Effects of 2°C Warming

IMPACT2C modelling results: climate change and sea-level rise from a 2°C climate

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Summary

The IMPACT2C project provides information on the potential impacts of 2°C global warming for Europe and for three highly vulnerable non-European regions.

To help summarise the result of the project, a series of Policy Briefing Notes are being produced. This note – Briefing note 2 – provides a summary of the detailed regional climate modelling results for Europe. The note is framed around a series of questions concerning the international goal to limit global warming to 2°C relative to pre-industrial levels.

When might we hit 2°C?

The IMPACT2C project has analysed the RCP (Representative Concentration Pathways) to see when global mean warming might exceed the 2°C goal, relative to pre-industrial levels. With the exception of the deep mitigation RCP2.6 scenario, the results indicate we are likely to pass the goal before the middle of the century.

The analysis indicates that under a high emission scenario (RCP8.5), the 2°C goal will be exceeded in the next 30 years, at around 2040. Even under the RCP4.5 stabilisation scenario, the goal will be exceeded before 2050. However, these are central (mean) estimates, and there is a considerable range around these, reflecting projections from different climate models. Indeed, the models that project faster levels of warming indicate that the 2°C goal could be exceeded as early as 2030, under both RCP4.5 and 8.5 scenarios.

These results have major implications for the speed and urgency of the current policy discussions. It also indicates that early adaptation is likely to be needed to address the changes anticipated over the next 20 to 30 years.

What does 2°C of global change mean for the climate of Europe?

The project has analysed regional climate modelling results for Europe, using the EURO-CORDEX simulations. This provides information on the warming that could be experienced in Europe at 2°C of global warming.

The analysis finds that Europe will warm more than the global average, i.e. much of Europe will experience more than 2°C of warming (relative to pre-industrial levels) even if the global goal is achieved. This effect is very large in some regions. At 2°C of global mean warming, the Iberian Peninsula and other parts of the Mediterranean could experience 3°C of warming in summer, and Scandinavia and the Baltic 4°C of warming in winter. These areas will also experience 2°C of local warming much earlier in time than the global average.

There are also increases in extreme events projected for Europe for 2°C of global change. The analysis projects large increases in daily maximum temperature over parts of Southern and South-Eastern Europe and increases in heavy precipitation across all of Europe. These will cause more frequent and severe high impact events.

A key finding is that the pattern of warming and extreme events in Europe increases relative risks, compared to a situation where Europe warms equally. This is of high policy relevance: even if the 2°C goal is achieved, Europe will experience strong distributional impacts. A 2°C world is therefore not benign for Europe and further work to explore these hotspots and to advance early adaptation is needed.

What is the rate of climate change, and how does this affect potential adaptation?

The rate of climate change is important for many impacts and it also influences the ability to adapt effectively. Historical rates of global change have averaged just over 0.1°C warming per decade. However, analysis in the project indicates that these will increase rapidly in the period up to 2°C of global warming, with a median rate of warming in Europe of 0.25°C per decade under RCP4.5 and 0.3°C per decade under RCP8.5.

For regions of Europe that warm faster than the European average, these changes are even more pronounced, for example Scandinavia could experience warming of around 0.4°C per decade (median), and as much as 0.5°C per decade under some model projections.

What does 2°C mean for sea level rise?

The IMPACT2C project has looked at the global sea level rise projections for the RCP projections. The analysis indicates that even if surface temperatures stabilise and the 2°C goal is achieved, sea-level rise will continue over the century. The earlier 2°C is reached, the greater the potential for higher levels of sea-level rise.

What does 2°C of Warming Mean for Water?

Climate change is projected to have a significant impact on global and regional water cycles. The IMPACT2C project has assessed the impacts of climate change on the terrestrial water cycle in Europe for 2°C of global warming, relative to pre-industrial levels.The analysis considered the uncertainty around the future climate, using the European-wide downscaled simulations, and fed these into five different hydrological models.

The results show a projected increase in mean annual river flow in the east and the far north of Europe, but decreases in parts of the Mediterranean.However, there are seasonal patterns to these changes.The models indicate higher river flow in most of Europe in winter, especially in Scandinavia.The summer patterns are more complex, with a reduction in some parts of the south of Europe, as well as in the Alps and the Norwegian and Swedish mountains.This latter change is due to a projected reduction in summer snow melt in mountain regions.The analysis also shows an increase in flood risks for 2°C global warming for most of Europe, linked to an increase in heavy precipitation events, with floods projected to become more severe and frequent.

At the same time, there are potential changes in drought intensity and duration, in terms of low flows in rivers (streamflow drought) and soil moisture levels (agricultural drought). Low flow droughts are important for water availability for power production, water supply, irrigation and river ecosystems, while low soil moisture levels affect agricultural production, demand for irrigation water and land ecosystems. These changes also show a very strong distributional pattern across Europe. Low flow (streamflow drought) periods are projected to become more intense and last longer in the Mediterranean, France and parts of the British Isles. Alongside this, there are projected decreases in soil moisture levels in the Mediterranean.These combined changes indicate potential increases in water deficits for a number of water-dependent sectors in Southern Europe. In particular where soil moisture and streamflow drought coincide, irrigation demands may not be met, resulting in reduced agricultural production.

Overall, the results show that potentially important changes to water resources will arise in Europe even in a + 2°C warmer world, though there are differentiated patterns of change across the continent.Importantly, many of the projected changes will increase the existing risks today, notably for the areas of current flood risk in Central and Eastern Europe and water stress in the south.

Introduction

In Europe and internationally, there is an ambition to limit global warming to 2°C relative to pre-industrial levels. This goal is in broad alignment with the objective of the United Nations Framework Convention on Climate Change (UNFCCC) to prevent dangerous anthropogenic interference with the climate system.

The IMPACT2C project (see box) aims to provide information and evidence on the impacts of 2°C global warming for Europe and other key vulnerable global regions, and thus provide policy relevant evidence. This includes detailed analysis using regional climate models and impact assessment models.

To help summarise and disseminate the results and information from the project, a series of Policy Briefing Notes are being produced. This Policy Brief (Number 2) provides a summary of the main climate modelling findings of the project. The note provides discussion around a number of key questions that are relevant in the context of the 2°C goal. These are:

- When might we hit 2°C?
- What does 2°C of global change mean for Europe?
- What is the rate of climate change, and how does this affect potential adaptation?
- What does 2°C mean for European vulnerability hot-spots?
- What does 2°C mean for sea-level rise?

The IMPACT2C Project

Political discussions on the European goal to limit global warming to 2°C need to be informed by the best available science on projected impacts and possible benefits. IMPACT2C enhances knowledge by quantifying climate change vulnerability and impacts, using a clear and logical structure. It also considers the economic costs of these impacts, as well as potential responses, within a pan-European sector-based analysis. The project uses a range of models within a multi-disciplinary international expert team and assesses effects on water, energy, infrastructure, coasts, tourism, forestry, agriculture, ecosystems services, and health and air quality-climate interactions. IMPACT2C introduces a number of key innovations.

First, harmonised socio-economic assumptions/scenarios are being developed, using the new RCP and SSPs (Representative Concentration Pathways and Shared Socio-economic Pathways), to ensure that both individual and cross-sector assessments are aligned to the 2°C scenario for both impacts and adaptation. Second, a core theme of uncertainty has been developed to integrate uncertainties from the climate projections, socio-economic scenarios and impact models within and across sectors. In so doing, analysis of adaptation responses under uncertainty will be enhanced.

Finally, a cross-sectoral perspective is adopted to look at linkages between sectors, to capture direct and indirect effects and to look at areas of Europe that are particularly vulnerable (hot-spots) even to 2°C of warming.

While the focus is on Europe, a number of case studies are being developed to investigate some of the world’s most vulnerable regions, i.e. those most at risk under 2°C of warming, with analysis in Bangladesh, Africa (Nile and Niger basins) and the Maldives.

The IMPACT2C aims to integrate and synthesize the findings for awareness-raising and to communicate to a wide audience, relevant for policy.

When might we hit 2°C?

The European Union (CEU, 1996: 2004; CEC, 2005; 2007) has set a goal for limiting global warming to 2°C relative to pre-industrial levels, recognising that the failure to do so could put the world at substantial risk of dangerous climate change. These concerns have been recognised by the G8 (G8, 2007), and at the UNFCCC Conference of the Parties in Cancun (UNFCCC, 2010). At the latter, the Parties agreed to a goal to reduce global greenhouse gas emissions so as to hold the increase in global average temperature below 2°C above pre-industrial levels, and to consider lowering the goal to 1.5°C in the near future. However, there has already been an increase of about 0.85°C over the period 1880–2012 (IPCC, 2013), and at the current time, international negotiations have had modest success: current commitments and pledges are therefore not on track to achieve the 2°C goal (IEA, 2012: UNEP 2013).

Against this background, a useful question to ask is when might we exceed the 2°C global goal? The answer is informative in highlighting the further implications of inaction. However, this question is actually quite difficult to answer, because it depends on socio-economic and emission pathways over the next few decades, and how the climate responds to these (i.e. to the forcing from emissions).

The IMPACT2C project set out to investigate this question – and to examine uncertainty – using existing climate model results. An initial analysis (Vautard et al. 2014) used the previous global socio-economic and emissions scenarios, i.e. the SRES (Special Report on Emissions Scenarios).

However, these scenarios have been replaced by the Representative Concentration Pathways (RCPs), which were used in the IPCC 5th Assessment Report. These include a set of four new pathways developed for the climate modelling community as the basis for long-term and near-term modelling experiments. These scenarios cover the range from scenarios consistent with the 2°C goal to high emission futures (see box).

The Representative Concentration Pathways

The RCPs are different to the SRES, in that they are not unique and self-consistent socio-economic scenarios and emission pathways over time. The four RCPs span a range of possible future emission trajectories over the next century, with each scenario corresponding approximately to a level of total radiative forcing (W/m^2) in the year 2100.

The first RCP is a deep mitigation scenario that leads to a very low forcing level of 2.6 W/m^2 (RCP2.6), only marginally higher compared to today's situation (2.29 W/m^2, IPCC, 2013). It is a "peak-and-decline" scenario and is representative of scenarios that lead to very low greenhouse gas concentration levels. This scenario has a good chance of achieving the 2°C goal.

There are also two stabilization scenarios (RCP4.5 and RCP6). RCP4.5 is a medium-low emission scenario in which forcing is stabilised by 2100. It is similar to the A1B scenario from the SRES. It is stressed that even in this scenario, it is likely that annual emissions (of CO_2) will need to sharply reduce in the second half of the century, and thus it is likely to require significant climate policy (mitigation).

Finally, there is one rising (non-stabilisation) scenario (RCP8.5), which is representative of a non-climate policy scenario, in which greenhouse gas emissions carry on increasing over the century and end up with very high concentrations by 2100.

These scenarios corresponds to CO_2 concentrations reaching 421 ppm (RCP2.6), 538 ppm (RCP4.5), 670 ppm (RCP6.0), and 936 ppm (RCP 8.5) by the year 2100 (IPCC, 2013).

Source: van Vuuren et al, 2011: IPCC, 2013.

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The new RCP scenarios were used in the recent Fifth Assessment Report of the IPCC (IPCC, 2013).

The IMPACT2C project has looked at the global climate model simulations for these new scenarios, from the Coupled Model Intercomparison Project Phase 5 (CMIP5) results, to look which year the 2°C goal could be exceeded. This compares results from the available model runs to look at the central year (in a 30–year time window) when the goal is exceeded for each RCP.

The results are first shown for the RCP2.6 mitigation scenario. This shows that there is a good chance that the 2°C goal will be achieved under this scenario, as more than half the modelled projections do not reach the goal. It is noted, however, that even under this deep mitigation scenario, some models still project higher levels of warming and thus exceed the goal.

The analysis has then considered the higher RCP4.5 stabilisation scenario, and the non-stabilisation RCP8.5 scenario.

The results are striking. The mean of the model simulations indicates that the 2°C goal could be exceeded by around 2040 under RCP8.5 (only thirty years away) and 2049 under RCP4.5. There is a considerable spread across the models. Importantly, models that have faster warming indicate the 2°C goal could be exceeded by 2030 under both (RCP4.5 and 8.5) scenarios, only fifteen years away. Moreover, even the model simulation with the slowest rate of warming shows that the 2°C goal will be exceeded before 2060 under high (RCP8.5) pathways.

This has major implications for the speed and urgency of the current policy discussions. It also indicates that early adaptation is likely to be needed to address the changes already anticipated over the next 20 to 30 years.

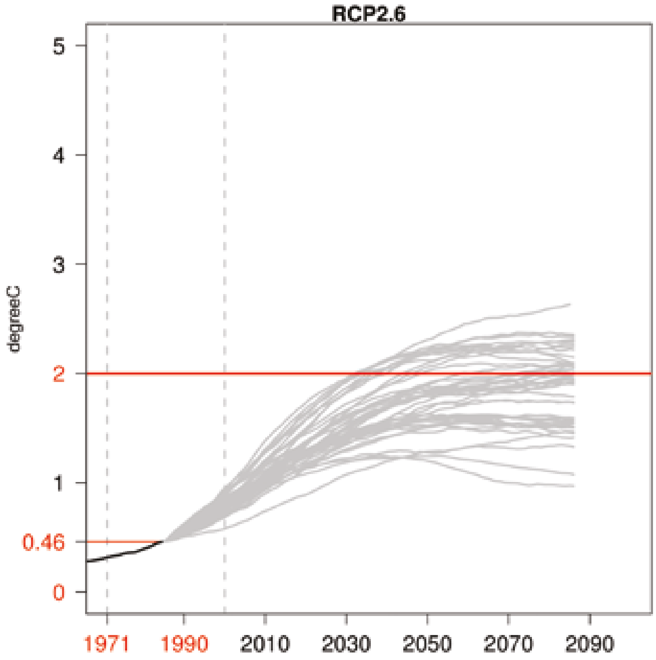

Figure 1. When do we hit 2°C under an RCP2.6 scenario?

Analysis of global temperature change and the 2°C goal. Observed historical (black line) and future projections from different Global Climate Models (GCMs) based on the RCP2.6 scenario. Time series are smoothed using a 30-year running mean. The 2 °C threshold is marked in red.

Source: Andreas Gobiet and Thomas Mendlik, 2014.

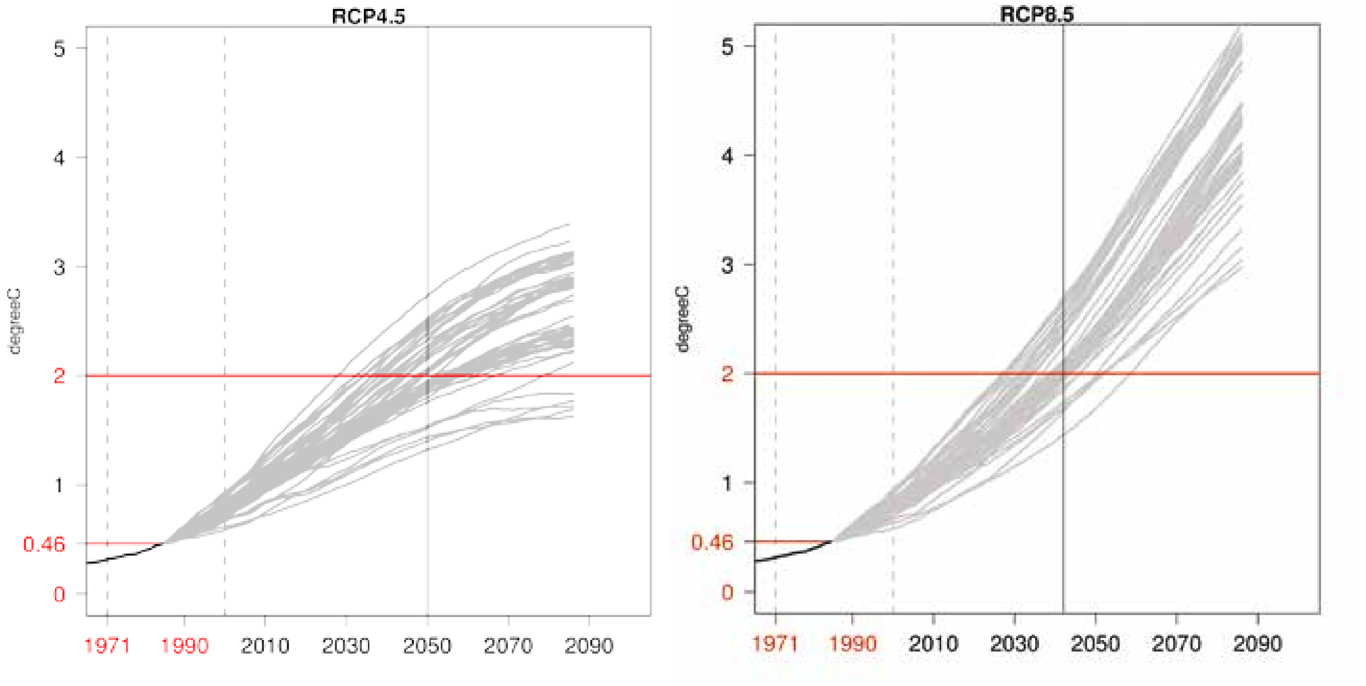

Figure 2. When might we hit 2°C under medium-low (RCP4.5) and high (RCP8.5) emission scenarios?

