and E1) are shown for the time period 2071-2100. These reveal there are important end-of-century differences between the A1B and E1 scenarios, although the scenarios only really start to diverge in the period 2041-2070 (mid-century, not shown). By the later time period (2070-2099), there are major differences. Indeed, the projections for the E1 2080s are similar to the projections for A1B for the 2050s.

The bottom of the figure, series 3) the '**Range across the model projections**', shows the low – central – high range across the 11 models for the A1B scenario in the final time period (2071-2100), showing the very high uncertainty in the range of change. In many areas of Europe, the direction of the change is different across the range of model projections. **This uncertainty is critical for the consideration of adaptation.**

Furthermore, while all models indicate drying in the south and wetting in the north, the position of the exact dividing line at which the positive or negative climate change signal starts is not certain - it varies over a broad band somewhere between mid-Scandinavia and the Alps. This is extremely important for the consideration of adaptation in these regions.

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Figure 7. Relative change in **summer precipitation** (%) for summer (June, July and August) in 11 RCM simulations from the ENSEMBLES archive, showing trends 1) over time for the median A1B change from 1961-1990 for 2011-2040, 2041-2070 and 2070-2099, 2) for different scenarios with the A1B and E1 median scenarios for 2070-2099 and 3) across the alternative model projections for the same time period and emissions scenario (the central panel shows the central, the left the lowest and the right the highest of the models considered, all for the period 2070-2099 for A1B).



The same plots for winter precipitation are shown in Figure 8.

Again, there are strong variations 1) over time, 2) between alternative emissions scenarios and 3) for individual climate-model projections for the same emissions scenario.

There is a pattern of increasing winter precipitation in the north and north-east, and minor decreases in the southernmost part of Europe in all periods.

Again, for the 2080s, the comparison across the model projections shows that the exact position of the dividing line between positive and negative signal varies between Spain/Italy and Northern Germany.

