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The European climate under a 2 °C global warming

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Abstract
A global warming of 2 °C relative to pre-industrial climate has been considered as a threshold which society should endeavor to remain below, in order to limit the dangerous effects of anthropogenic climate change. The possible changes in regional climate under this target level of global warming have so far not been investigated in detail. Using an ensemble of 15 regional climate simulations downscaling six transient global climate simulations, we identify the respective time periods corresponding to 2 °C global warming, describe the range of projected changes for the European climate for this level of global warming, and investigate the uncertainty across the multi-model ensemble. Robust changes in mean and extreme temperature, precipitation, winds and surface energy budgets are found based on the ensemble of simulations. The results indicate that most of Europe will experience higher warming than the global average. They also reveal strong distributional patterns across Europe, which will be important in subsequent impact assessments and adaptation responses in different countries and regions. For instance, a North–South (West–East) warming gradient is found for summer (winter) along with a general increase in heavy precipitation and summer extreme temperatures. Tying the ensemble analysis to time periods with a prescribed global temperature change rather than fixed time periods allows for the identification of more robust regional patterns of temperature changes due to removal of some of the uncertainty related to the global models' climate sensitivity.

Keywords: regional climate change, extreme events, European climate

1. Introduction

Internationally, there is an ambition to limit global average surface temperature to 2 °C relative to pre-industrial levels.

This is in broad alignment with Article 2 of the objectives of the United Nations Framework Convention on Climate Change (UNFCCC 1992), i.e. 'stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. The 2 °C goal was initially advocated (WBGU 1995) on the basis of the evidence of the IPCC 2nd Assessment Report (IPCC 1995) with the aim of avoiding serious adverse effects to water resources, ecosystems, biodiversity and human health. More recent IPCC assessments broadly reinforce the goal. The Third Assessment Report (TAR: IPCC 2001) outlined greater negative impacts and more widespread and greater risks with rising temperature (as presented in the reasons for concern 'burning embers' diagram), while the Fourth Assessment Report (AR4: IPCC 2007) stated it was 'very likely that all regions will experience either declines in net benefits or increases in net costs for increases in temperature greater than about 2–3 °C'. The European Union agreed to the proposed goal (CEU 1996, 2004, CEC 2005, 2007), and at the UNFCCC Conference of the Parties in Cancun (UNFCCC 2010), there was international agreement to 'establish clear goals and a timely schedule for reducing human-generated GHG emissions over time to keep the global average temperature rise below two degrees'.

One element of these review assessments—and the 2 °C goal—is the potential risk of catastrophic events (global or regional discontinuities), known as tipping points or tipping elements (Lenton *et al* 2008). While information on the likelihood of such events remain subjective, and the critical threshold temperatures that might trigger them are highly uncertain, previous studies (Smith *et al* 2008, Kriegler *et al* 2009) indicate potential concerns of shifting too far away from the present climate, and especially for moving above 2 °C of warming.

However, even the achievement of the 2 °C goal will be accompanied by a significantly changed climate from today, and will necessitate adaptation. In order to have a comprehensive picture of the consequences of a 2 °C warmer climate for Europe, climate projections with a higher spatial resolution than global climate projections (such as provided by the World Climate Research Program 'Climate Model Intercomparison Project' CMIP3 (Meehl *et al* 2007) and CMIP5 (Taylor *et al* 2012)) are needed, with a rigorous assessment of uncertainties. These goals can be achieved by ensembles of climate projections using regional, limited-area models to downscale global climate projections. Such ensembles have been produced in recent studies dedicated to Europe as in the EU FP5 project PRUDENCE (Christensen *et al* 2007) and EU FP6 project ENSEMBLES (van der Linden and Mitchell 2009).

However, none of these downscaled studies specifically investigated the climate associated with 2 °C warming. Instead, they investigated climate change and its uncertainty in fixed future timed periods. Also, most of the socio-economic scenarios used for these projections (SRES A1B, Nakićenović *et al* 2000) were not designed to reach a stabilized 2 °C warming and therefore, reach a warmer climate over the century. While a small number of simulations have investigated a 2° stabilization scenario (e.g. the ENSEMBLES E1 scenario, van der Linden and Mitchell 2009, Jacob and Podzun 2010), their small number does not allow for robust uncertainty estimation. New simulations carried out in the framework of the CMIP5 and EURO-CORDEX (Jacob *et al* 2013) have used a scenario that drives to a likely warming lower than 2 °C (RCP2.6), but at the time of writing the number of simulations using this scenario also remains too small to study uncertainty. The identification of changes corresponding to the 2 °C global warming thus requires using scenarios overpassing this target value with a snapshot approach.

Here we use the ENSEMBLES regional simulations of the A1B scenario (Nakićenović *et al* 2000), which are now well studied (Kjellström *et al* 2013, Déqué *et al* 2012). The GCMs driving these regional simulations have different sensitivities to natural and anthropogenic climate forcing and reach the target warming at different times. Our method is to collect changes in climate parameters associated with these different times and a reference period for each simulation and gather them in a '2 °C ensemble'. This ensemble thus includes uncertainties in the simulation of regional processes simulations and their responses to the global warming and reduces some of the uncertainty due to driving GCM sensitivity. There are limitations to this approach as it does not account for the contributions to uncertainty from systems that have response times longer than the 2 °C time period. This letter reports the most likely changes and their uncertainties calculated from this ensemble. It also aims to estimate the part of the uncertainty that is removed due to considering a period defined by a fixed global warming target instead of fixed time target. We focus on main variables such as temperature, precipitation, sea level pressure and winds, changes in their average and extremes, and on less classical but more explanatory variables such as surface fluxes. By doing so, we provide a unique assessment of what the 2 °C goal might mean for Europe's climate, overall and across regions, and how this compares to the global average.