Analysis of global temperature change and the 2°C goal. Observed historical (black line) and future projections from different Global Climate Models (GCMs) based on the RCP4.5 and 8.5 scenario. Time series are smoothed using a 30-year running mean. The 2°C goal is marked in red, and the grey line shows the time period when the middle of the 30 year period exceeds the goal.

Source: Andreas Gobiet and Thomas Mendlik, 2014.

Key message. An analysis of climate model projections for the new RCP scenarios indicates that the 2°C goal could be exceeded in the next 30 years, at around 2040 under a high emission (RCP8.5) scenario, and just before 2050 under the RCP4.5 stabilisation scenario. However, there is a considerable range around these mean estimates, as projected from different climate models.

Under the worst case scenario, the 2°C goal could be exceeded by around 2030, under both RCP4.5 and 8.5 scenarios. This has major implications for the speed and urgency of the current policy discussions. It also indicates that early adaptation is likely to be needed to address the changes anticipated over the next 20 to 30 years.

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What does 2°C of global warming mean for Europe?

Climate change does not happen equally across the world. In terms of temperature, 2°C of average warming at the global level translates into different levels of warming for Europe, and also different levels of warming across Europe.

A critical question is therefore how much Europe warms under a global 2 degrees scenario, and whether individual regions and countries will experience more or less warming.

To answer this question, the IMPACT2C project considered a large number of European regional climate model simulations (an ensemble) for the new RCPs, drawing on the new high-resolution regional climate change ensemble from the EURO-CORDEX initiative (Jacob et al, 2013).

The analysis looked at how the temperature increases in Europe as a whole – and in different regions – at the point when a global increase of 2°C relative to pre-industrial levels occurs.

The results for RCP4.5 are shown in Figure 4 below. This shows the temperature change in regions of Europe from the present day climate (1971–2000) and thus already includes the 0.5°C of warming that has occurred since pre-industrial. Areas that warm faster than the global average are shown in red, while those that warm slower are shown in blue.

EURO-CORDEX

The EURO-CORDEX initiative is the European branch of the international CORDEX initiative, a program sponsored by the World Climate Research Program (WRCP) Regional Downscaling Experiment, which has organized a coordinated framework to produce improved regional climate change projections for all land regions world-wide.

The EURO-CORDEX simulations have unprecedented resolution, with regional climate projections for Europe at 50 km (EUR-44) and 12.5 km (EUR-11) resolution. A large number (25) of simulations exist for the RCP4.5 and RCP8.5 scenario, with combinations of different Global Climate Models (GCM) and different Regional Climate Models (RCMs), as well as a smaller number of simulations for RCP2.6. A number of these runs were funded under the IMPACT2C project.

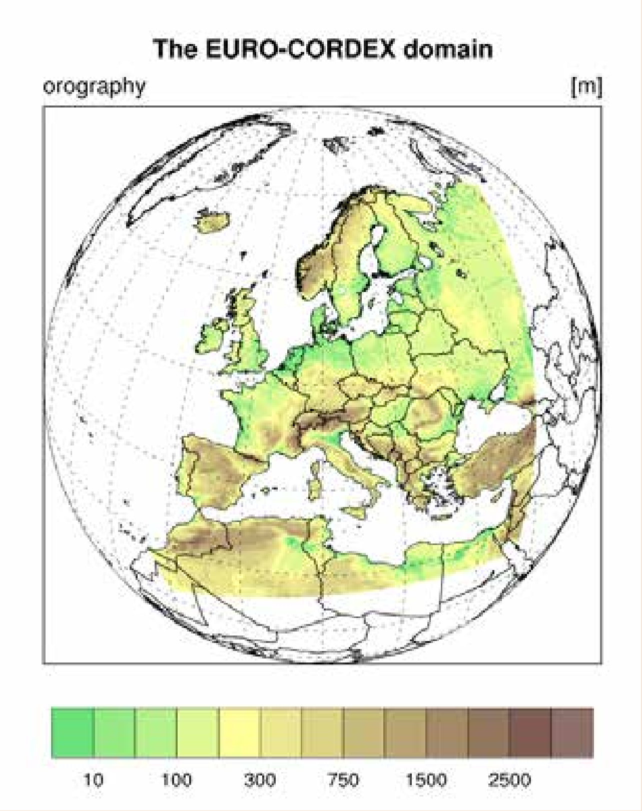


Figure 3. The EURO-CORDEX domain.

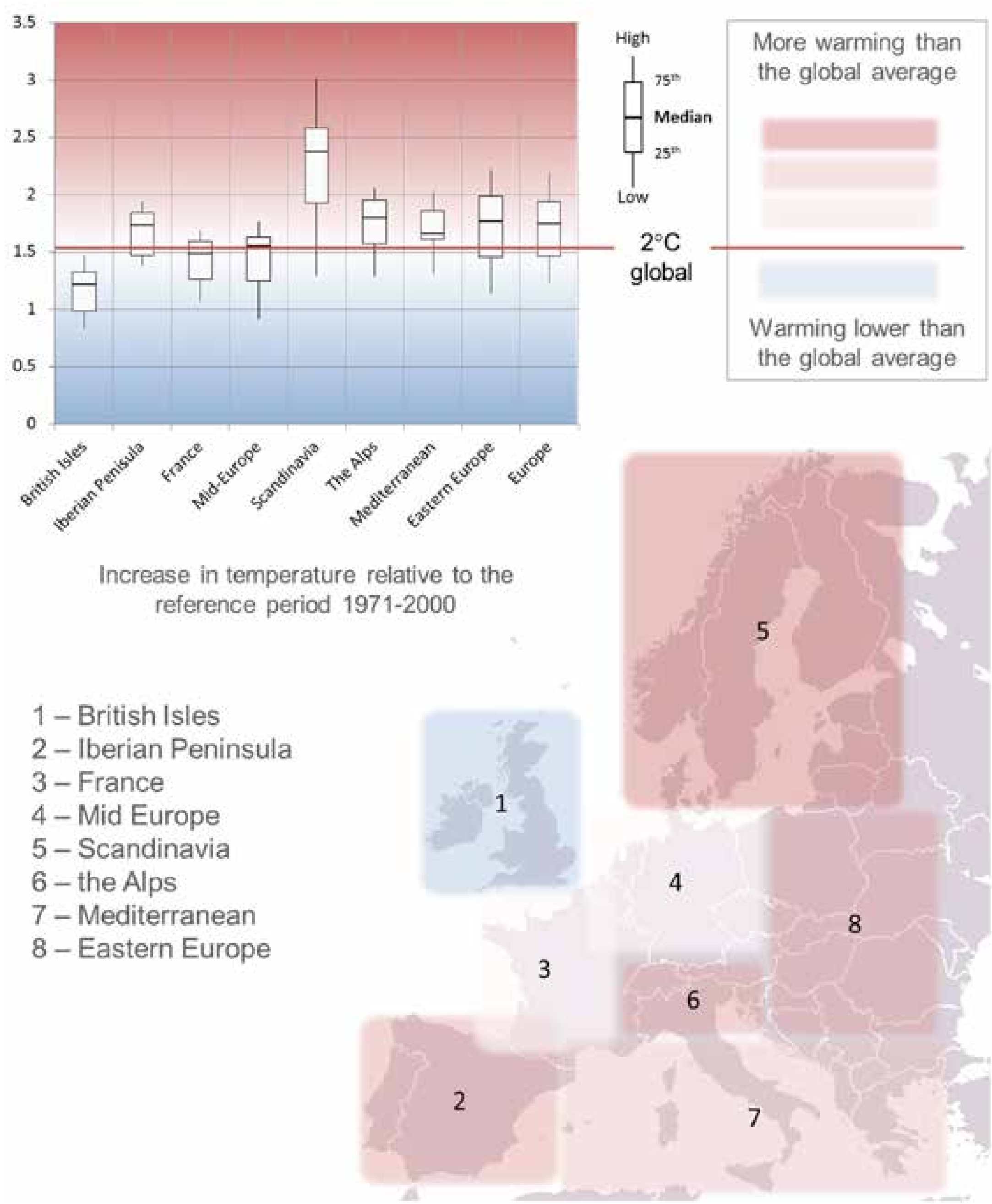


Figure 4. How much does Europe warm compared to the global average?

Analysis of temperature change in Europe for global 2°C of warming for RCP4.5.

The figure shows the results for 12 EURO-CORDEX Regional Climate Model Simulations for Europe (representing different GCM-RCM combinations) for the RCP4.5 scenario. The 2°C period has been estimated as the 30-year interval when the global mean temperature reaches +2°C relative to 1881-1910 (the pre-industrial period) in the driving global models (noting this varies with each GCM). The figure shows the warming in Europe, relative to the global average (associated with 2°C), from the 1971-2000 baseline period. The figure shows the range (whiskers), 25/75th percentile (box) and median (bold line) from the simulations. Results are for EUR-44 (50 km resolution).

Source: Cathrine Fox Maule and Ole Bøssing Christensen, 2014.

The first finding is that on average Europe warms at a higher level compared to the global average. Relative to the period 1971–2000, Europe is projected to warm by 1.76°C compared to the global average of 1.54°C. This is expected, as in general, areas of land-mass warm faster than the oceans. However, this means that even if the global 2°C goal is achieved, Europe will experience warming above 2°C.

The second key finding is that many regions of Europe – notably the Iberian Peninsula, the Alps, Scandinavia, Eastern Europe and the Mediterranean – will experience much greater warming than the global average. They will also experience warming of 2°C much earlier than the global time period shown in Figure 2. The only region that warms more slowly than the global average is the British Isles, which is heavily influenced the slow warming of the surrounding seas, while France and Mid-Europe warm at a similar level to the global average.

Similar patterns of change are seen in Europe (to above) under the RCP8.5 scenario. However, the key difference here is that these higher levels of warming then occur much earlier. On average, the driving global models indicate that we will hit 2°C of warming at 2040 (RCP8.5) compared to approximately 2050 (RCP4.5). The levels of warming shown in the figure above therefore occur a decade earlier (on average). This has important implications for the rate of warming and adaptation, discussed in a later section.

Key message. Europe warms more than the global average, i.e. much of Europe will experience more than 2°C of change (relative to pre-industrial) even if the global goal is achieved. This also means that they will experience 2°C of warming much earlier than the global average, especially under higher warming scenarios.

What are the Implications of 2C warming for Europe?

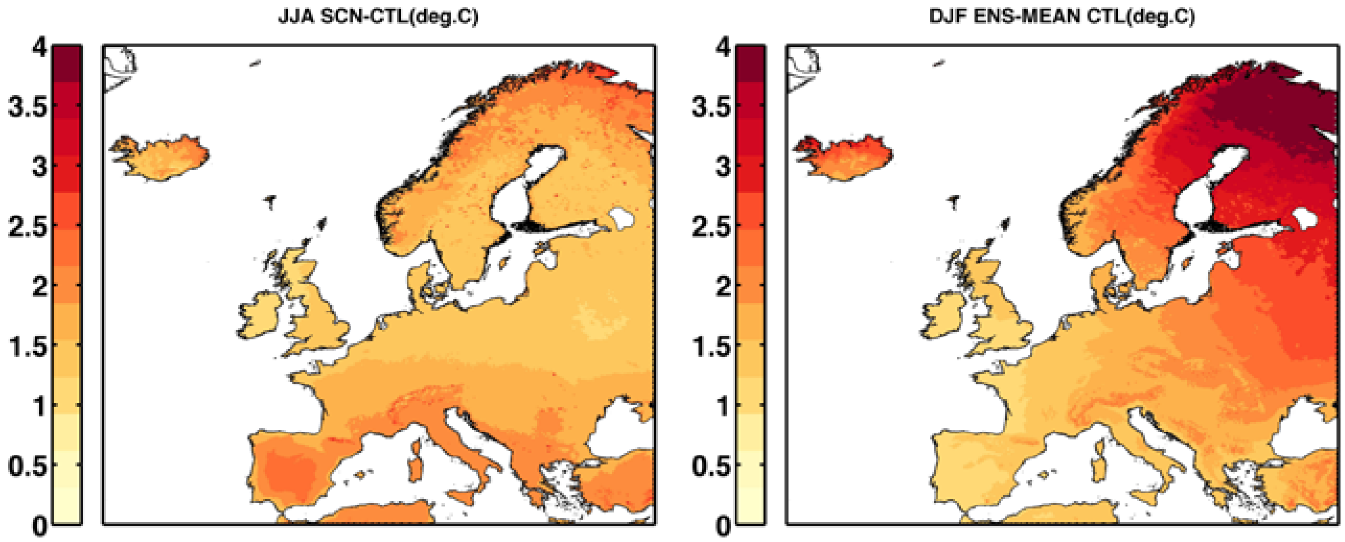
The previous section outlined the annual average projections of warming in Europe. While these provide important findings, it is also critical to look at the seasonal changes and the potential changes in climate variability and extremes.

To investigate this, the IMPACT2C project has used the new EURO-CORDEX results, which provide much greater spatial resolution (12.5 km by 12.5 km), the effects of which are most apparent along the coasts and near mountainous terrain. The study has looked at ensembles of simulations for the new RCPs. It has also used the same approach as the previous section, reporting on what changes arise at 2°C global mean warming.

An important advance from the previous analysis (Vautard et al, 2014) is a stricter analysis of robustness, investigating the statistical significance, model agreement and signal-to-noise. This provides information to help communicate what we know, i.e. where we have higher confidence in the projections.

The analysis has first looked at the patterns of warming in summer and winter in Europe, shown in Figure 5. This shows the results from the analysis of ten climate models for the RCP4.5 scenario, showing the warming signal (the increase in temperature) for summer (left) and winter (right). The results show a very strong distributional and temporal pattern across Europe, and highlights that some countries experience much greater warming than others.

In summer, there are much higher levels of warming in the Iberian Peninsula, as well as the



Summer

Winter

Figure 5. The increase in seasonal temperature (from 1971–2000) across Europe at 2°C of global average warming (RCP4.5).

Average simulated temperature (°C) for summer (left) and winter (right) between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C. Note that this takes account of the 0.5°C of warming that has already occurred, and that those areas that are orange or red are warming faster than the global average. Results of 10 GCM-RCM combinations for RCP4.5.

Source: Stefan Sobolowski et al, 2014.

Mediterranean and the Artic. All of these areas are projected to experience much higher than 2°C of warming (for global mean warming of 2°C). In winter, a different pattern emerges, with the warming highest in Scandinavia and the Baltic, where warming is approximately double the global average, i.e. 4°C of change.