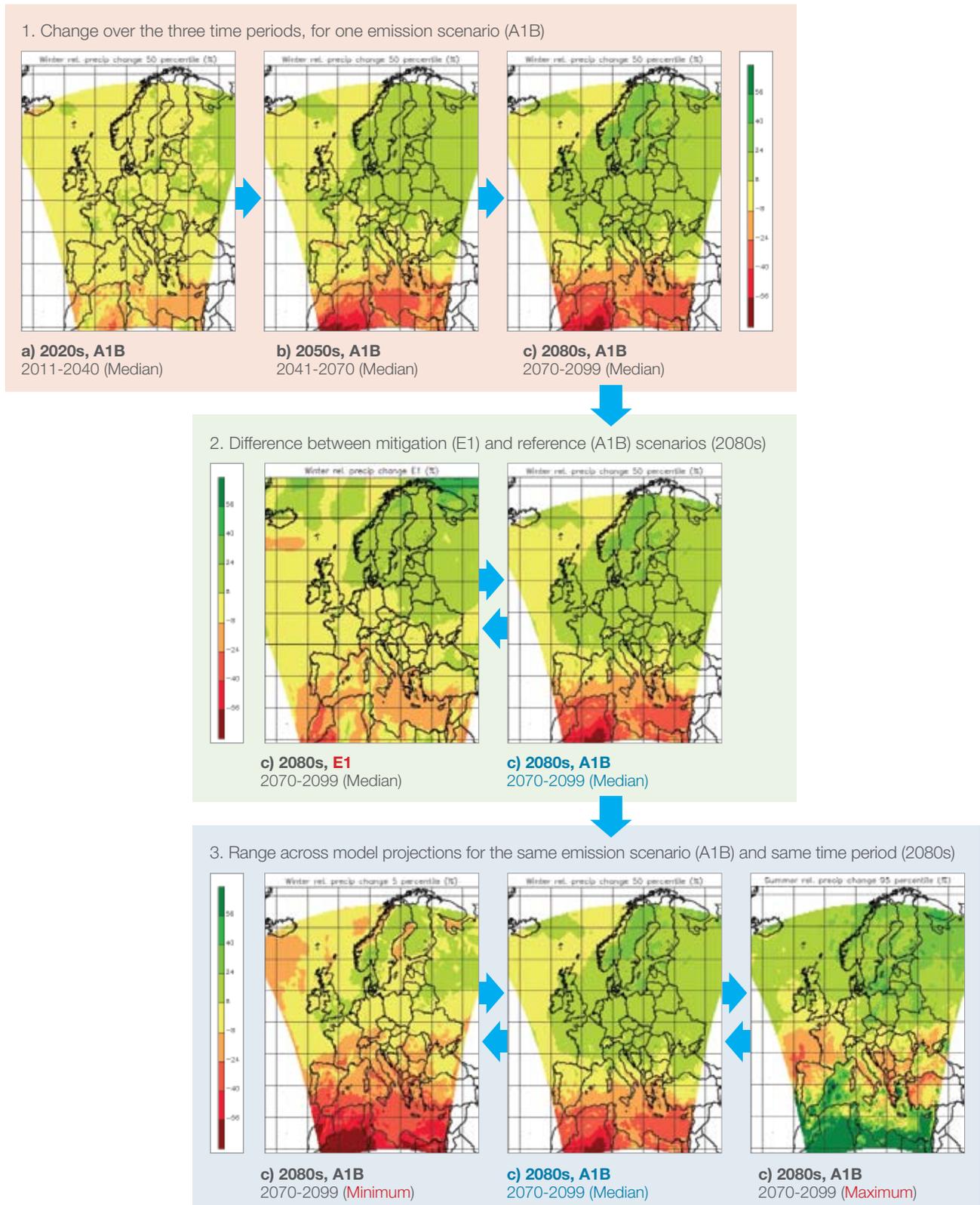
4.4 Other parameters

As well as the consideration of temperature and precipitation, the information from the climate models has been used to provide additional information for ClimateCost, consistent with the input data required for the impact models. This includes, for example, cooling and heating degree days, which are used in the energy analysis. These are reported in TPBNs (the sector results).

There are projected changes in precipitation across Europe, but the magnitude of the change is uncertain in many regions and, in some cases, even the direction of change is unknown.

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Figure 8. Relative change in **winter precipitation** (%) for winter (December, January and February) in 11 RCM simulations from the ENSEMBLES archive, showing trends 1) over time for the median A1B change from the 1961-1990 baseline for 2011-2040, 2041-2070 and 2070-2099, 2) for different scenarios with the A1B and E1 median scenarios for 2070-2099 and 3) across the alternative model projections for the same time period and emissions scenario (the central panel shows the central, the left the lowest and the right the highest of the models considered, all for the period 2070-2099 for A1B).



5 Quantification of the uncertainty in the climate model results

As highlighted in sections 3 and 4, there are substantial differences in the temperature and precipitation results from the different models. As well as the uncertainty associated with these individual parameters, it is also extremely useful to consider the uncertainty when they are combined because this leads to a much greater overall spread of plausible futures. Information on this can be presented with plots that combine the changes of temperature and precipitation.

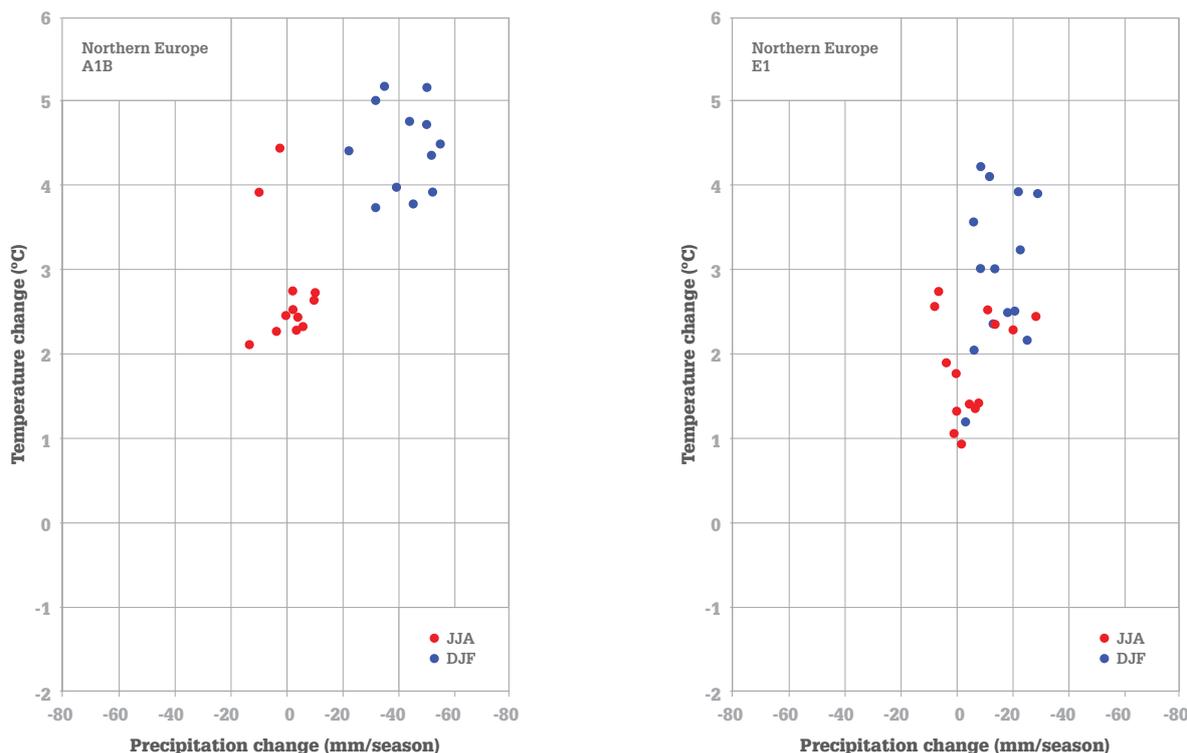
Examples for the four sub-regions of Europe are presented in Figures 9 to 12. They show the inter-model spread of change from the GCMs for 2071-2100 for mean winter (blue dots) and summer (red dots) for temperature (vertical axis) and precipitation (horizontal axis). Each dot represents a different model projection for the same emissions scenario.