2. GCM and RCM simulations used

In the subsequent analysis, we analyze 15 out of 22 RCMs from ENSEMBLES with a horizontal resolution of about 25 km. The 22 RCMs are driven by 6 different A1B GCMs, however, not each of the regionalized climate simulations has a sufficiently long time series to reach +2 °C warming. This leaves 15 RCM simulations driven by 6 different GCMs (table 1).

Two of the GCMs (bccr_bcm2_0-r1, mpi_echam5-r3) are realizations from the CMIP3 multi-model dataset (Meehl *et al* 2007), three models (HadCM3Q0, HadCM3Q3, HadCM3Q16) stem from the Hadley Centre perturbed physics GCM ensemble 'QUMP' (Quantifying Uncertainty in Model Predictions) (Collins *et al* 2011). One GCM (ARPEGE; Salas y Mélia *et al* 2005) is a spectral model with a stretched grid (Fox-Rabinovitz *et al* 2008).

In order to account for RCM and GCM errors, we used a model output statistic (MOS) approach (Maraun *et al* 2010), namely quantile mapping (QM) as described by Themeßl *et al* (2011), based on Déqué (2007). The observational reference was the E-OBS version 5 dataset on a regular 25 km × 25 km

Table 1. Time period for which +2 °C and +1.5 °C compared to pre-industrial times was reached in ENSEMBLES A1B global climate projections.

GCM	RCM	+2 °C central year	+2 °C period	+1.5 °C central year	+1.5 °C period
bccr_bcm2_0-r1	RCA HIRHAM	2052	2038–2067	2039	2025–2053
HadCM3Q0	RRCMCLM HadRM	2035	2021–2050	2022	2008–2037
HadCM3Q16	RCA HadRM	2028	2014–2043	2016	2002–2031
HadCM3Q3	RCA HadRM	2047	2033–2062	2028	2014–2043
mpi_echam5-r3	RegCM REMO HIRHAM RACMO RCA	2048	2034–2063	2035	2021–2050
ARPEGE	ALADIN HIRHAM	2043	2029–2058	2028	2014–2043

grid (Haylock *et al* 2008) in the period 1965–2010. We used bias corrected data whenever available, i.e. for daily mean, minimum, and maximum temperature and daily precipitation sum.

Themeßl *et al* (2012) demonstrated the successful application of QM to future scenarios of daily precipitation and Wilcke *et al* (2013) for other meteorological variables. This implementation is very stable and flexible and has been demonstrated to have higher skill in systematically reducing RCM biases than parametric methods (Gudmundsson *et al* 2012). In order to avoid the suppression of new extremes in the future periods (i.e. values outside the calibration range), our implementation uses the correction terms of minimum and maximum values of the calibration range outside of the calibration range. Although this simple heuristic extrapolation can probably be improved by using methods of the extreme value theory, it proved to be stable and to lead to better results than the uncorrected model output (Themeßl *et al* 2012). However it has to be kept in mind that while quantile mapping is very successful in removing biases and adjusting distributions, it cannot substantially improve the temporal structure of time series from RCMs (e.g., Maraun 2012 and Wilcke *et al* 2013) or properly correct biases in atmospheric circulation (Eden *et al* 2012). Further, several studies show that bias correction can moderately modify the climate change signal of a simulation (Christensen *et al* 2008, Themeßl *et al* 2012, Boberg and Christensen 2012, Dosio *et al* 2012). However, we conducted a parallel analysis based on raw RCM output (not shown), which led to similar qualitative conclusions as the presented study for mean changes.

3. When is global climate likely to reach a 2 °C warming?

In this study the +2 °C period is defined as the time when the 30-year average global mean temperature reaches +2 °C, compared to a 'pre-industrial' period 1881–1910. To define the +2 °C period, we analyzed past observed and future projected temperatures. The following global observational datasets have been analyzed for this purpose: GISS LOTI (1880–2011) (http://data.giss.nasa.gov/gistemp/), HadCRUT3 (1850–2011) (www.cru.uea.ac.uk/cru/data/temperature/), and NOAA NCDC (1880–2011) (www.ncdc.noaa.gov/cmb-faq/anomalies.php). The time period common to all datasets matching best the pre-industrial period is 1881–1910. Thus, we consider past pre-industrial warming until the base period as the temperature rise in a 30-year running mean from 1881–1910 to 1971–2000 (figure 1). The three datasets show an average past warming from the pre-industrial period until the base period of 0.46 K (GISS LOTI: 0.437 K, HadCRUT3: 0.475 K, NOAA NCDC: 0.477 K). Thirty-year running means, starting from the base period 1971–2000, are calculated for the 6 GCMs used. The +2 °C period is determined by the year when the 30-year running mean crosses the +2 °C threshold. The projected +2 °C periods show considerable spread, reaching from 2014–2043 (HadCM3Q16) to 2038–2067 (BCM) (figure 1) with corresponding central years at 2028 and 2052, respectively. The subset of 6 GCMs used in this analysis (table 1) still spans the same range for global temperature, so no considerable information should be lost in this respect compared to the full set of ENSEMBLES GCMs, even though possibly reducing the range for regional variables. Also, compared to the entire CMIP3 A1B ensemble with 53 simulations, the ENSEMBLES GCMs miss some lower sensitivity simulations. The CMIP3 simulations project +2 °C warming from 2029 up to 2075, with a median of 2049, whereas the selected ENSEMBLES GCMs reach +2 °C around 2045. Figure 1 (bottom panels) shows for comparison global warming in the new CMIP5 simulations for the representative emission pathways RCP2.6, RCP4.5 and RCP8.5. While most of the RCP2.6 simulations don't reach +2 °C at all, the RCP4.5 simulations reach it around 2050 and the RCP8.5 simulations around 2042 (median). This means, except for RCP2.6, all shown emission scenarios most likely to lead to +2 °C warming in a relatively narrow time window between 2042 and 2050, while much stronger differences between the scenarios can be expected in the second half of the 21st century.