On average, we find that a global temperature change of 2°C leads to a more intense warming in Northern and Eastern Europe in Winter and in Southern Europe in Summer. There is a similar or slightly lower level of warming with respect to the global average over coastal areas of North-Western Europe (in all seasons). This is expected due to the modulating effect of the oceans.

This relative change – with increased summer warming in the Southern European countries in summer – will increase heat-related impacts in countries that already experience high temperatures, notably heat-related health impacts and energy for cooling demand (EEA, 2012).

There is an even stronger relative increase in warming the Artic, which is important in relation to impacts on ecosystems. However, it is also noted that the higher warming in Northern and Eastern Europe in winter will have a mix of positive as well as negative effects. While there will be benefits (EEA, 2012) in reducing current cold-related mortality and winter heating costs, as well as extending growing seasons, there will also be negative impacts, such as on winter tourism and ecosystems. These differences will get larger in later years after 2050.

Key Message: Some parts of Europe will experience much higher and intense levels of warming than the global average, with potentially 3°C of warming in the Iberian Peninsula and other parts of the Mediterranean in summer, and 4°C of warming for Scandinavia and the Baltic in winter, for 2°C of global mean warming.

The IMPACT2C project has also investigated the robustness of these findings (see Figure 6) (based on Sobolowski et al. 2014). This is important in understanding the confidence in the results. Figure 6 shows the analysis of mean temperature change (summer) for the analysis of the level of agreement (robustness) of the models, the standard deviation across the models (a measure of the 'spread of uncertainty') and the signal-to-noise ratio.

This illustrates two key findings. First, all of the models agree (universally) on the warming signal for Europe, and they also show high agreement on the distributional pattern of warming across Europe. Second, the uncertainty is much smaller than the amplitude of changes.

The analysis has also looked at the patterns of daily maximum temperatures (Tmax) in summer, and daily minimum temperatures (Tmin) in winter. These exhibit similar patterns and levels of robustness to the mean seasonal temperatures, but they present additional information that is relevant for impacts.

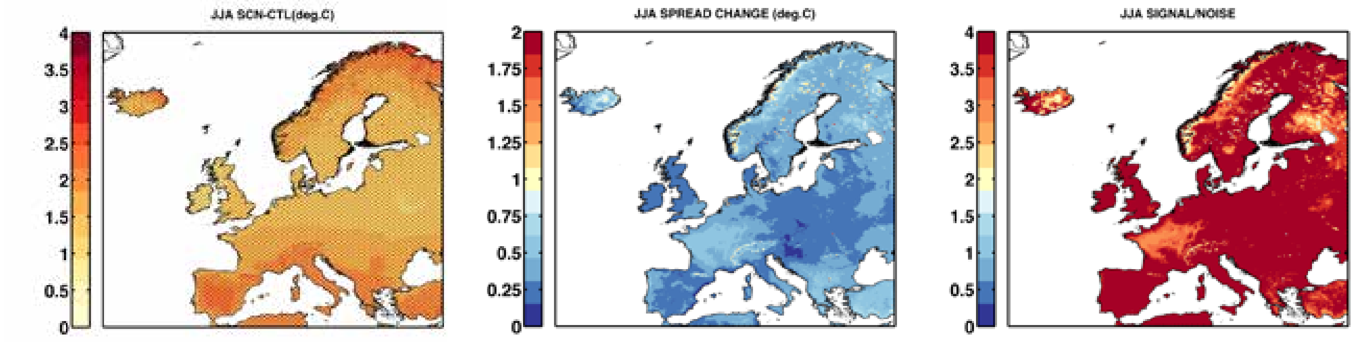
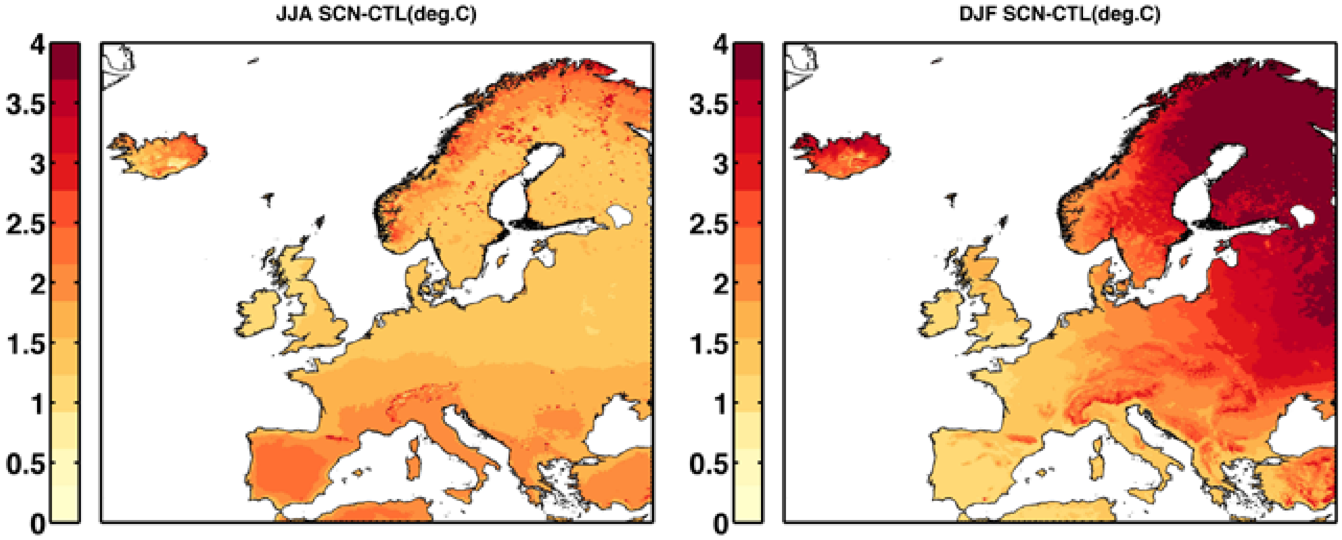


Figure 6. Robustness of the findings (summer)

Left. Robust changes, where models agree on the sign of the change and changes are significant, are indicated with stippling,. Middle. Standard deviation of the climate change signal °C. Right .Signal to noise ratio, defined as ensemble mean change over the standard deviation of the climate change signal (unitless).

Analysis of RCM simulated temperature (°C) summer season, between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C for 10 GCM-RCM combined RCP4.5 simulations.

Source: Stefan Sobolowski et al, 2014.



Tmax summer

Tmin winter

Figure 7. Seasonal mean Tmax (summer) and Tmin (winter)

Average simulated Tmax (°C) for summer (left) and Tmin winter (right) between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C. Stippling not shown here due to the fact that all land areas exhibit robust changes in these variables. Note that this takes account of the 0.5°C of warming that has already occurred, and that those areas that are orange or red are warming faster than the global average. Results of 10 GCM-RCM combinations for RCP4.5.

Source: Stefan Sobolowski et al, 2014.

Under the 2°C scenario, the largest summertime changes in daily maximum temperature (3-4°C) are found over South-Eastern Europe and the Iberian Peninsula. These will increase heat related impacts. The largest increases in daily minimum temperatures are in the winter in the North (Scandinavia), and these show very large increases apparent around mountainous areas such as the Pyrenees, Alps and Scandinavia where the minimum daily temperatures are projected to increase from 3 to 6 degrees. This will have a major impact on winter freeze-thaw cycles (infrastructure and the built environment), winter tourism and on ecosystems, although it will have benefits in reducing winter cold extremes.

Temperature extremes

While changes in seasonal averages are important, the change in the frequency and/or intensity of extreme events may have early and potentially more significant consequences to society (see IPCC, 2012). One of the key concerns for Europe is the potential increase in summer extreme heat, which is linked to health impacts and temperature related mortality (Baccini et al. 2008). To investigate these issues, the IMPACT2C project has looked at the changes in extremely hot days (shown in Figure 7), using the metric of the 20-year return values (i.e. the peak event that happens on average once every 20 years). Under the 2°C scenario, the largest increases (up to and more than 4°C) in extreme (peak) events are found over South-Eastern Europe and the Iberian Peninsula in summer (Figure 8, left). In areas where this value is highest (Iberian Peninsula, France, the Balkans) the 20-year return value is expected to rise well above 40°C (see Figure 8, right). These trends are robust.

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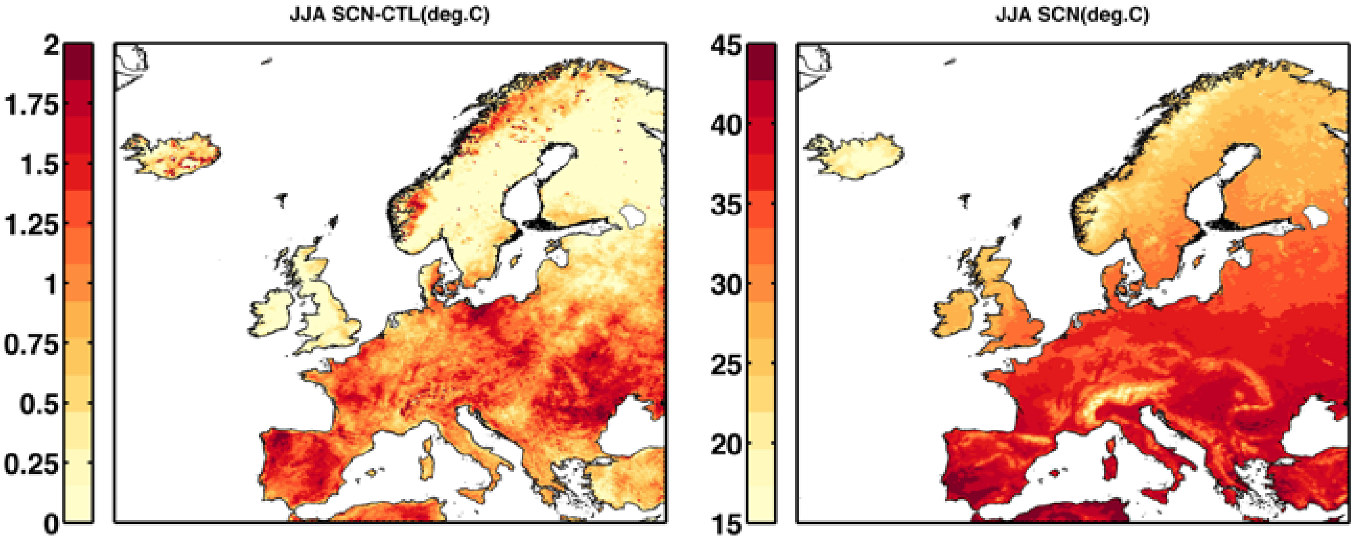


Figure 8. Left: The change in 20 year return value for European daily maximum temperature (Tmax). Right: The mean absolute 20-year return value for the +2°C climate.

Left. Analysis between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C period corresponding to global temperature difference for 7 GCM-RCM combined RCP4.5 simulations.

Average simulated Tmax (°C) for summer (left) and Tmin winter (right) between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C. Note that this takes account of the 0.5°C of warming that has already occurred. Results of 7 GCM-RCM combinations for RCP4.5.

Source: Stefan Sobolowski et al, 2014.

This pattern of change – with a higher relative change in the South of Europe – is likely to exacerbate existing distributional impacts, i.e. to further increase the high levels of heat related mortality and energy for cooling in these regions (though higher heat extremes will also be important in other countries that are not used to high temperatures). However, lower extremes of daily minimum temperatures occur in some Northern areas of Europe, which will have benefits, for example in reducing winter cold extremes and cold related mortality.

The analysis has also considered the potential change in heat-waves, defined as 6 days or more with Tmax over 5°C over the mean (May-Sep). This shows the strongest increase in the number of heatwaves in Mediterranean and especially the Iberian peninsula, but also North-East Europe: the analysis also finds these projections are robust, even at 2°C of warming.

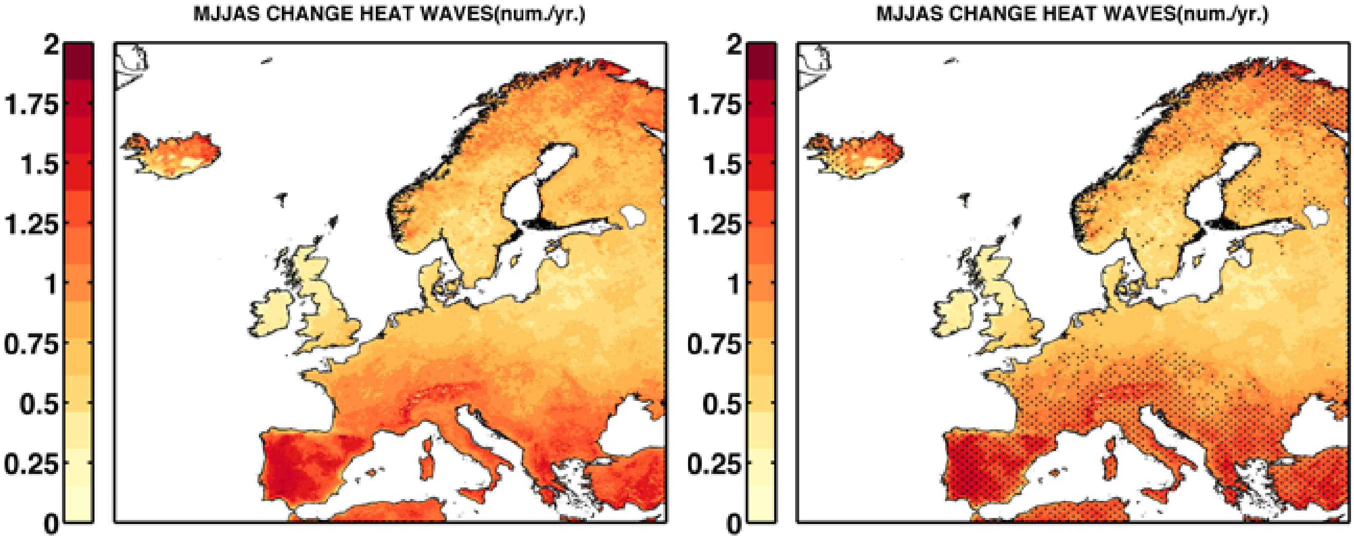


Figure 9. The change in Heatwaves, number (left) and robustness (right)

Average simulated number of heatwaves, defined as 6 days or more with Tmax > 5°C over mean (May-Sep of the 1971–2000 reference period). (°C) without (left) and with (right) stippling indicating robustness. Differences taken between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C. Note that this takes account of the 0.5°C of warming that has already occurred. Results of 7 GCM-RCM combinations for RCP4.5.