This shows that the regional uncertainty is very large. The figures show uncertainty in the direction as well as

magnitude of change, particularly for winter precipitation. At the global level, the direction of change is more robust, showing an increase in temperature and precipitation for the A1B and E1 emissions scenarios (see figures in Section 3 and 4).

As an illustration of the size of the potential change, the ensemble-mean winter precipitation change for Southern Europe under the E1 scenario is +4 mm per season. However, the model range is -31 mm to +34 mm per season. Thus, even the sign of the change is uncertain. Uncertainties in precipitation projections are even greater for Western Europe. For the A1B scenario, the mean-ensemble winter change is +24 mm per season, with a range across the models of -26 mm to +51 mm per season.

Figure 9. Projected changes for Northern Europe in mean temperature (°C, vertical axis) and precipitation (mm per season, horizontal axis) for 2071-2100 minus the 1961-1990 baseline for the A1B (left) and E1 (right) emissions scenarios for winter (December, January and February in blue) and summer (June, July and August in red).



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Figure 10. Projected changes for Southern Europe in mean temperature ($^{\circ}\text{C}$, vertical axis) and precipitation (mm per season, horizontal axis) for 2071-2100 minus the 1961-1990 baseline for the A1B (left) and E1 (right) emissions scenarios winter (December, January and February in blue) and summer (June, July and August in red).