4. Robustness assessment

Recently a number of approaches to assess and communicate robustness of projected climate change have been proposed (Tebaldi *et al* 2011), distinguishing model agreement in sign and some indication of statistical significance of individual models changes. They also generally make some attempt to show areas where the climate change signal is low relative to internal variability, but may still contain useful information for policy makers (e.g. a projected change is small and not statistically significant but the models agree on the sign). Here we simply define robustness based on agreement between models. In order for the ensemble change to be considered robust 12 of the 15 models at least must agree on the sign

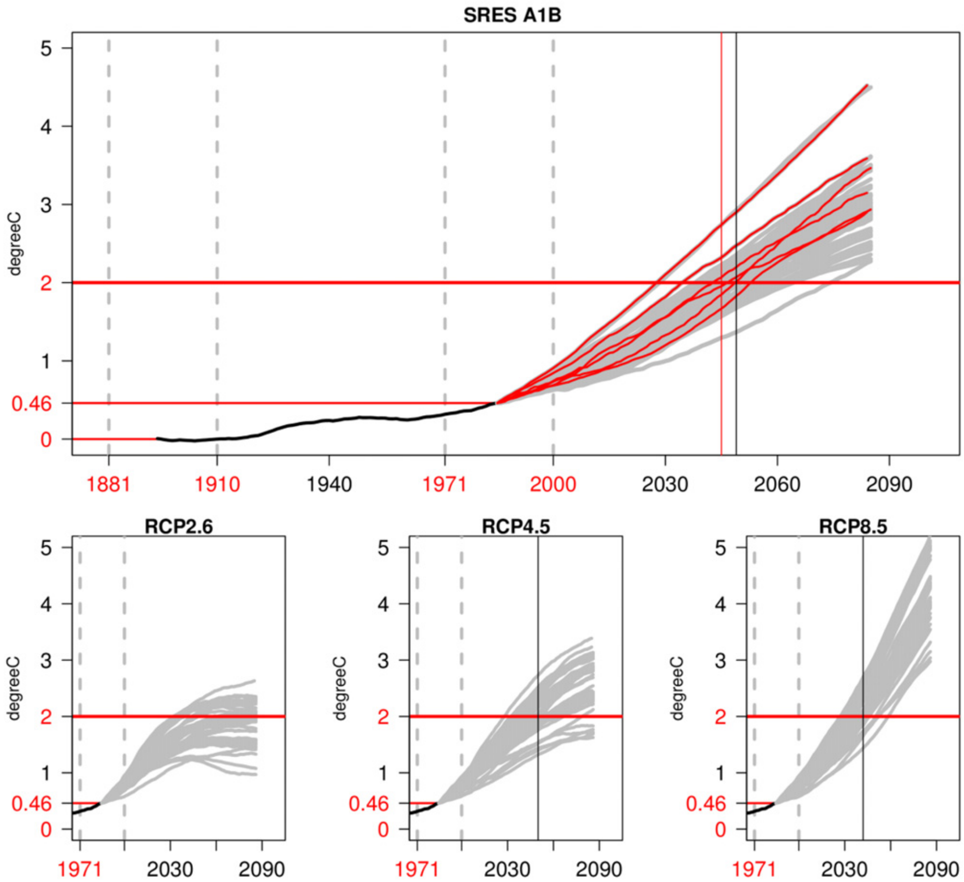

Figure 1. Global mean temperature (30-year running mean; gray lines) for the SRES A1B ensemble (top panel) and for the RCP2.6, RCP4.5 and RCP8.5 CMIP5 simulations (bottom panels) exceeding the +2 °C threshold (bold red horizontal line). The average observed temperature compared to pre-industrial (1881–1910) is depicted in the upper panel as black line. The CMIP3 and CMIP5 ensemble median years of reaching the 2 °C target for each emission scenario are shown as black vertical lines, whereas the red vertical line represents the median year of the six driving GCMs of this study, which are highlighted in red. Since most RCP2.6 simulations stabilize below +2 °C, no median exceedance year is shown.

(threshold based on the 95% confidence interval of a binomial test with 50% chance of success). In subsequent figures, areas where such an agreement is not obtained are filled by gray color. A more in-depth investigation of uncertainty will be carried out in a future study using a broader ensemble of EURO-CORDEX simulations and multiple socio-economic scenarios.