Source: Stefan Sobolowski et al, 2014

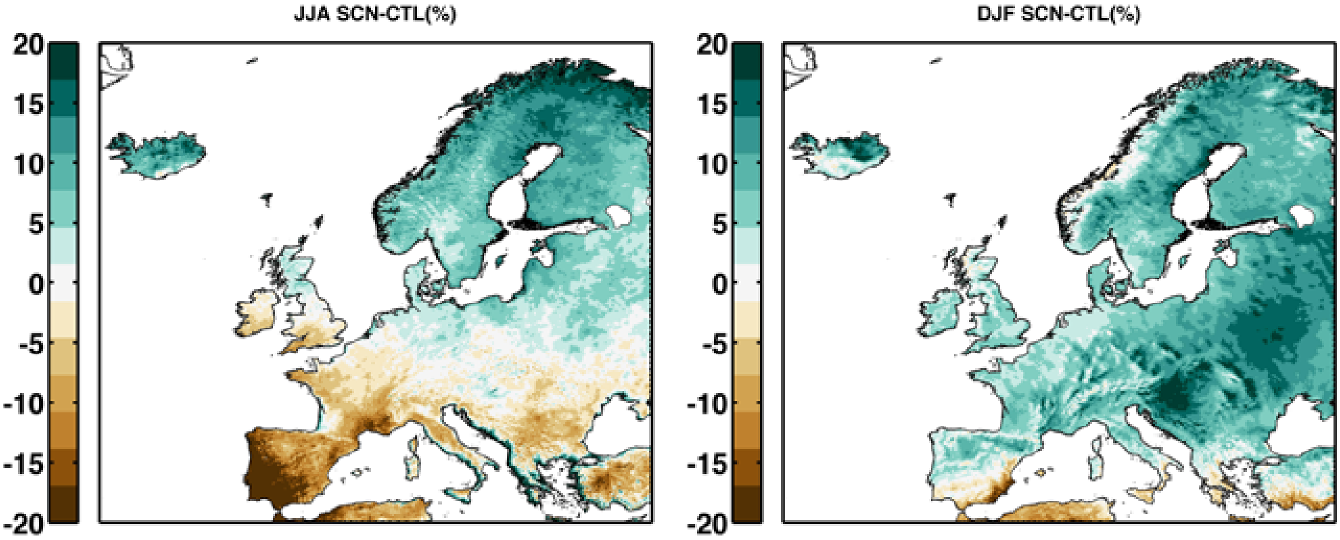
Precipitation

The IMPACT2C project has also analysed the changes in precipitation in Europe for a 2°C world. The change in precipitation projected from different climate simulations varies more from model to model than for temperature and the distributional patterns are more pronounced. Part of this difference is caused by the fact that the climate is variable, even in the absence of changes in greenhouse gas concentrations. Nonetheless, there are patterns of change. The changes are shown in Figure 10 for winter and summer mean precipitation.

For 2°C of global average warming, increases in winter precipitation (Figure 10, right) are projected on average over Central and Northern Europe, of the order of +10-15%, and increases in summer precipitation are also projected for Northern Europe.

At the same time, decreases in summer precipitation, of the order of –10-20%, are projected for Central/Southern Europe (Figure 10, right). These changes exacerbate existing water management issues in these areas of Europe, i.e. potentially increasing water deficits in the South during summer. There are also increases in summer precipitation over Scandinavia).

In other parts of Europe, the changes are more uncertain, and there are larger differences in the direction of change, i.e. whether increases or decreases will occur.



Summer

Winter

Figure 10. The change in seasonal European precipitation (%) (from 1971–2000) with 2°C global average warming. Left (summer). Right (winter).

Average RCM simulated precipitation between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C. Results of 7 GCM-RCM combinations for RCP4.5.

Source: Stefan Sobolowski et al, 2014

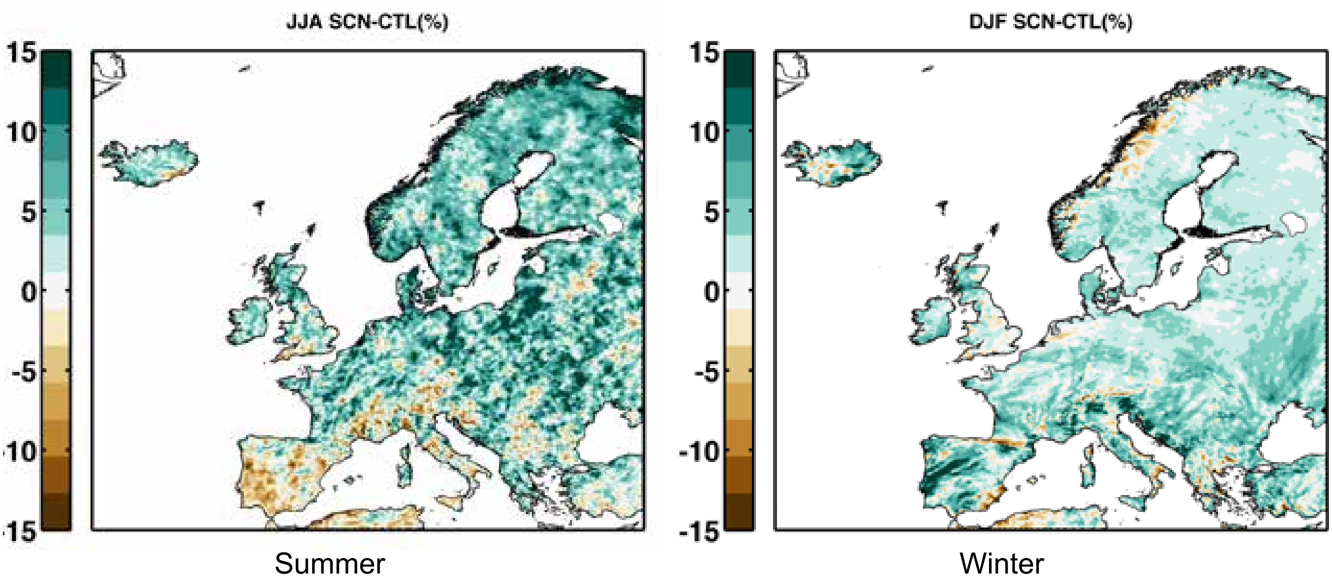
Under the very strict criteria, the changes are not robust anywhere in Europe, in either winter or summer. This reflects that fact that natural variability is likely to remain an important factor in the near term. Nonetheless, there is a strong pattern of change seen in relation to the North-South response. Further there is strong agreement on the direction of the change over many areas of Europe. In particular, most models agree that Southern Europe/Scandinavia become drier/wetter in Summer and that Central-Northern Europe becomes wetter in Winter.

Heavy precipitation extremes

Floods are among the most important weather-related loss events in Europe and can have large economic consequences: ABI (2005) reported average annual losses are €6 to 7 billion in Europe and the EEA (2010) reports total losses of over €50 billion have occurred over the past decade. The analysis has therefore considered changes in heavy precipitation, associated with higher flood risks, again looking at the 20-year return value.

The model simulations (Figure 11) show increases across much of Europe in both summer and winter, with (ensemble mean) intensity increasing by +5% to 15% (and in some areas, even more). The increase in heavy precipitation found under the 2°C scenario therefore has the potential to increase flood risks. The increase is marked over Eastern Europe and Scandinavia in summer and over Southern Europe in winter. The increase in Eastern Europe is a particular concern because this is one of the existing flood hot-spots in Europe.

It is important to notice that in summer, both increases in heavy precipitation and drought (not shown) are projected in South/Central Europe.



Summer

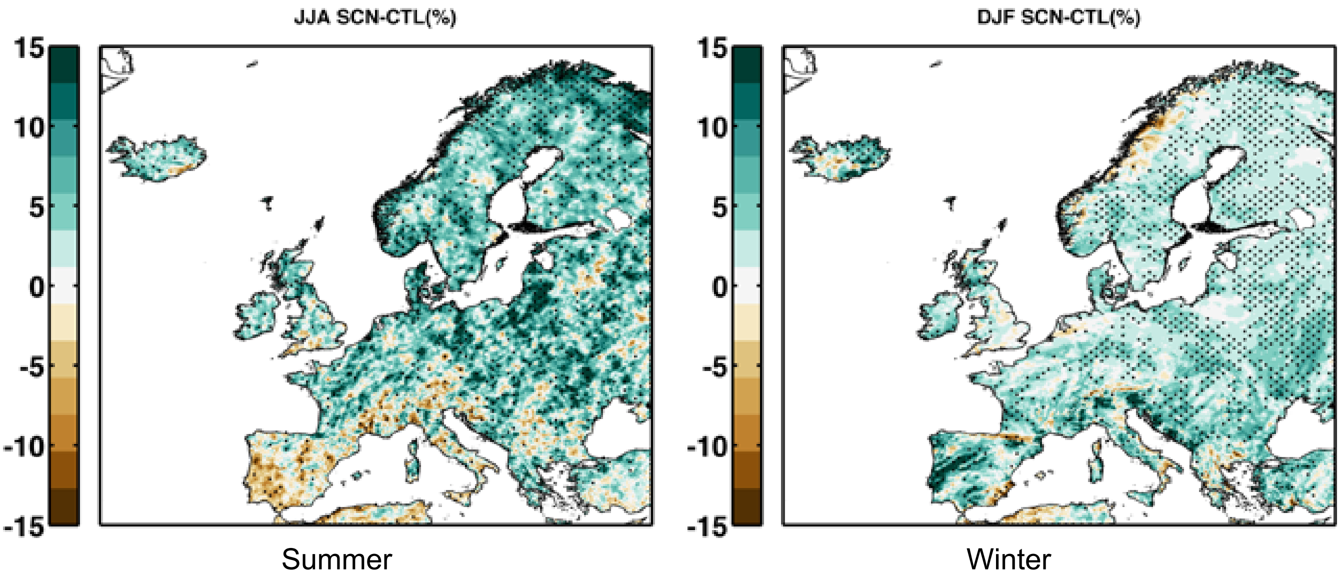
Winter

Figure 11. The increase in heavy precipitation events with a return period of 20 years.

Average RCM simulated heavy precipitation for summer (left) and winter (right). Differences taken between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C for Results of 7 GCM-RCM combinations for 7 RCP4.5 simulations.

Source: Stefan Sobolowski et al, 2014

The changes in heavy precipitation are more robust than for average change, and are shown in Figures 11 and 12. There are robust patterns of increasing extremes in Northern and Eastern Europe in both winter and summer.



Summer

Winter

Figure 12: Robust patterns in Precipitation 20yr return values; winter(left) summer (right) (%).

As in Figure 11, but stippling signifies agreement on sign of change.

Source: Stefan Sobolowski et al, 2014

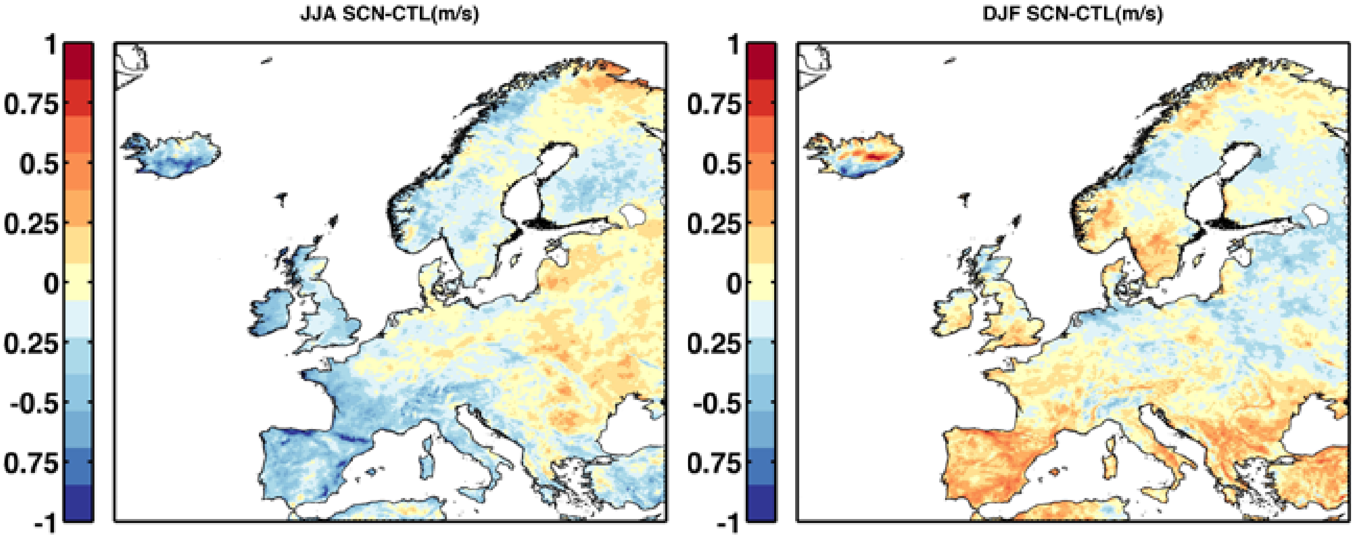
Key message. Under the 2°C of global change, there are large increases in extreme events for Europe, with much larger increases in daily maximum temperature over parts of Southern and South-Eastern, as well as increases in heavy precipitation across all of Europe. These will cause more frequent and severe high impact events.

Wind Storms

The analysis has also looked at the potential changes in wind storms, which are among the most damaging extreme events in Europe (ABI, 2005). The analysis has considered the change in the 99th percentile of the daily maximum 10-meter wind speed for each season (I99), with results shown in Figure 13.

While there is a general trend of modest increases of extreme winds, none of the changes are robust. There are indications of an increase over some areas of Northern and Central Europe (consistent with more zonal westerly flows) in winter, and modest decreases along Western coastal areas in the summer.

Interestingly the patterns of change are shifted somewhat southward (compared with earlier work) and indicate modest increases over the Iberian Peninsula – Southern Europe in winter, and over Eastern Europe in the summer, but with modest decreases along Western coastal areas in the summer.



Summer

Winter

Figure 13. The increase in extreme winds (m/s).

Average RCM simulated extreme winds (I99) for summer (left) and winter (right) between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C.

Summary

Overall, there is also a strong distributional pattern of warming seen across Europe (and thus different countries) under 2°C of global change. Many of the changes – in terms of the sign and magnitude as well as the spatial location and distributional pattern – will exacerbate existing weather related impacts across Europe.

As an example, there is higher relative warming and greater relative increases in heat extremes in southern Europe in summertime, which will drive heat related impacts such as cooling and mortality. Similarly, there are higher relative (and more robust) signals for increased precipitation and heavy precipitation events in Eastern Europe along existing flood risk corridors, but lower projected summer rainfall in the Mediterranean which will increase pressures on water and drought management.

Even in areas where there will be benefits (e.g. higher winter warming in the north, which will have the benefit of reduced winter mortality and reduced winter heating demand), there will also be negative impacts, such as on winter tourism and natural ecosystems. A general finding is that the distributional pattern of changes across Europe will increase relative risks compared to a scenario where Europe warms equally. This is of high policy relevance: even if the 2°C goal is achieved, Europe will experience strong distributional impacts: a 2°C world in Europe is therefore not benign and further work to explore these key hotspots and advance adaptation is needed. These will be considered in the next phase of the IMPACT2C project.

What do the climate projections tell us about the rate of climate change – and the possible limits of adaptation?

Most climate change assessments report on the future level of projected change. While this is extremely important, it is also becoming clear that the rate of change, as well as the absolute level of warming, is important.

This is because the speed of change is critical in the ability of natural, physical and economic sectors to adapt. This is linked to the emerging concept of the limits of adaptation, which may relate to absolute limits, but also to the speed of change in relation to economic, social or behavioural limits. As an example, at high rates of climate change, species migration rates maybe exceeded. Similarly, the rate of change maybe too fast for standard investment renewal and replacement cycles, significantly increasing the costs of adaptation, and potentially leading to stranded assets.

Historically, the global combined land and ocean temperature data show an increase of about 0.85°C over the period 1880–2012 as a linear trend (IPCC, 2013). Over the last sixty years (1951–2012) the rate of change has been 0.12°C per decade [with a range of 0.08 to 0.14 °C].

However, the increases in emissions in recent historic years – plus the likely short-term emission trends over the next few decades – will lead to an acceleration of future rates of climate change and warming. This is an important issue for Europe – as it warms faster than the global average – and especially the regions of Europe that warm fastest (e.g. see Figure 14).

The IMPACT2C project has investigated the rates of change in Europe, using the EURO-CORDEX downscaled regional climate models. The results are shown below, presented as the projected increase per decade, over the period from the baseline (1971–2000) to the point where 2°C global average temperature (relative to pre-industrial) is exceeded.

This shows a significant increase relative to historically observed rates, especially in the fastest warming regions of Europe. They also

show that the rates of change are significantly higher under higher emissions paths.
At the European level, the median rate of warming (up 2°C global average warming) is 0.25°C per decade for RCP4.5 and 0.31°C per decade for RCP8.5. However, there is a considerable range around this, and the 75th percentile is significantly higher, at 0.33°C per decade for RCP4.5 and 0.37°C per decade for RCP8.5. This is already a significant increase compared to historical rates.