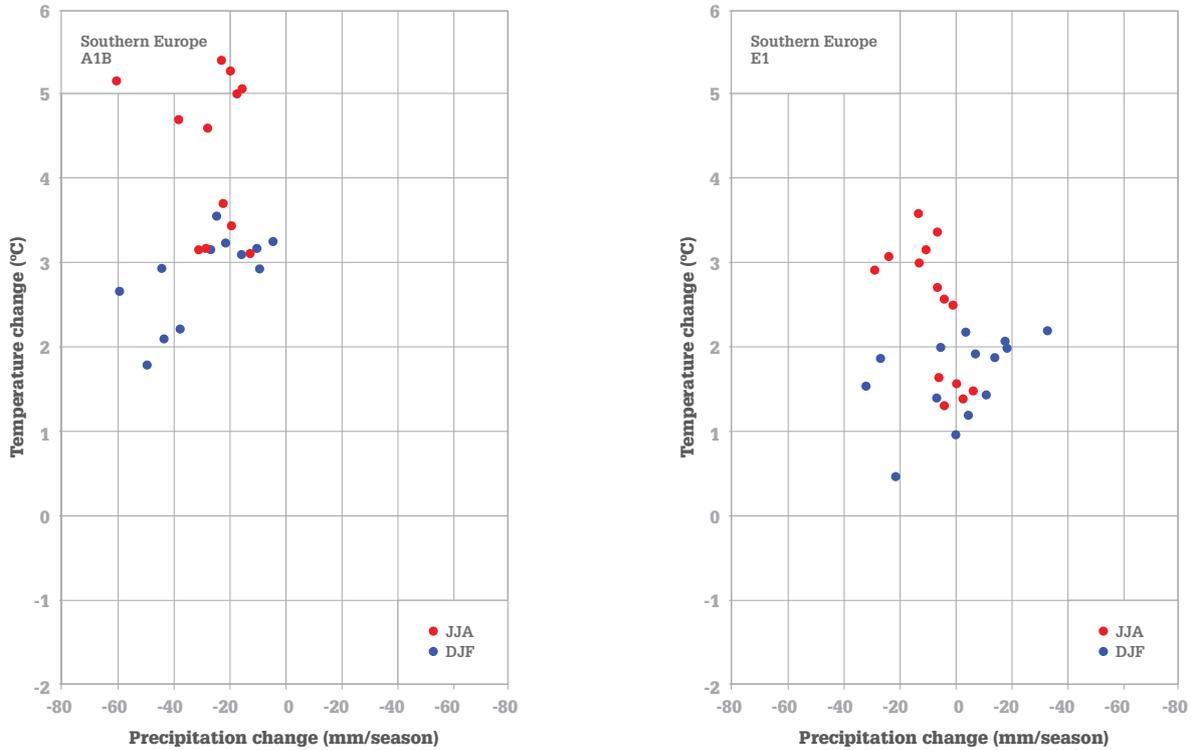


Figure 11. Projected changes for Eastern Europe in mean temperature ($^{\circ}\text{C}$, vertical axis) and precipitation (mm per season, horizontal axis) for 2071-2100 minus the 1961-1990 baseline for the A1B (left) and E1 (right) emissions scenarios for winter (December, January and February in blue) and summer (June, July and August in red).