5. Changes in Europe at 2 °C average global warming

Under a 2 °C global warming (+0.46 °C from pre-industrial to 1971–2000 and +1.54 °C from 1971–2000 to the 2 °C period), ensemble-averaged projected European regional warming generally ranges between 1.5 and 2.0 °C depending on the region. European temperatures therefore mainly exceed the global warming after 1971–2000 (figure 2(a)). Only North-Western Europe (British Isles and France in particular) witness a lower relative increase in warming, i.e. below 1.54 °C. The warming is higher in winter (mean = 1.99 °C, 25% = 1.65 °C, 75% = 2.34) than in summer (mean = 1.72 °C, 25% = 1.45 °C, 75% = 1.99) (figure 2(c)). The spread of simulated changes, measured as the standard deviation between individual model changes, ranges between about 0 and 1 °C depending on season (not shown). The removal of the uncertainty related to transient climate response to radiative forcing in the GCMs can be readily seen when comparing the spread of simulated temperature changes at +2 °C to those from a fixed time period of 2031–2060, which has a roughly equivalent mean temperature change (figure 2(c)).

Figure 3 (left panels) shows the mean temperature changes simulated by the RCMs between the control period and the +2 °C period, in winter and summer separately. This provides information on the pattern of warming across Europe. Average changes have similar patterns as those described for fixed time periods in several regional ensemble studies (Fischer and Schär 2010, Kjellström *et al* 2011): a temperature increase is found everywhere for all models, with enhancement in North-Eastern and Eastern parts of Europe in winter (2–3 °C) and in Southern Europe in summer (2–3 °C). The regional warming exceeds the global warming in most areas except the British Isles and Iceland, where the influence of the moderate warming of the North Atlantic is seen in all seasons. In summer, a relatively small warming is also seen close to the North Sea and the

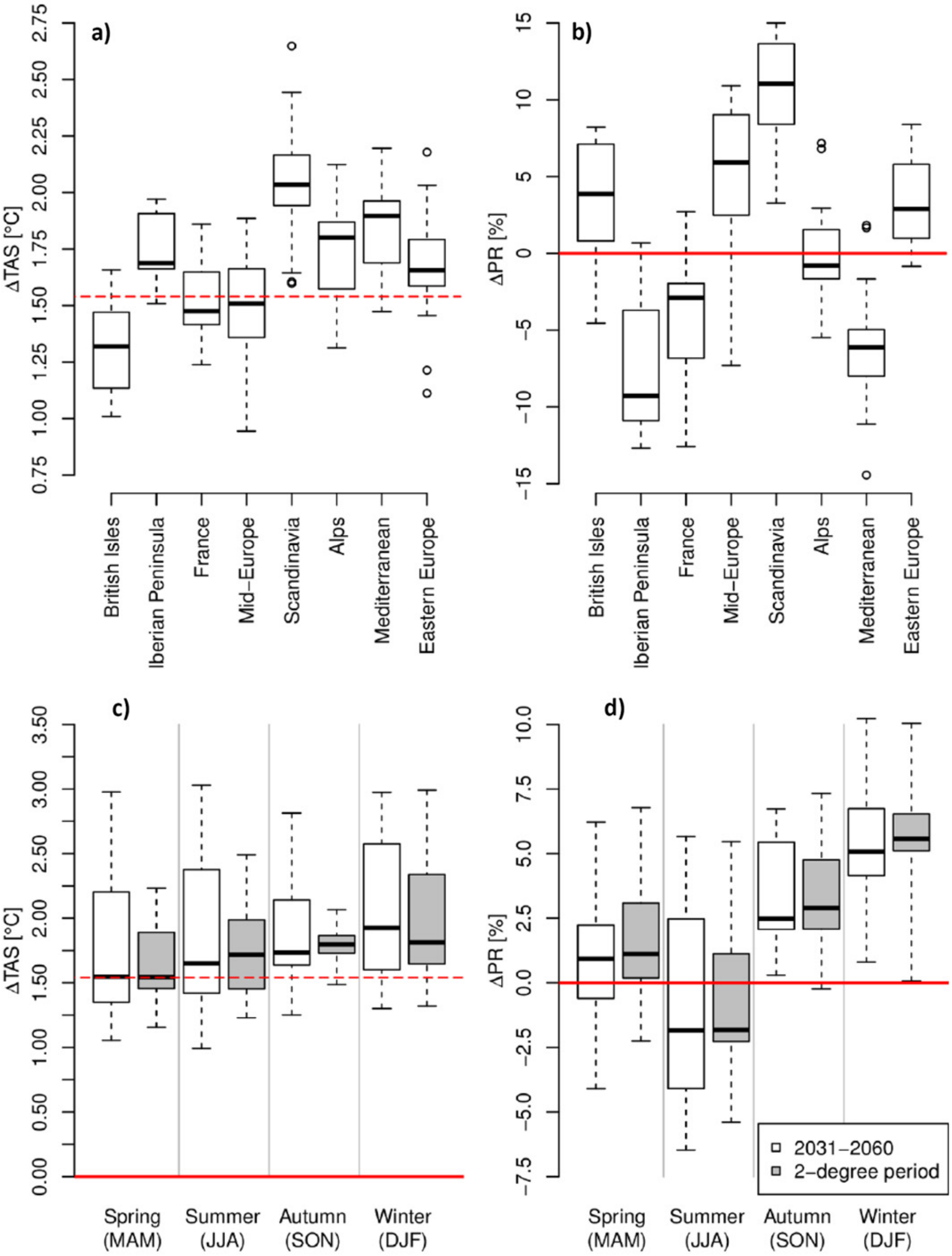

Figure 2. (a) Yearly averaged change—relative to the reference period 1971–2000—in yearly mean temperature in the different European regions for periods corresponding to +2 °C of global average change. The global temperature change (1.54 °C) between 1971–2000 and the 2 °C period is marked as a dotted line. (b) Same as (a) for precipitation in % of change. The solid red line indicates no change for precipitation and the red dotted line a change of 1.54 °C for temperature, corresponding to a global warming of 2 °C relative to pre-industrial. (c) Spatial average over land of changes in temperature and (d) precipitation, together with the range of changes for the GCM–RCM ensemble (median, 25–75% range and min and max values). The open bars refer to fixed time future period (2031–2060), the gray bars to the temperature controlled (+2 °C) period.