However, the most striking finding is in relation to the areas of Europe that warm fastest. For Scandinavia, for example, the median rate of warming is 0.36°C per decade for RCP4.5 and 0.41°C per decade for RCP8.5, and the rate of change for the 75th percentile (under RCP8.5) is almost 0.5°C per decade. This level of warming is unprecedented in recent periods and it will have significant implications for coping with the rate of change and the potential for adaptation.

The figure shows the results for EURO-CORDEX Regional Climate Model Simulations for Europe (representing different GCM-RCM combinations) for the RCP4.5 scenario (12 simulations) and RCP8.5 scenario (13 simulations). The 2°C period has been estimated as the 30-year interval when the global mean temperature reaches +2°C relative to 1881–1910 (the pre-industrial period) in the driving global models (noting this varies with each GCM). The figure shows the decadal rate of warming in Europe (associated with 2°C of warming from the baseline), from the 1971–2000 baseline period. The figure shows the median and 25/75th percentile (whiskers). Results are for EUR-44 (50 km resolution).

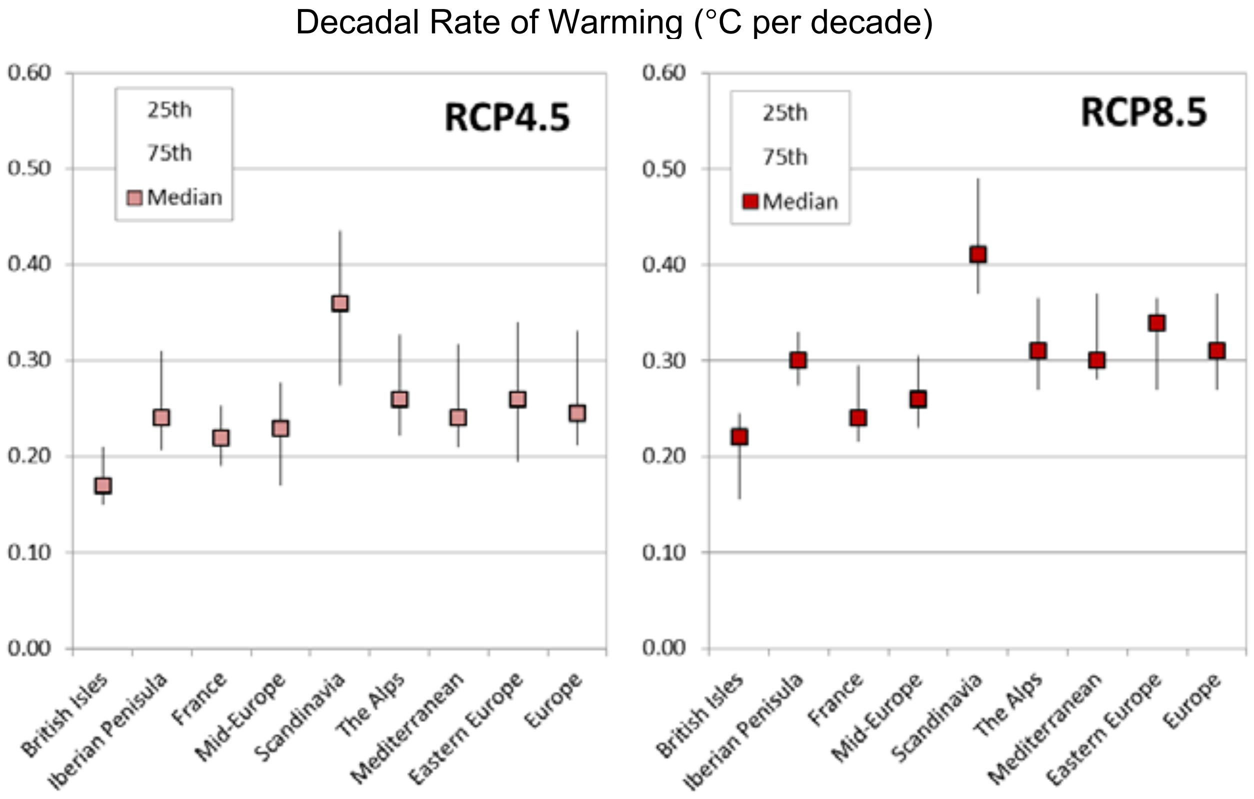


Figure 14. What is the rate of warming in Europe?

Analysis of the rate of temperature change in Europe for RCP4.5 and 8.5 from 1971–2000 for up to global 2°C of warming.

Source: Cathrine Fox Maule and Ole Bøssing Christensen, 2014.

Key message. The rate of climate change is important for many impacts and it also influences the ability to adapt easily and cost-effectively. Historical rates of global change have averaged just over 0.1°C warming per decade. However, these rates are projected to increase in the near future. Analysis indicates that the median rate of warming in Europe (up 2°C global average warming) is 0.25°C per decade for RCP4.5 and 0.3°C per decade for RCP8.5, but with faster rates of change from warmer models.

For regions of Europe that warm faster than the European average, these changes are even more dramatic, for example Scandinavia could experience warming of around 0.4°C per decade (median), and as much as 0.5°C per decade under some model projections.

What does 2°C of warming mean for sea-level rise?

Coastal zones contain high population densities, significant economic activities and important ecosystems (McGranahan et al. 2007). These are at risk from sea-level rise as well as other coastal change (Nicholls et al. 2008; Brown et al. 2014).

Sea-levels have been changing for thousands of years, in response to natural processes. However, there are increasing concerns that the rate of sea-level rise is changing in response to human activity. From 1901 to 2010, global mean sea-levels rose by 0.17±0.02 metres (Church et al. 2013), with higher rates recorded over the last few decades (from 1993 to 2010 global mean sea-level rise increased by 3.2mm/year).

Climate change, and the associated rise in global mean temperature, is projected to lead to accelerated sea-level rise over the 21st century. This will be caused by thermal expansion (due to warming oceanic temperatures), melting of the large ice sheets of Greenland and Antarctica as well as smaller glaciers and ice caps, and changes in the distribution of land-water storage and discharge. Projecting sea-level rise is, however, complex, and a range of uncertainty is usually given in projections.

The increase in sea-levels will lead to potentially increased risk of flooding of low-lying areas, as well as increased erosion, salinization, and loss of coastal habitats. However, the effects of climate change need to be seen in the context of other natural process and socio-economic drivers.

The IMPACT2C project has looked at the global sea level rise projections for the new RCP projections and also, considered the ISI-MIP results (Hinkel et al. 2014). The analysis has followed the framing used in IMPACT2C, and considers the sea-level rise associated with the 2°C goal with respect to pre-industrial, and other higher temperature levels. However, unlike other climate parameters, sea-levels do not respond immediately to an increase in global mean surface temperature as there is a time lag between surface warming and oceanic response. This could take several decades up to millennia. The process is known as the commitment to sea-level rise (Wigley and Raper, 1993).

This has two important implications. First, the time profile and rate of warming affects sea-level rise, thus the increase in SLR can vary even for the same level of temperature rise. Second, even if emissions and temperature could be stabilised

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today, there would be an increase in sea levels from past warming, e.g. Levermann et al. (2013) estimate that GMSL will rise on average by about 2.3 metres per degree centigrade of global warming within the next 2000 years. Under present levels of global warming, this means that we are already committed to an average of 1.3 metres of future sea-level rise above current levels (Strauss 2013).

This commitment to sea-level rise means that information for sea-level rise cannot be presented in exactly the same way as earlier sections, i.e. there are no definite projections of the sea-level rise for 2°C. Taking account of these issues leads to extremely interesting results.

The projections of sea-level rise are first shown for the RCP2.6 mitigation scenario for the climate model HadGEM2-ES, which has a good chance of achieving the 2°C goal. This shows the pattern of global sea level rise (relative to 1985–2005) on the y-axis, plotted against global mean temperature on the x-axis (relative to pre-industrial levels). The central projection and the uncertainty associated with ice melt are shown.

The figure shows the commitment to sea-level rise, as even when temperatures in this scenario stabilise temperatures around the 2°C goal, sea-level continues to rise over the rest of the century (and even beyond) – shown by the line moving vertically up the figure. While sea-levels could rise anywhere between 0.09m (in 2030) and 0.52m (in 2100), the rate of sea-level rise slows over time due to stabilising temperatures.

This can be compared to the RCP4.5 and RCP8.5 scenarios. RCP4.5 is also a stabilisation scenario, but compared with RCP2.6, temperatures, and therefore sea-levels stabilise later in time. Thus there is a similar trend

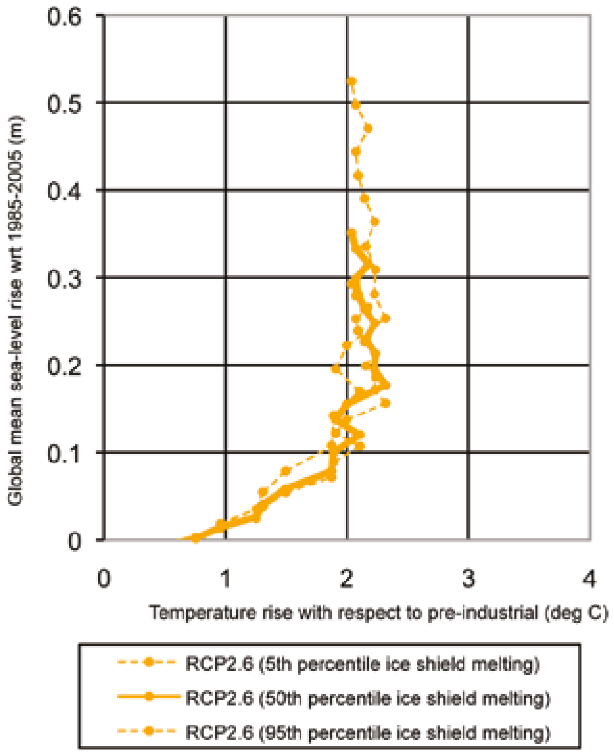

Figure 15. Global mean sea-level rise under the RCP2.6 scenario

Source: Brown et al, 2015. Figure shows global mean sea-level rise based on HadGEM2-ES runs.

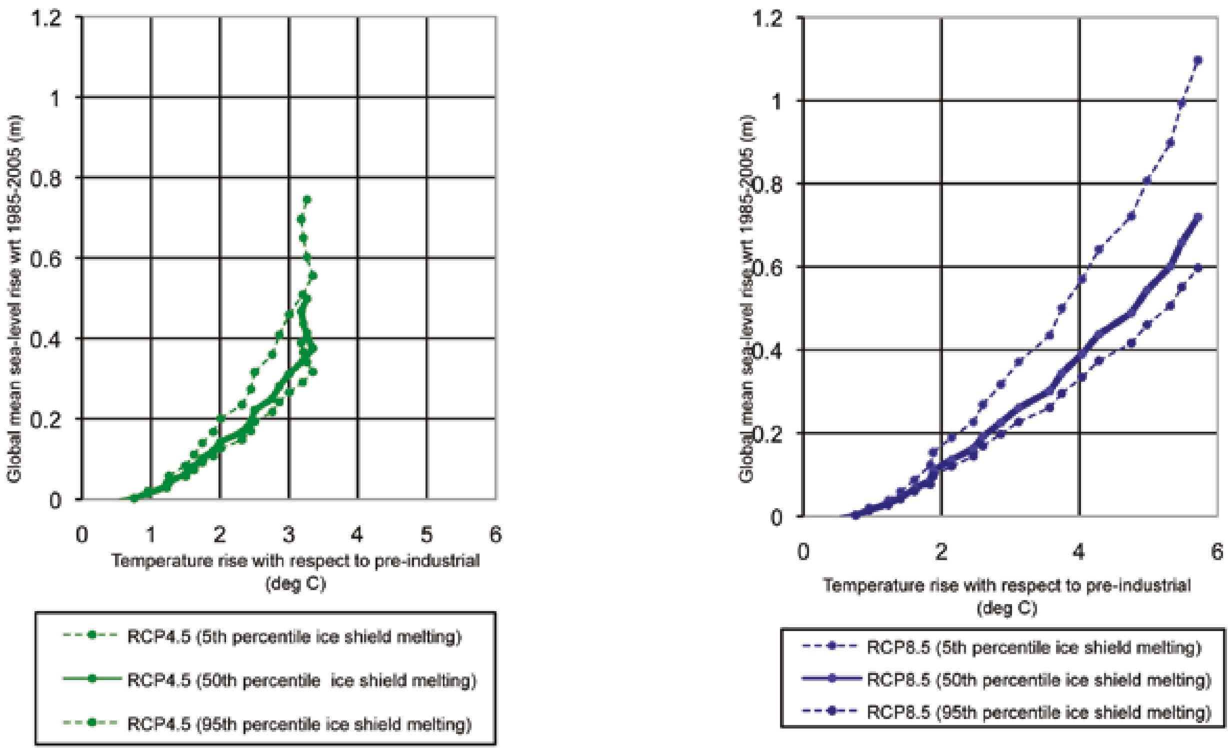

Figure 16. Global mean sea-level rise under the RCP4.5 and 8.5 scenario

Source: Brown et al, 2015. Figure shows global mean sea-level rise based on HadGEM2-ES runs.

between the two scenarios. However, the pattern for RCP8.5 differs dramatically, as temperatures and sea level rise continue to increase over the century and beyond.

The three central projections are compared below, showing the very different patterns according to whether the 2°C goal is achieved or not.

Sea-level rise may also extend beyond the RCP8.5 scenario if ice sheets melt quicker than presently anticipated (in this century or beyond), as ice sheet dynamics could lead to the partial collapse of ice shelves (Joughin et al, 2014: Rignot et al, 2014). This could result in a further rise in sea-level of several tens of centimetres (Church et al. 2013).

So far, the observations have been presented as the global mean, but in reality global variations are expected to occur following present day trends. Therefore, some places around the world would be expected to experience higher-than-average sea-level rise, whereas others experience lower-than-average. These trends

Key message. Even if surface temperatures stabilise and achieve the 2°C goal, sea-level rise will continue over the century. The earlier 2°C is reached, the greater the potential for higher levels of sea-level rise.

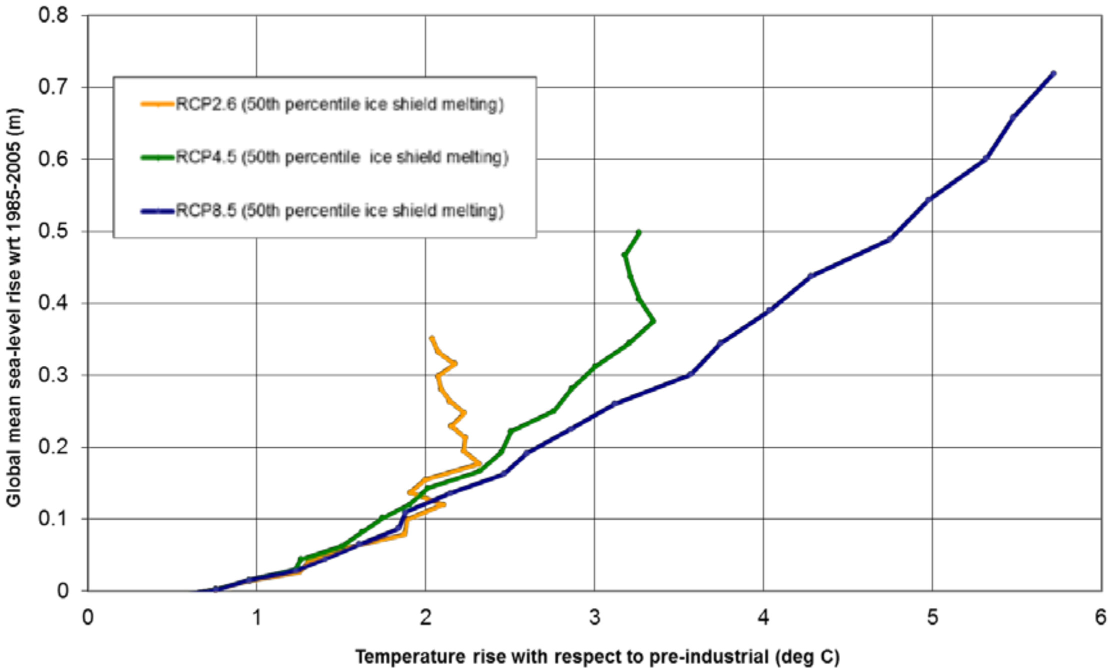

Figure 17. Global mean sea-level rise under the different RCP scenarios

Source: Brown et al, 2015. Figure shows global mean sea-level rise based on HadGEM2-ES runs.

are known as patterns, and they occur because of ocean dynamics, thermal and salinity mixing, or changes in the gravitational field due to ice melt redistribution (Pardeans et al. 2011; Slangen et al. 2014).