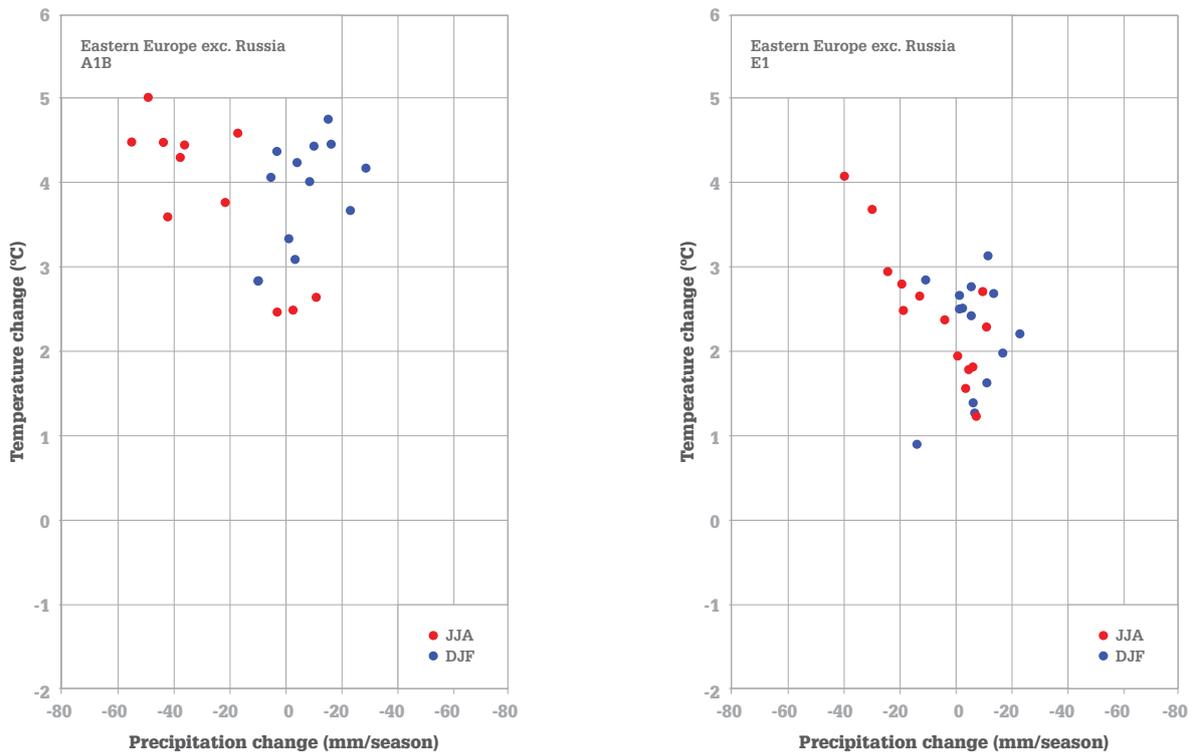
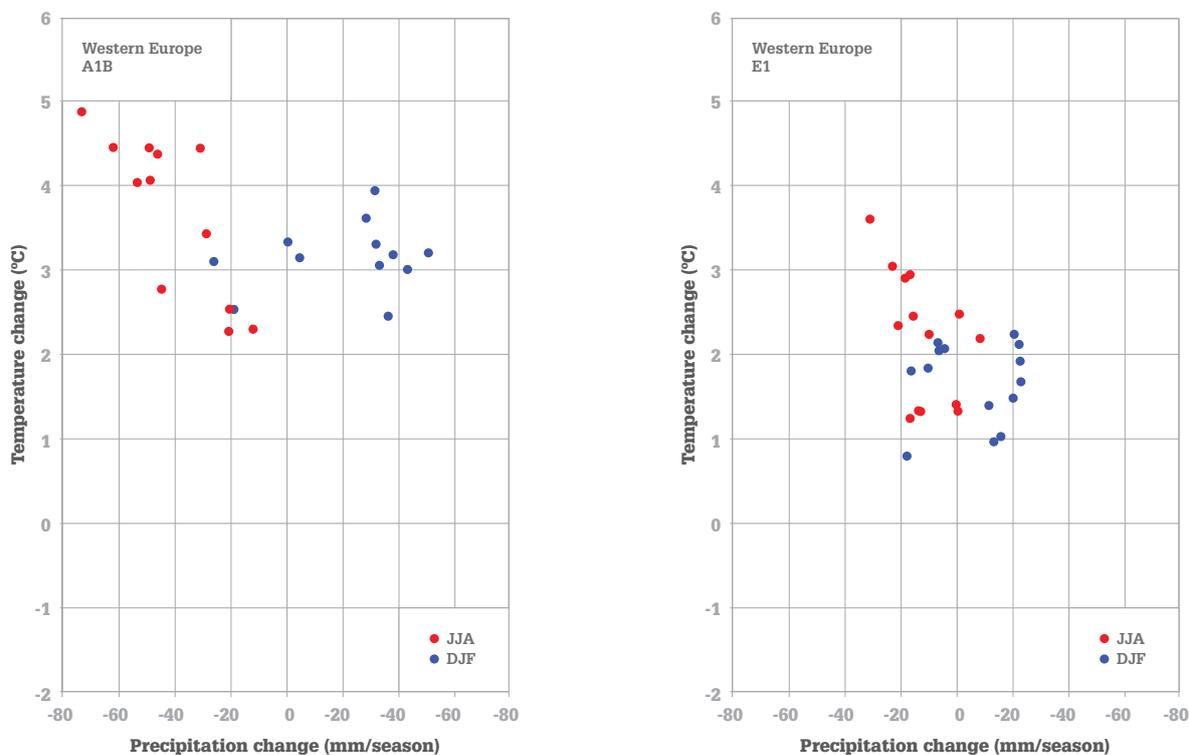


Figure 12. Projected changes for Western Europe in mean temperature (°C, vertical axis) and precipitation (mm per season, horizontal axis) for 2071-2100 minus the 1961-1990 baseline for the A1B (left) and E1 (right) emissions scenarios for winter (December, January and February in blue) and summer (June, July and August in red).



Note that in interpreting these data, ENSEMBLES does not reflect the full uncertainty captured through the full model community.

See the Annex for a key to countries included by region.

The projections of future climate change are uncertain. It is essential to recognise and to try to quantify this uncertainty, not to ignore it. There is also a need to plan robust strategies to prepare for uncertain futures, rather than using uncertainty as a reason for inaction.

Uncertainty is fundamental to ClimateCost because the variation in climate change due to a variation in carbon emissions is exactly what leads to the need for mitigation and adaptation studies. This is the reason that three different emission scenarios have been studied in the project and that, as far as possible, a range of model projections has been considered for each impact category.