Baltic Sea. All areas undergo robust warming (robustness not shown for temperature because it covers all areas). The ensemble standard deviation of the changes remains much smaller than the amplitude of changes (about 3–10 times smaller) everywhere (not shown).

These spatial differences are important with respect to subsequent impacts. Higher summer temperature changes are found in the Iberian Peninsula and the Mediterranean region, and will thus compound existing temperature-related impacts such as energy use for cooling (EEA 2012). However, the higher winter warming in Northern Europe will have a mix of positive as well as negative effects, including reduced winter heating. This reveals important distributional consequences

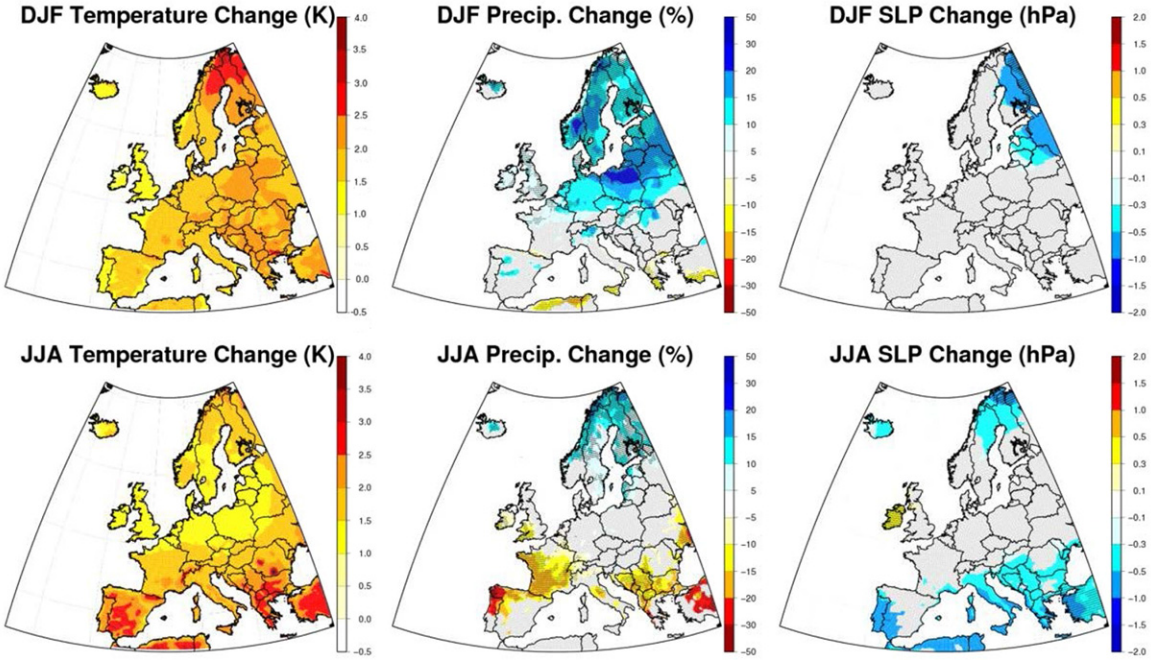

Figure 3. Seasonal mean changes of temperature (left panels), precipitation (middle panels) and sea level pressure (right panels), between the 1971–2000 and the +2 °C periods. Top panels show wintertime changes and bottom panels show summertime changes. Only areas where at least 12 models agree on the sign of the change are colored and areas where at least 14 models agree on the sign of the change are dotted areas. For temperature the agreement on the sign of the change was found everywhere and is not shown.

across Europe, in terms of the patterns of likely impacts, even under the 2 °C goal.

A similar analysis has been undertaken for precipitation. When averaged over the PRUDENCE regions, annual average precipitation robustly decreases by up to about 10% in Southern sub-regions while it may increase with more than 10% in Northern Europe (figure 2(b)). When averaged over European land areas for each season, mean precipitation significantly increases in autumn (mean = 3.3%, 25% = 2.1%, 75% = 4.8%) and winter (mean = 5.3%, 25% = 5.1%, 75% = 6.5%) but changes in spring (mean = 1.7%, 25% = 0.2%, 75% = 3.1%) and summer (mean = −0.5%, 25% = −2.3%, 75% = 1.1%) do not show a clear sign (figures 2(b)–(d)). In winter, a general increase is found with maximum values in Northern Europe, especially along many coastal areas, where all models agree upon an increase of 10–15% (figure 3 middle panels). In Southern Europe the models do not agree on sign except over a few areas (Southern Italy, Greece). By contrast, in summer, the models agree on a robust decrease of precipitation in South-Central Europe of about 10–15%, together with an increase in precipitation over Scandinavia. These changes may exacerbate existing water management issues across Europe, i.e. potentially increasing water deficits in the South during the already heat and evaporation stressed summer. The only area where all models agree on the sign of change is Scandinavia (increase in both seasons) and some smaller areas in South-Eastern Europe and the West coasts of the Iberian Peninsula, France and the Southern British Isles (decrease in summer).