For the latter sea-levels are expected to fall closest to the ice mass that is melting, with a rise on the opposite side of the world. As a result, European sea-level will rise more with the melting of Antarctica than of Greenland. Furthermore, there are some indications that some small islands in the Indian Ocean (including the Maldives) – which are particularly vulnerable to sea-level rise – could experience 10%-20% sea-level rise from ice sheets when compared to the global mean as both the Greenland and Antarctic ice sheet contributions have similar magnitudes in this region (Perrette et al. (2014).

Part of the work on the IMPACT2C project has used patterned scenarios, to reflect these differences, as generated by Hinkel et al. (2014). The figure below shows the magnitude of sea-level rise for four climate models from CMIP5 for the three RCP scenarios in 2100.

The figure illustrates the differences between low and high emission scenarios (left to right) and for different models (top to bottom). It also shows the different patterns projected across these.

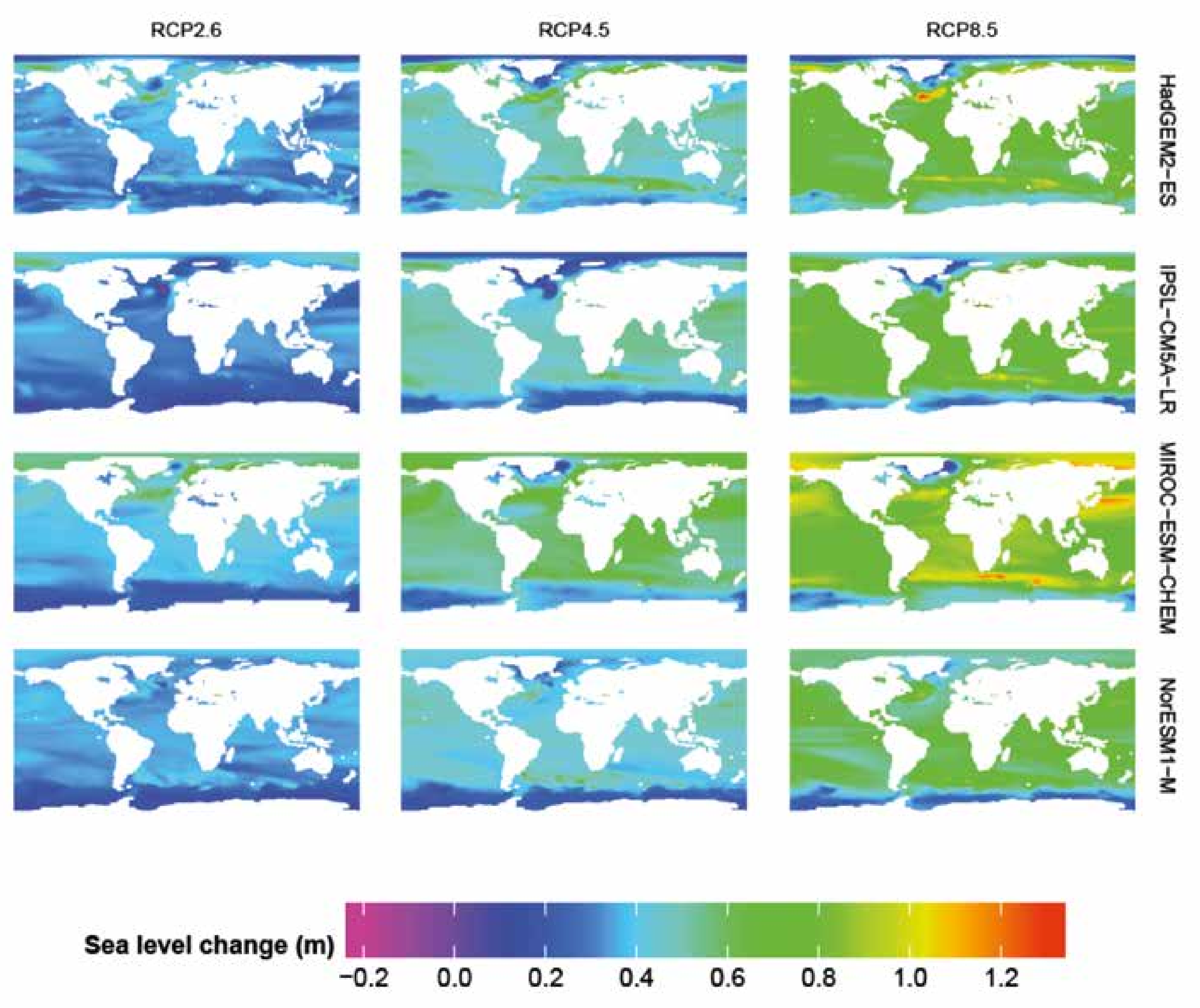

Figure 18. Projected patterns of global sea-level rise in the 2100 with respect to 1985-2005, showing central values of ice melt uncertainity.

Data extracted from Hinkel et al. (2014).

Key message. While sea-level rise is usually reported as a global mean, variations occur. There are some places around the world that experience higher-than-average sea-level rise, whereas others experience lower. Interestingly, there are potential differences in the pattern of sea-level rise (by location) with ice-sheet melt.

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What does 2°C of Global Warming Mean for the Water Cycle in Europe?

Climate change is projected to disrupt global and regional water cycles, though the exact effects will vary with region and by season (IPCC, 2013). Changes in precipitation, evapotranspiration, snow storage, glacier melt, runoff and river discharge have the potential to intensify a number of potential risks. These include more frequent and/or intense floods (Kundzewicz et al., 2014), changes to the water supply-demand balance including potential water deficits, and decreasing water quality (IPCC, 2014). In turn, these could affect many water-dependent sectors and activities.

To investigate this, the IMPACT2C project assessed the impacts of climate change on the terrestrial water cycle in Europe for scenarios of 2°C mean global warming, relative to pre-industrial levels. A key part of this analysis was to understand the uncertainty around both the future climate and the terrestrial water cycle. The analysis therefore sampled different Relative Concentration Pathways and different climate model simulations – see earlier discussion in this brief – feeding the results into a number of conceptually different state-of-the art hydrological models.

The analysis was undertaken for eleven EURO-CORDEX climate change simulations, comprised of five different GCM/RCM combinations each driven by three RCPs (RCP2. 6, 4. 5 and 8. 5). The bias-corrected output from the climate simulations was used to force five pan-European hydrological models (E-HYPE, Lisflood, LPJmL, VIC and WBM), resulting in an ensemble of 55 simulations (11 climate simulations x 5 hydrological models). Each of the models represents details of the hydrological cycle and processes in a slightly different way, thus combining them provides more comprehensive information on the possible changes to European water fluxes and stores. The large number of climate and hydrological simulations also allowed a statistical analysis of the uncertainty by quantifying the mean and standard deviation (a measure of uncertainty) of the results across the ensemble and using these to calculate the significance of the results.

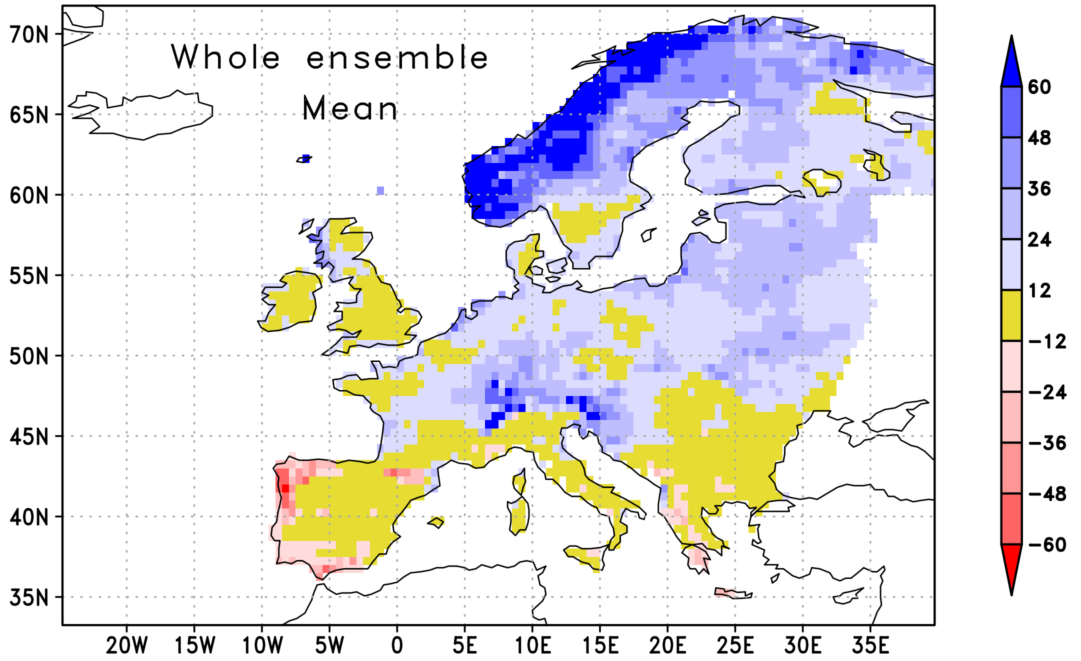
The analysis first looked at changes in precipitation at 2°C of warming, and the associated impacts on runoff (local runoff from land to rivers, lakes and groundwater), discharge (runoff accumulated in rivers, i.e. including upstream contributions) and evapotranspiration (the sum of evaporation from soils, waterbodies and vegetation canopies and plant transpiration).

As shown earlier in this policy brief, under 2°C of global warming, precipitation is projected to increase in most parts of Europe, especially in winter, though with potential decreases in Southern Europe in the summer. The changes in runoff, discharge and evapotranspiration largely follow these patterns, i.e. the extra precipitation will partly contribute to increased evapotranspiration and partly runoff, increasing discharge levels.

Figure 19 shows the simulated changes in runoff and river discharge under 2°C of warming, highlighting the increase in most areas of Europe. However, there is a strong north-south gradient to the projected changes. The largest increases are seen in the east and the far north of Europe. By contrast, there are decreases in parts of the Mediterranean, especially in the south of Spain, Sicily and parts of Greece, resulting from decreases in precipitation and higher temperatures leading to higher evapotranspiration.

A model comparison revealed that the spread in results was small over much of Europe, indicating the robustness of the results. Significant increases in runoff were found in Northern and Central Eastern Europe, as well as significant negative changes (decreases) along parts of the Iberian coast. These areas of significance are shown by the coloured areas in Figure 20 below. Further analysis revealed that the primary source of the uncertainty in runoff was the climate models (rather than the hydrological models).

The analysis then considered the future change in evapotranspiration at 2°C, shown in Figure 21. In Northern and Central Europe, there is an increase due to the combination of higher



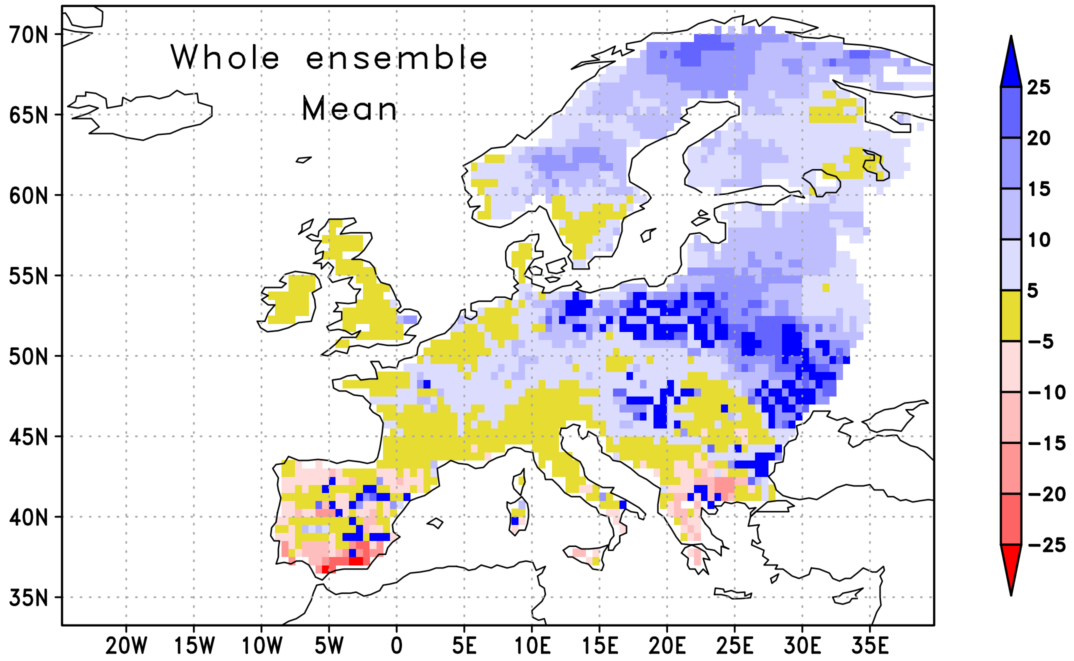


Figure 19. Absolute change in runoff (mm/year) (top) and relative change in discharge (%) (bottom) at 2°C of global average warming.

Results are calculated from the ensemble of 55 climate and hydrological model combinations.The change is calculated as the mean for the period at which the underlying GCM reaches 2°C global warming, minus the mean for the baseline period (1971–2000). Source: Greuell et al., 2015.

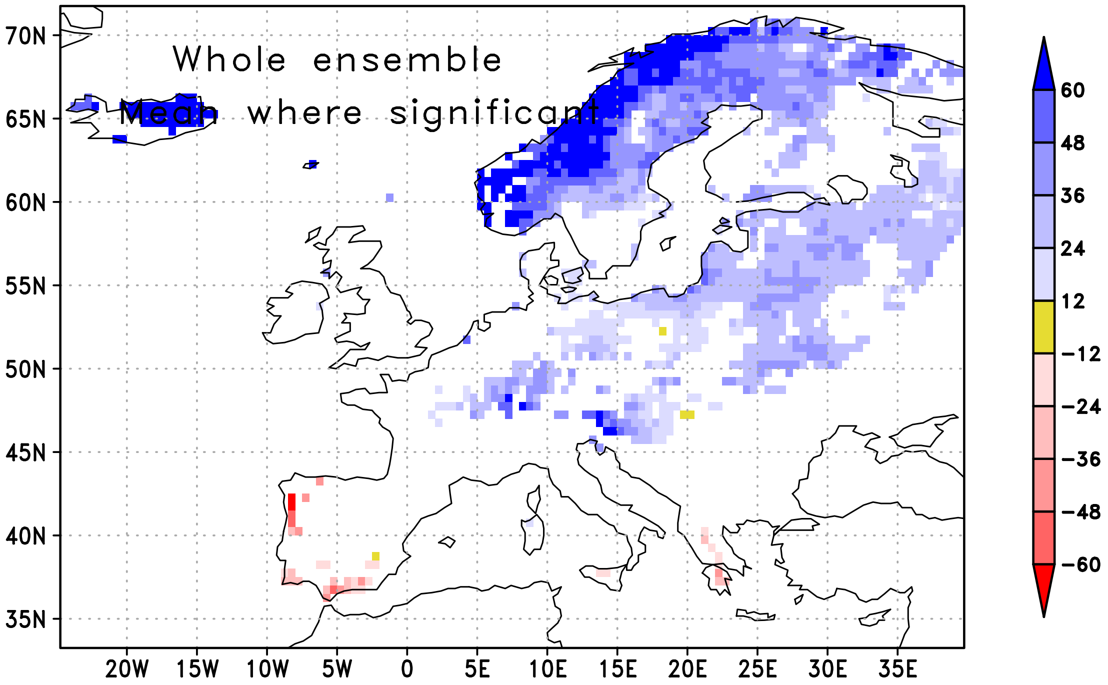


Figure 20. Areas where the change in mean annual runoff (mm/year) is significant at 2°C of global average warming.