The range of model results highlights the uncertainty in projecting future climate change. This leads to wide variations in the level of damage costs. Perhaps, more importantly, it also affects the costs and benefits of adaptation – and even potentially the type of adaptation response. It is essential to recognise and try to quantify this uncertainty, not to ignore it. In ClimateCost, this has been addressed by the use of multi-model analysis for impact assessment. Following on from this, there is a need to plan robust strategies to prepare for uncertain futures, rather than using uncertainty as a reason for inaction. This is also feeding through to the consideration of adaptation, where a framework of decision-making under uncertainty is being considered.

6. Acknowledgements

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Appendix

The data for the figures in the note – for global and Northern, Southern, Eastern and Western Europe, are shown below.

Actual climate change		Temperature (°C)		Precipitation (mm/season)	
Scenario	Model run	Winter (DJF)	Summer (JJA)	Winter (DJF)	Summer (JJA)
A1B Global	Ensemble Minimum	2.52	2.20	-3.21	-4.51
A1B Global	Ensemble Mean	3.01	2.73	9.53	8.57
A1B Global	Ensemble Maximum	3.52	3.17	18.48	17.00
E1 Global	Ensemble Minimum	0.77	0.62	-0.70	-0.42
E1 Global	Ensemble Mean	1.53	1.40	4.00	4.34
E1 Global	Ensemble Maximum	2.09	1.85	11.03	10.73
A1B N Eur	Ensemble Minimum	3.74	2.12	22.29	-13.37
A1B N Eur	Ensemble Mean	4.46	2.74	42.37	0.58
A1B N Eur	Ensemble Maximum	5.17	4.44	54.88	10.07
E1 N Eur	Ensemble Minimum	1.20	0.94	3.30	-7.64
E1 N Eur	Ensemble Mean	2.98	1.86	15.10	5.56
E1 N Eur	Ensemble Maximum	4.22	2.74	29.12	28.58
A1B S Eur	Ensemble Minimum	1.78	3.10	-59.45	-60.61
A1B S Eur	Ensemble Mean	2.84	4.31	-28.97	-26.40
A1B S Eur	Ensemble Maximum	3.55	5.39	-4.57	-12.78
E1 S Eur	Ensemble Minimum	0.46	1.30	-32.04	-28.73
E1 S Eur	Ensemble Mean	1.65	2.44	1.32	-7.64
E1 S Eur	Ensemble Maximum	2.19	3.58	32.97	6.26
A1B E Eur	Ensemble Minimum	2.84	2.47	-9.78	-55.08
A1B E Eur	Ensemble Mean	3.95	3.95	7.70	-28.46
A1B E Eur	Ensemble Maximum	4.75	5.09	28.57	10.81
E1 E Eur	Ensemble Minimum	0.90	1.23	-13.53	-39.53
E1 E Eur	Ensemble Mean	2.21	2.45	6.00	-7.25
E1 E Eur	Ensemble Maximum	3.13	4.08	23.16	11.34
A1B W Eur	Ensemble Minimum	2.45	2.28	-26.06	-73.33
A1B W Eur	Ensemble Mean	3.16	3.67	21.22	-40.90
A1B W Eur	Ensemble Maximum	3.95	4.88	50.84	-12.06
E1 W Eur	Ensemble Minimum	0.80	1.25	-17.51	-30.87
E1 W Eur	Ensemble Mean	1.68	2.20	6.49	-11.85
E1 W Eur	Ensemble Maximum	2.24	3.61	23.19	8.64

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The countries included in each region are as follows

Western Europe (W EUR)	
AT	Austria
BE	Belgium
FR	France
DE	Germany
LI	Liechtenstein
LU	Luxembourg
MC	Monaco
NL	Netherlands
CH	Switzerland

Northern Europe (N EUR)	
DK	Denmark
EE	Estonia
FI	Finland
IE	Ireland
IS	Iceland
LV	Latvia
LT	Lithuania
NO	Norway
SE	Sweden
UK	United Kingdom

Southern Europe (S EUR)	
AL	Albania
AD	Andorra
BA	Bosnia and Herzegovina
HR	Croatia
GR	Greece
IT	Italy
FYR MK	Macedonia
MT	Malta
PT	Portugal
SM	San Marino
SI	Slovenia
ES	Spain
YU	Yugoslavia

Eastern Europe (E EUR)	
BG	Bulgaria
CZ	Czech Rep
HU	Hungary
MD	Moldova, Rep
PL	Poland
RO	Romania
SK	Slovakia

Further information

To find out more about ClimateCost, please visit:
www.climatecost.eu

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