Some climate change signal is found in sea level pressure (figure 3, right panels) in the winter season with lower pressure in the Northeast, but the signal is not very robust. This is however consistent with the temperature and precipitation changes and suggests expansion of the subtropical dry zone into Southern Europe and an enhanced hydrological cycle in Northern Europe and Scandinavia. The summer signal is more robust with most of the models agreeing on modest decreases in SLP across Southern Europe. This modest response could be indicative of localized thermal low pressure due to heating. This is a common feature in the Iberian Peninsula under present conditions but any future increase of said phenomenon requires further elucidation than the present study allows. The summer pattern also indicates an increase in the North–South pressure gradient over the Northern part of the North Atlantic in the domain as pressure increases over the British Isles and decreases over Iceland. Such an increase may help to explain the increase in precipitation in parts of Scandinavia as partly being a consequence of enhanced moisture transport from the North Atlantic.

6. Extremes

Extreme temperature is here defined as the daily maximum temperature that is exceeded on average only once every 20 years. This is termed the return value and 20 years the return period. Changes in extreme temperature are thus, characterized through changes in the 20-year return values. Return values are estimated using the block maxima method for which the generalized extreme value (GEV) distribution describes the behavior of said maxima (Coles 2001). The approach closely follows that of Nikulin *et al* (2011) and further details are provided therein.

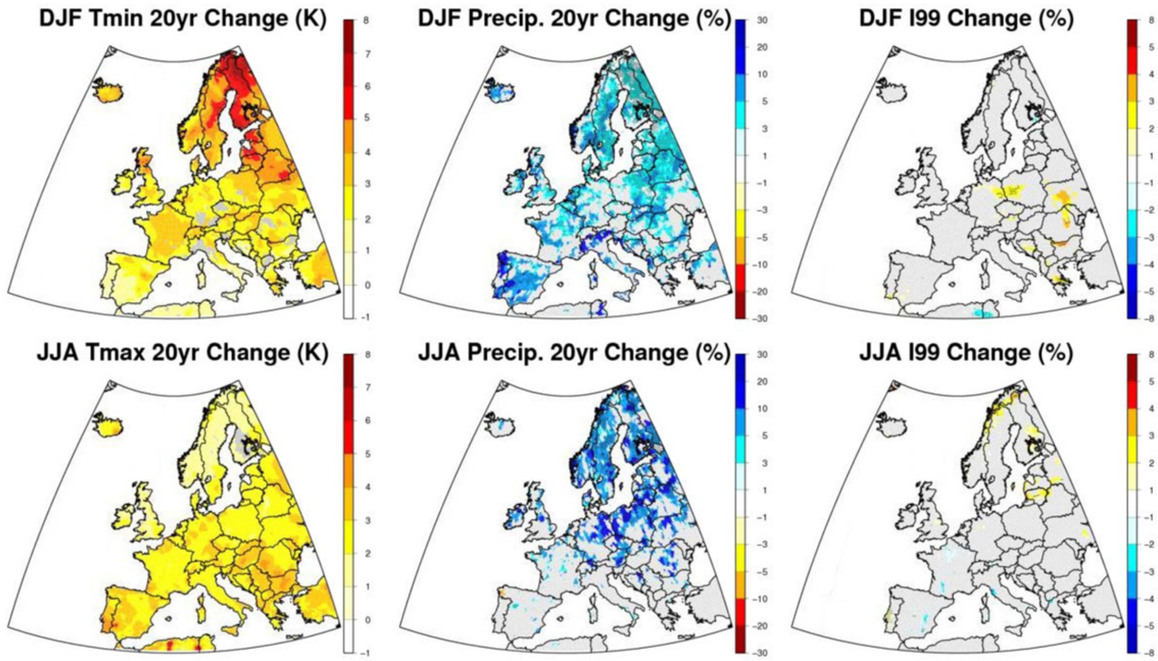

Figure 4. Changes, between the 1971–2000 and the +2 °C periods, in the 20-year return value for Tmin in winter (upper left), Tmax in summer (lower left), heavy precipitation in winter (top middle) and in summer (bottom middle), extreme winds (I99) in winter (top right) and in summer (bottom right). Only areas with at least 12 models agreeing on change sign are colored. Areas where at least 14 models agree on change sign are highlighted with dots (except for temperature where almost all areas satisfy this).

For summer daily maximum temperatures (figure 4), the largest changes (3–4 °C) are found over South-Eastern Europe and the Iberian Peninsula. In areas where this value is highest under today's conditions (Iberian Peninsula, France, the Balkans) the 20-year return value is expected to rise well above 40 °C. As increases in summer extreme heat are linked to health impacts in the form of temperature-related mortality (Baccini *et al* 2008) the pattern of changes projected under 2 °C is likely to have important health impacts in the more vulnerable regions of Europe. Conversely, the extremes of daily minimum temperatures are reduced most notably in Northern and Eastern areas of Europe, which will have benefits in reducing current winter cold extremes and cold-related mortality as well as winter heating costs (EEA 2012), though there would also be negative impacts, such as on winter tourism and ecosystems.