Results are calculated from the ensemble of 55 climate and hydrological model combinations. The change is calculated as the mean for the period at which the underlying GCM reaches 2°C global warming, minus the mean for the baseline period (1971–2000). The areas where the change is significant are coloured, while those that are not are shown in white. Source: Greuell et al., 2015.

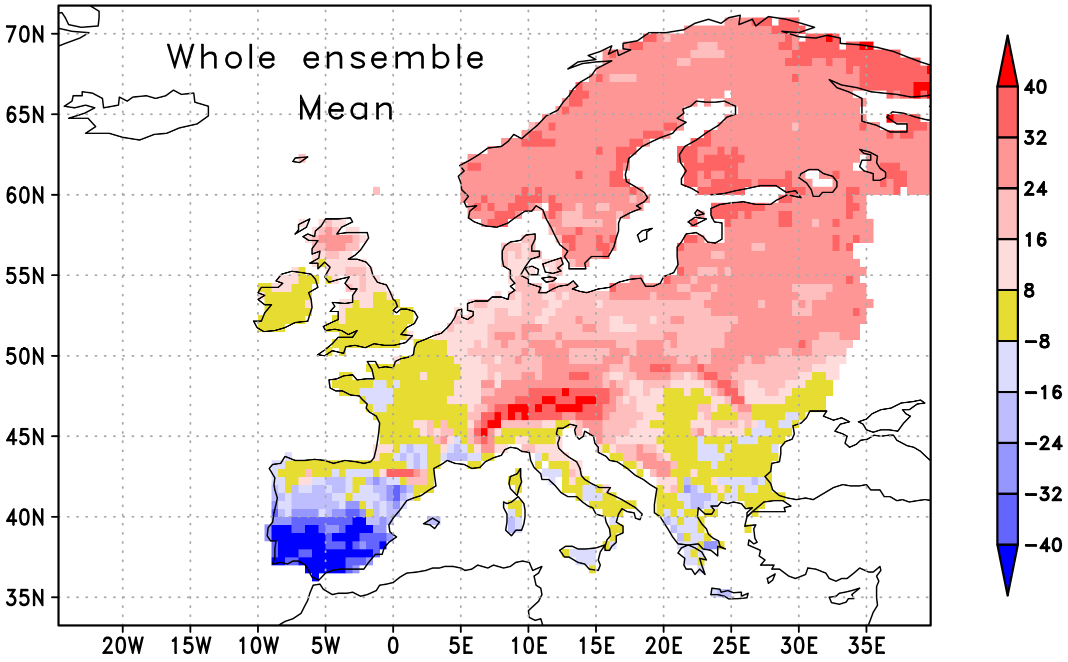
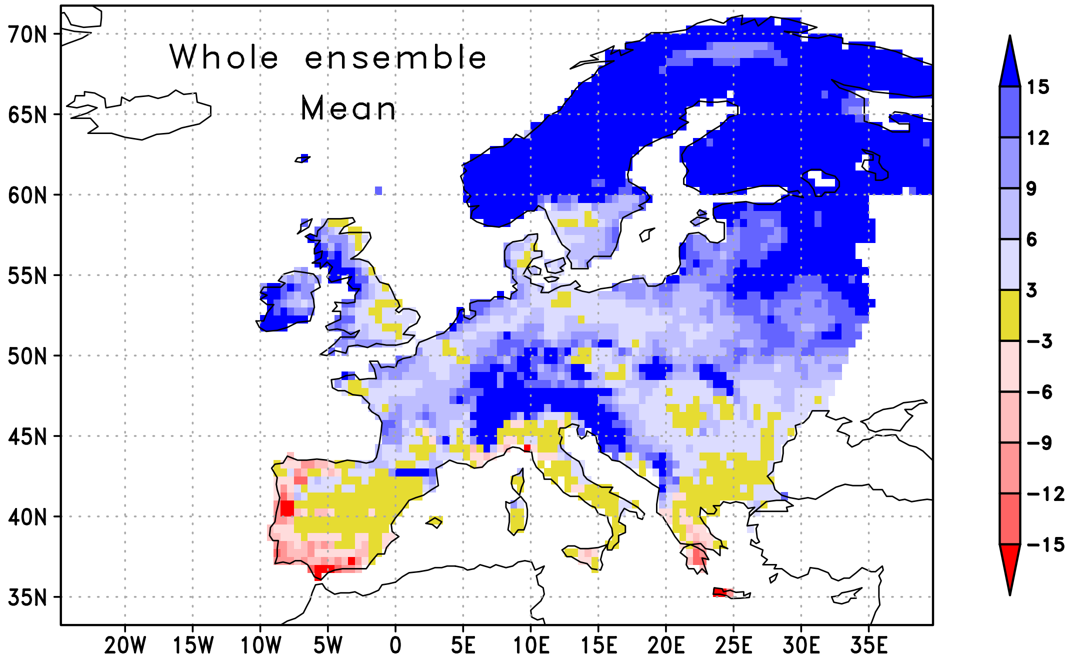


Figure 21. Change in evapotranspiration (mm/year) at 2°C of global average warming.

Results are calculated from the ensemble of 55 climate and hydrological model combinations.The change is calculated as the mean for the period at which the underlying GCM reaches 2°C global warming, minus the mean for the baseline period (1971–2000). Source: Greuell et al., 2015.



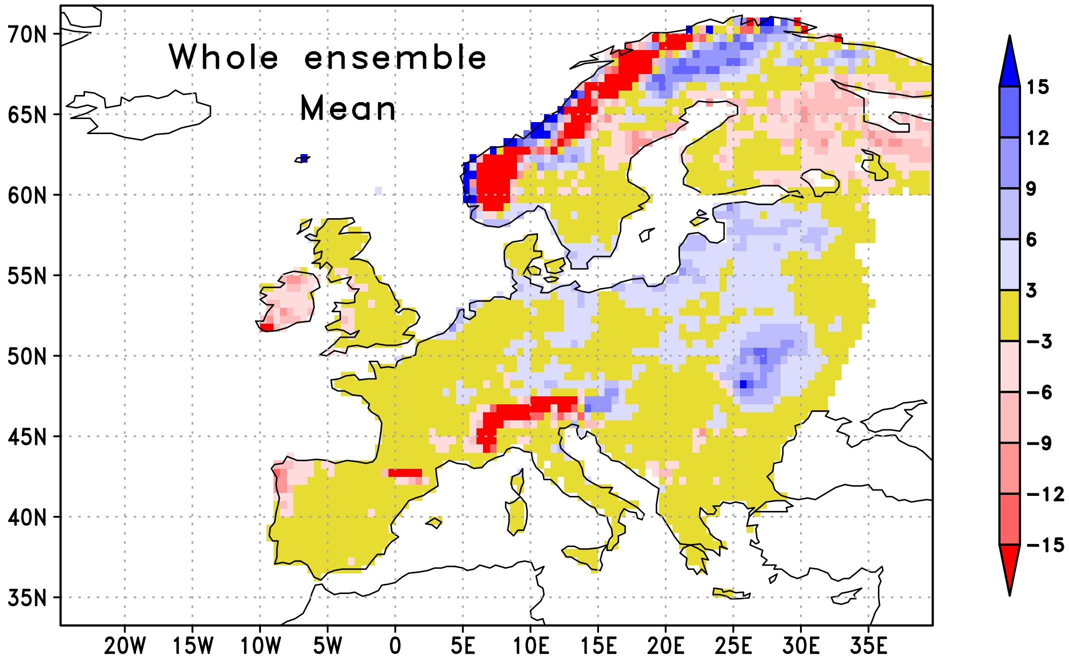


Figure 22. Seasonal change in total runoff (mm) for winter (top) and summer (bottom) at 2°C of global average warming.

Results are calculated from the ensemble of 55 climate and hydrological model combinations.The change is calculated as the mean for the period at which the underlying GCM reaches 2°C global warming, minus the mean for the baseline period (1971–2000). Winter = DJF, Summer = JJA. Source: Greuell et al., 2015.

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temperatures (leading to higher atmospheric moisture deficit) and higher rainfall (leading to higher water availability in the soils). However, in Southern Europe, and particularly on the Iberian Peninsula, decreases are projected: while potential evapotranspiration increases with increasing temperatures, less soil moisture will be available as precipitation decreases, ultimately limiting evapotranspiration.

There are also seasonal patterns to these changes. The climate models indicate that winter precipitation increases in most of Europe (Figure 22 top). This leads to more runoff across most of the continent, especially in Scandinavia where a larger proportion of the precipitation falls as rain in a warmer climate rather than snow.

The changes in summer are, however, more complex (Figure 22 bottom). There is a reduction in runoff in some parts of Southern Europe, reflecting the patterns of rainfall described above, but there are also decreases in runoff in the Norwegian and Swedish mountains, due to the reduction in summer snow melt. This occurs as a result of the warming climate, as the snowpack melts earlier in the year and precipitation storage in the snowpack is likely to be smaller. Similar effects also explain the summer decrease in runoff in the Alps. Increases in summer runoff are also seen in some locations in Eastern Europe, where summer precipitation significantly increases.

With the increase in heavy precipitation events (see the earlier section in this policy brief), there is a potential for higher flood risks. The IMPACT2C project has investigated this by looking at the change in flood risk using the metric of a 1 in 10 year return period flood (i.e. the discharge that statistically occurs once every 10 years). The results are shown below. These consider how the increase in rainfall events (assessed as the daily precipitation event occurring 1 in every 10 years) could subsequently affect flood risk. This analysis focused on the three hydrological models that are best set up to analyse floods (thus

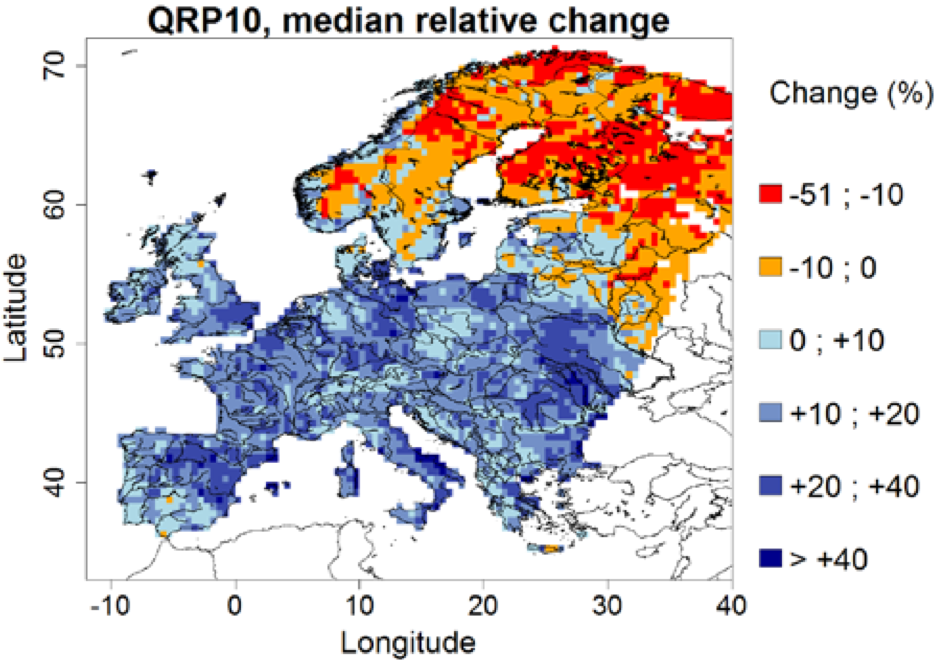

Figure 23. The change (%) in the magnitude of one-in-10-year floods at 2°C of global average warming.

Results are calculated from the ensemble of 33 climate and hydrological model combinations.The change is calculated as the median for the period at which the underlying GCM reaches 2°C global warming, minus the median for the baseline period (1971–2000). Source: Roudier et al, 2015.

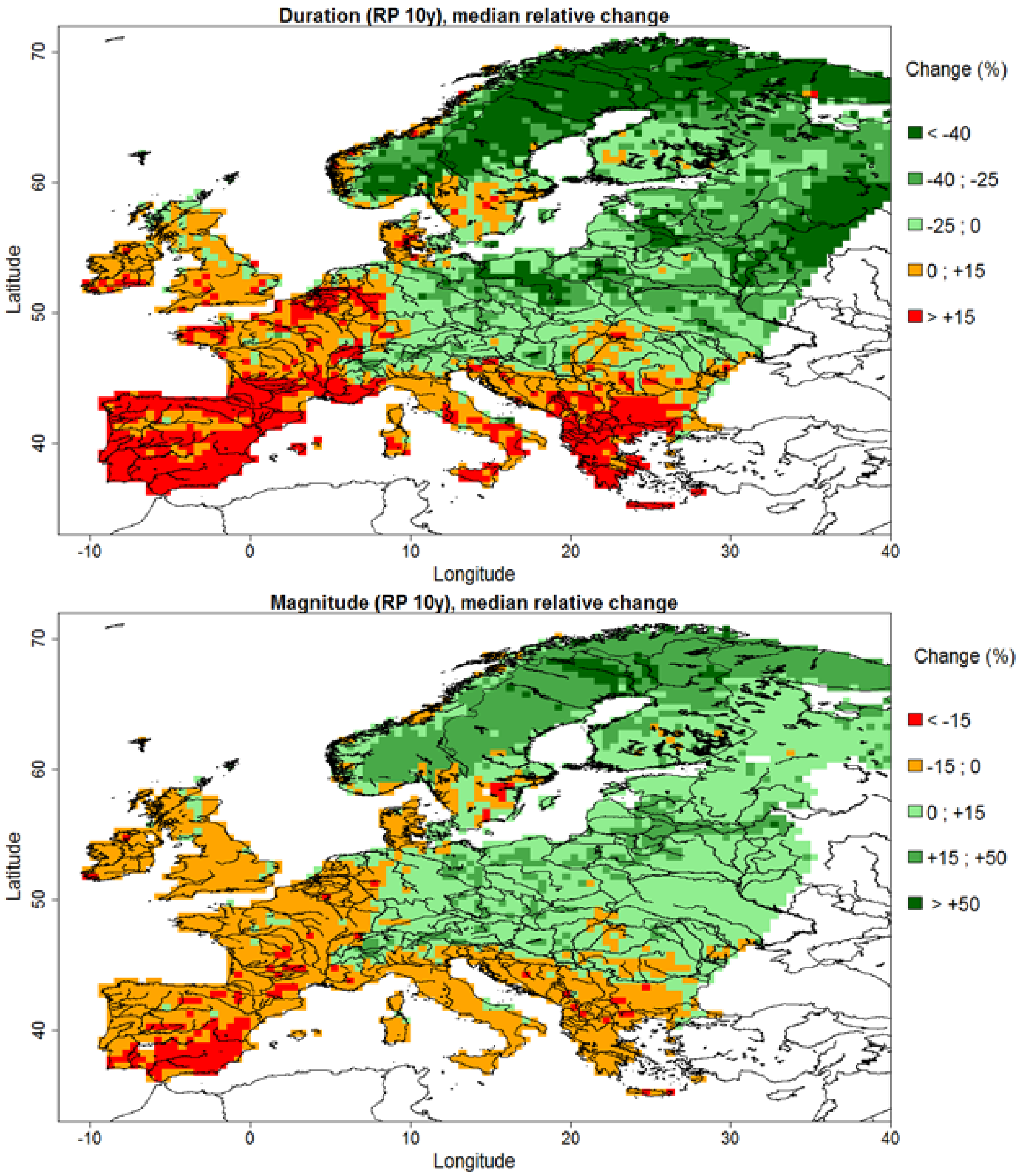

Figure 24. The change (%) in the duration (top) and magnitude (bottom) of one-in-10 year low flows (stream flow droughts) at 2°C of global average warming.