All temperature changes are found to be robust but the spread between models is high in Central and North-Eastern Europe. In parts of this area, notably in Northern Sweden and Finland, there are even models indicating no increase in extreme maximum temperatures. Discrepancies in this area may to some extent be related to how different RCMs treat lakes as parts of this area has a large fraction of lakes that have an impact on the regional climate (Samuelsson *et al* 2010). Extremes of wintertime daily minimum temperature (figure 4) undergo a large positive change in winter, ranging from 2–3 °C in Central and Southern Europe to 5–8 °C in Scandinavia and Russia. These changes are robust but again a large spread in model responses is found over Central Europe, where some models do not even agree on the positive sign of the change in extreme temperatures.

Changes in extremes of heavy precipitation defined as the 20-year return value calculated from extreme value theory in the same way as outlined for temperature above are shown in figure 4. The ensemble mean exhibits positive changes in almost all areas both in summer and winter, with amplitude ranging from 5% to about 15%. The increase is marked over Eastern Europe and Scandinavia in summer and over Southern Europe in winter. In contrast to this study, where no overall trend in extreme summer precipitation in Southern Europe is found, Kendon *et al* (2008) and Maraun (2013) found a decrease for extreme summer precipitation in this region. The difference in the findings might be related to the fact that the negative trend emerges relatively late and thus might not have emerged for some ensemble members when reaching the +2 °C period. It may also result from the way extremes are defined and the different sets of selected simulations, indicating a lack of robustness of a possible decrease.

The increases in heavy precipitation are an important factor with respect to flood risks, thus the increases in heavy precipitation found under the +2 °C scenario are likely to enhance the potential for these events. Floods are among the most important weather-related loss events in Europe and can have large economic consequences: the EEA (2010) reports total losses of over €50 billion over the past decade. The projected increase in Eastern Europe is a particular concern because this is one of the existing flood hot spots. Uncertainties remain large in the southernmost areas of Europe. Compared to the changes in seasonal means the changes in extremes are less spatially coherent and individual models exhibit patchy structures.

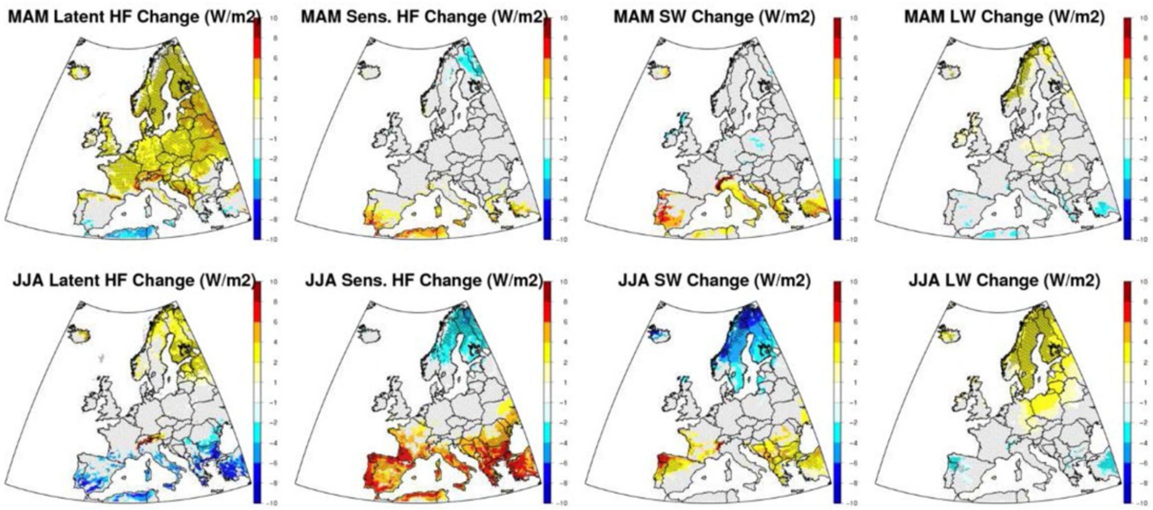

Figure 5. Changes, between the 1971–2000 and the +2 °C periods, in surface energy fluxes. Left panels: latent heat fluxes; second left panels: sensible heat fluxes; second right panels: net short-wave fluxes; right panels: net long-wave fluxes. Upper panels: MAM, Lower panels: JJA. Only areas with at least 12 models agreeing on change sign are colored. Areas where at least 14 models agree on change sign are highlighted with dots (except for temperature where almost all areas satisfy this).

Windstorms are also among the most damaging extreme events in Europe (ABI 2005). Extreme winds are calculated here as the 99th percentile of the daily maximum 10-meter wind speed for each season (I99). Figure 4 (right panels) show the ensemble mean relative changes in I99 (in %) winds as simulated by the RCMs, in winter and summer. Robust increases of extreme winds of up to 10% are only seen over small scattered areas of Central/Eastern Europe in winter. Over most regions the change is generally positive but not robust.

7. Surface energy budget

Surface weather changes are influenced both by larger scale dynamical changes and by local changes in the physics of the vertical column above the surface. These latter changes are due to clouds, atmospheric composition, turbulence, soil moisture and temperature as well as land use properties. All these processes influence the surface energy budget (SEB), characterized by radiative and heat fluxes. Changes in the SEB are particularly important for driving changes in summer temperature and precipitation, which involve amplifying feedback processes (Seneviratne *et al* 2010, Fischer *et al* 2007). They also have impacts on drought changes, river discharge, water and energy resources, with important economic implications.

We consider net short- and long-wave fluxes, sensible and latent upward fluxes, only in spring (MAM) and summer (JJA) in order to analyze the evolution of heat fluxes across the growing season. Spatial patterns of latent and sensible heat flux changes are shown in figures 5(a)–(d). In spring, almost all models agree on an increase of latent heat except in southernmost areas and in other smaller areas such as North-Western coastal areas (this is also the case in fall and winter). This distribution is consistent with the energy-limited nature of evapotranspiration in Europe in spring (Teuling *et al* 2009). In summer, the latent heat increase is restricted to Northern areas while Southern areas, including large parts of Central Europe, have decreasing latent heat due to drought increase and soil-moisture limitations. This drying causes an increase in sensible heat in summer in this area, with large model agreement, while over Scandinavia sensible heat fluxes decrease due to a wetter and cloudier climate. In spring, sensible heat flux only increases with high model agreement in the southernmost areas.

However, it is suspected that these fluxes are biased on ensemble average in the ENSEMBLES simulations. Stegehuis *et al* (2013) showed that several models in the ensemble have large evapotranspiration in the spring, which induces a dry, soil-moisture limited regime in summer, with large sensible heat flux accompanied by a low latent heat flux. This effect can lead to an overestimate of the ensemble mean changes and an underestimate of the inter-annual variability changes (Fischer *et al* 2012). This could also contribute to the nonlinear temperature bias found in this dataset by Boberg and Christensen (2012), which probably induces an overestimation of mean summertime warming in Southern Europe.

Heat flux changes respond to the changes in net radiative fluxes (figure 5). In the two seasons a robust increase in short-wave radiation is found in Southern Europe and robust increase in long-wave radiation is found in Northern Europe. In summer, the short-wave radiation increase extends Northward over central Europe where drying, increase of sensible heat and temperature also occurs. This extension is consistent with the Northward propagation of drought and heat in the spring–summer transition described in Zampieri *et al* (2009). It is noteworthy that sea level pressure, however, does not exhibit an associated robust increase in anticyclonic weather over Mediterranean areas in summer, which could be due to compensation due to heating-induced thermal surface pressure lows. In Northern Europe, wetter and cloudier weather induces an increase in long-wave radiation.

8. Conclusions

We have identified changes in European regional climate associated with a +2 °C global warming relative to pre-industrial climate. The +2 °C period was characterized using 30-year periods of an ensemble of global climate simulations of the SRES Scenario A1B, downscaled at a 25 km resolution by an ensemble of regional climate models (RCMs), simulations carried out in the framework of the FP6 ENSEMBLES project. The robustness of these changes has been quantified by measuring model agreement on the sign of the change and by assessing the statistical significance of the change.

The main characteristics of the changes in Europe expected for a +2 °C global warming relative to a reference period of 1971–2000 are:

(1) Europe generally experiences higher warming than the global average, i.e. it will experience more than 2 °C of warming even if the 2 °C goal is achieved. There is also a strong distributional pattern of warming across Europe (and thus different countries). A warming over all European regions is found, with slightly weaker amplitude than the global warming over North-Western Europe but a more intense warming (up to +3 °C) in Northern and Eastern Europe in Winter and in Southern Europe in Summer.

(2) A robust increase of precipitation over Central and Northern Europe in winter and only over Northern Europe in summer, while precipitation decreases in Central/Southern Europe in summer, with changes reaching 20%.

(3) A marked trend with an increased amplitude of up to more than 4 °C in the 20-year return value of the summer daily maximum and an even larger warming (up to more than 6 °C) over Scandinavia for extreme cold daily minima in winter.

(4) A robust increase in heavy precipitation everywhere and in all seasons, except Southern Europe in summer, with amplitudes in the range 0–20%.

(5) A modest and marginally robust increase in extreme winds in parts of Central Europe in winter, while in summer wind extremes changes are not robust.

(6) Sensible and latent heat flux changes have a strong seasonality with increasing (almost everywhere) evapotranspiration in spring, while it decreases in Southern/Central Europe; sensible heat fluxes exhibit an opposite pattern with an even higher amplitude in Southern/Central Europe; In summer fewer clouds in this area allow more intense net radiation input in this area. However models may overestimate evapotranspiration in spring, leading to an exaggerated drying and sensible heat flux increase in summer.

(7) The analysis also led us to conclude that a +2 °C change is, on average, approximately equivalent to a change for the 2031–2060 period in the A1B scenario. Choosing the time period reflecting a global mean change of +2 °C, however, reduces the spread in the results for temperature. A similar reduction in spread is not seen for other variables.

Many of the changes—in terms of the sign and magnitude of the change, and perhaps more importantly the spatial location and distributional pattern across Europe—will act to exacerbate existing and future impacts. For example, there is higher relative warming and greater relative increase in heat extremes in Southern Europe in summertime, which will drive heat and temperature-related impacts such as cooling costs and heat-related 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 pressure on water resource management. There are some exceptions (e.g. higher winter warming in the north, with the benefit of reduced winter mortality and winter heating demand, though there would also be negative impacts on winter tourism and ecosystems in these regions). However, the general findings are that the distributional patterns of change across Europe are likely to drive geographically specific negative impacts. This is of policy relevance: even if the 2 °C goal is achieved, Europe will experience impacts, and these are likely to exacerbate existing climate vulnerability. Further work on identifying key hotspots, potential impacts and advancing carefully planned adaptation is therefore needed.

While it does not qualitatively affect the robust patterns of climate changes for temperature and precipitation, the bias correction may in some areas slightly modify the amplitude of temperature changes (e.g. Dosio *et al* 2012). This was deduced from additional experiments (not reported here). Precipitation changes appear less sensitive to bias correction.

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