Results are calculated from the ensemble of 22 climate and hydrological model combinations.The change is calculated as the median for the period at which the underlying GCM reaches 2°C global warming, minus the median for the baseline period (1971–2000). Source: Roudier et al, 2015.

the ensemble consists of 33 simulations and the median is presented due to the smaller ensemble).

The results show that for much of Europe, the one-in-10-year flood event – as experienced in today's climate – is projected to become more severe. It can also be concluded that such events are likely to become more frequent, i.e. an event that currently occurs once every ten years today will occur more commonly at 2°C of warming (shown in Figure 23). However, in Finland, Northern Sweden and Northern Norway, the one-in-ten-year event is projected to decrease, i.e. to become less severe. This is because current flood risks in these areas are primarily driven by spring snow melt. As snow deposition is projected to decrease and snowmelt to occur earlier, this reduces flood risks. However, these same areas do experience an increase in rainfall driven flood risks.

There are also potential changes in hydrological drought intensity (defined here, analogous to the floods, as the low flow occurring statistically 1 every 10 years) and duration (the period of time below the 1:10 threshold). This analysis focused on the two hydrological models that are most suitable to analyse low flows (thus the ensemble consists of 22 simulations). Again, there is a very strong distributional pattern to these changes, above and below a diagonal split across Europe as shown in Figure 24 on previous page.

Low flow periods will become more intense (i.e. lower river flows) and last longer in the Mediterranean, in France, Belgium and parts of the British Isles, due to decreasing summer precipitation and increasing evapotranspiration. In the rest of Europe, low flows are projected to become less severe and will be shorter. In Finland, Sweden and Norway, where low flows generally occur in winter, they are projected to increase in magnitude because a larger part of precipitation will fall as rain instead of snow.

Finally, the study looked at the changes in soil moisture, which is important for sustaining growth and survival of plants including agricultural crops, grazing land and natural ecosystems. The analysis projected reduced soil moisture content in parts of the Mediterranean, but increases elsewhere in Europe, shown in Figure 25. This finding is

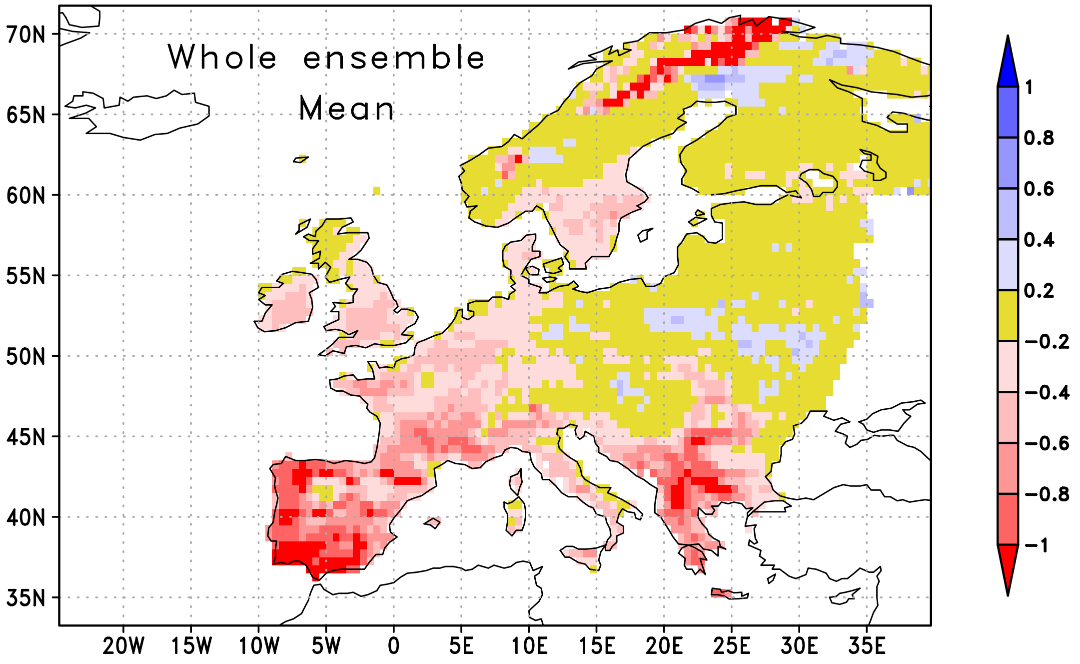

Figure 25. The change in the soil moisture at 2°C of global average warming.

Results are calculated from the ensemble of 55 climate and hydrological model combinations.The change is calculated as the mean for the period at which the underlying GCM reaches 2°C global warming, minus the mean for the baseline period (1971–2000). Source: Greuell et al., 2015.

important because it potentially increases water deficit risks in already water stressed regions. This may mean there is a need to supplement agriculture with irrigation – to the extent this is still possible, given the potential decreases in river flow shown above. There is therefore a potential increased risk of agricultural drought in irrigated and rainfed systems in the most vulnerable region of Europe, in the south, where the decreases in soil moisture were significant. A key difference here was that the uncertainty in the projections was dominated by the hydrological models rather than the climate models.

Overall, the results show that even in a + 2°C warmer world, there will be important changes to the European water cycle. These changes will affect water resources. They will also affect flood and drought risks. Importantly, the different regions of Europe will not be affected in the same way. Mean precipitation, evapotranspiration and runoff are projected to increase in central and northern areas of Europe. However, in the Mediterranean, the projections are for reduced runoff and discharge, which will decrease water availability. There are also potential increases in hydrological extremes and the risk of floods across much of Europe: the exception being North-East Europe, where floods could potentially decrease due to a decrease in snow-melt. Droughts and soil moisture stress are also projected to increase, particularly in Southern Europe which already experiences water stress today. These changes will have an important impact on water resource management and will affect multiple sectors, including agriculture, energy and river navigation, as well as the natural environment and ecosystems.

Key message. Even under 2°C of global change, there are potentially important impacts for the water cycle in Europe. These will affect water resources, and change flood and drought risks, though the changes differ across the continent. Precipitation, evapotranspiration and runoff are projected to increase in Central and Northern Europe, but decrease in the Mediterranean. There are also potential increases in flood risks across much of Europe, although droughts and soil moisture stress are projected to increase in the South, which already experiences water stress today.

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References

Association of British Insurers (2005). Financial Risks of Climate Change. Association of British Insurers: UK. (http://www.abi.org.uk/climatechange).

Baccini, M.; Biggeri, A.; Accetta, G.; Kosatsky, T.; Katsouyanni, K.; Analitis, A.; Ross Anderson, H.; Bisanti, L.; D'Ippoliti, D.; Danova, J.; Forsberg, B.; Medina, S.; Paldy, A.; Rabczenko, D.; Schindler, C. and Michelozzi, P., (2008). Effects of apparent temperature on summer mortality in 15 European cities: results of the PHEWE project. Epidemiology 19 (5).

Brown, S., Nicholls, R.J., Hanson, S., Brundrit, G., Dearing, J.A., Dickson, M., Gallop, S., Gao, S. Haigh, I.D. Hinkel, J., Jiménez, J.A., Klein, R.J.T., Kron, W., Lázár, A.N., Neves, C.F., Newton, A., Pattiaratachi, C., Payo, A., Pye, K., Sánchez-Arcilla, A., Siddall, M., Tompkins, E.L., Vafeidis, A.T., van Maanen, B., Ward, P.J., Woodroffe, C.D. Commentary: Shifting perspectives on coastal impacts and adaptation. Nature Climate Change, 4, (9), 752–755.

Brown et al (2015). Projections of future seal level rise in Europe under a +2°C global warming. Deliverable from the IMPACT2C project.

CEU (2004). Spring Council meeting of the European Union, 2004.

CEC (2005). Winning the Battle Against Global Climate Change, Brussels, 9.2.2005. COM(2005)35 Final. Commission of the European Communities, Brussels.

CEC (2007). Limiting Global Climate Change to 2 degrees Celsius The way ahead for 2020 and beyond COM(2007)2. Commission of the European Communities, Brussels.

CEC (2011). A Roadmap for moving to a competitive low carbon economy in 2050. COM(2007)112. Commission of the European Communities, Brussels.

Church, J.A. et al. (Eds.), 2013. Sea Level Change. Working Group I Contribution to the IPCC Fifth Assessment Report (AR5). Climate Change 2013: The Physical Science Basis

CEU (1996). Council of the European Union. 1939th Council Meeting, Luxembourg, 25 June 1996.

EEA (2010). Mapping the impacts of natural hazards and technological accidents in Europe. An overview of the last decade. EEA Technical report No 13/2010. ISSN 1725-2237.

EEA 2012. Climate change, impacts and vulnerability in Europe 2012. An indicator-based report. EEA, Copenhagen, 2012. ISBN 978-92-9213-346- (http://www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012). Accessed December 2013.

G8 (2007). Heiligendamm. http://www.g-8.de/Webs/G8/EN/Homepage/home.html

Greuell W., Andersson, J., Donnelly, C., Feyen, L., Gerten, D., Ludwig, F., Pisacane, G., Roudier, P., & Schaphoff, S. (2015). 'Validation of five hydrological models across Europe and their suitability for making projections of climate change' and 'Projections of water resources under a +2°C global warming'. Deliverable from the IMPACT2C project.

IEA (2012). World Energy Outlook. Published by the International Energy Agency, Paris, France, 2012

IPCC (2012): Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of the Intergovernmental Panel on Climate Change
[Field, C.B., et al (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC (2013). Summary for Policymakers Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis.

IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

Jacob, D.; Petersen, J.; Eggert, B.; Alias, A.; Christensen, O. B.; Bouwer, L.; Braun, A.; Colette, A.; Déqué, M.; Georgievski, G.; Georgopoulou, E.; Gobiet, A.; Menut, L.; Nikulin, G.; Haensler, A.; Hempelmann, N.; Jones, C.; Keuler, K.; Kovats, S.; Kröner, N.; Kotlarski, S.; Kriegsmann, A.; Martin, E.; Meijgaard, E.; Moseley, C.; Pfeifer, S.; Preuschmann, S.; Radermacher, C.; Radtke, K.; Rechid, D.; Rounsevell, M.; Samuelsson, P.; Somot, S.; Soussana, J.-F.; Teichmann, C.; Valentini, R.; Vautard, R.; Weber, B. & Yiou, P. (2013). EURO-CORDEX: new high-resolution climate change projections for European impact research Regional Environmental Change, Springer Berlin Heidelberg, 2013, 1–16.

Joughin, I., Smith, B.E., Medley, B., 2014. Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. Science 344, 735–738. doi:10.1126/science.1249055

Hinkel, J. et al., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proceedings of the National Academy of Science.

Kriegler, E, Hall, JW, Held, H, Dawson, R and Schellnhuber, HJ (2009). Imprecise probability assessment of tipping points in the climate system. PNAS March 16, 2009, doi:10.1073/pnas.0809117106PNAS March 16.

Kjellström, E., Thejll, P., Rummukainen, M., Christensen, J.H., Boberg, F., Christensen, O.B., Fox Maule, C., 2013. Emerging regional climate change signals for Europe under varying large-scale circulation conditions, Clim. Res. 56, 103–119, doi: 10.3354/cr01146

Kundzewicz, Z. W., et al. (2014), Flood risk and climate change: global and regional perspectives, Hydrological Sciences Journal, 59(1), 1–28.

Landgren, O., Engen-Skaugen, T., Haugen, J.E. and Kjellström, E., 2013. Evaluation of temperature and precipitation from global and regional climate models, a comparison between different regions in Europe. IMPACT2C Report, Met.NO

Lenton, T.M., Held, H. Kriegler, E.. Hall, J.W., Lucht, W., Rahmstorf S. and Schellnhuber H.J. (2008). Tipping elements in the Earth's climate system, Proceedings of the National Academy of Sciences USA 105(6), 1786–1793.

Levermann, A et al. (2012) Potential climatic transitions with profound impact on Europe: Review of the current state of six 'tipping elements of the climate system'. Climatic Change (2012) 110:845–878. DOI 10.1007/s10584-011-0126-5.

McGranahan G., Balk D.,Anderson B. 2007 The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones Environ. Urbanisation 19 17–37

Nicholls, R.J., Wong, P.P., Burkett, V., Woodroffe, C.D., Hay, J. (2008) Climate change and coastal vulnerability assessment: scenarios for integrated assessment. Sustainability Science. 3(1), 89–102.

Pardaens, A.K., Gregory, J.M. and Lowe, J.A., 2011. A model study of factors influencing projected changes in regional sea level over the twenty-first century. Climate Dynamics, 36(9–10), 2015–2033.

Perrette, M., Landerer, F., Riva, R., Frieler, K. and Meinshausen, M. (2013). A scaling approach to project regional sea level rise and its uncertainties. Earth System Dynamics, 4(1), 11–29.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., Scheuchl, B., 2014. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophys. Res. Lett. 41, 3502–3509. doi:10.1002/2014GL060140

Roudier et al. (2015). Projections of future floods and hydrological droughts in Europe under a +2°C global warming. Deliverable from the IMPACT2C project.

Slangen, A.B.A. et al., 2014. Projecting twenty-first century regional sea-level changes. Climatic Change, 124, 317-322.

Stefan Sobolowski, Erik Kjellstrom, Grigory Nikulin (2014). D1.1.6 Identification of robust climate change patterns in scenarios from M1.1.1 and M1.1.2 (Euro-CORDEX and Med-CORDEX). Deliverable of the IMPACT2C project.

Smith, J.B., Schneider, S.H., Oppenheimer, M., Yohe, G.W., Hare, W., Mastrandrea, M.D., Patwardhang, A., Burton, I., Corfee-Morlot, J., Magadza, C.H.D., Martin Füssel, H-M., Barrie Pittock, A.B., Rahman, A., Suarez, A., Ypersele, J-P (2008). Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". 2008. PNAS Early Edition. doi: 10.1073/pnas.0812355106.

UNEP (2013). The Emissions Gap Report 2013. United Nations Environment Programme (UNEP), Nairobi.

UNFCCC (2010). The Cancun Agreements. United Nations Framework Convention on Climate Change. Available at: http://unfccc.int/meetings/cancun_nov_2010/meeting/6266.php

Van Vuuren, D.P., Riahi, K., Moss, R., Edmonds, J., Thompson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S.K., Arnell, A. (2012), A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change 22 (1), 21–35.

Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., Mendlik, T., Landgren, O, Nikulin, G.,Teichmann, C., Jacob, D. (2014). The European climate under a 2°C global warming. Submitted to Environment Research Letters.

Wigley, T.M.L. and S.C.B. Raper, 1993: Global mean temperature and sea level projections under the 1992 emissions scenarios. In: Climate and Sea Level Change: Observations, Projections and Implications (Eds. R.A. Warrick, E.M. Barrow and T.M.L. Wigley), Cambridge University Press, pp.401 404.

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Further information

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To find out more about the IMPACT2C project, please visit:
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Cover photo: Damage to the shelter and sea wall during the February 2014 storms in Exmouth in south-west England. 02-07-14 © nicolamargaret. I-Stock. ©iStockphoto.com.

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