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Climate Impacts in Europe Under +1.5°C Global Warming

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Key Points:
- The results make clear that the world is likely to pass the +1.5°C global warming goal in the coming decades
- Climate system and economic impacts occur at +1.5°C of global warming simultaneously in more than one European sector
- Alongside some negative impacts for certain sectors and regions in Europe, a number of positive impacts are projected

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Abstract The Paris Agreement of the United Nations Framework Convention on Climate Change aims not only at avoiding +2°C warming (and even limit the temperature increase further to +1.5°C), but also sets long-term goals to guide mitigation. Therefore, the best available science is required to inform policymakers on the importance of and the adaptation needs in a +1.5°C warmer world. Seven research institutes from Europe and Turkey integrated their competencies to provide a cross-sectoral assessment of the potential impacts at a pan-European scale. The initial findings of this initiative are presented and key messages communicated. The approach is to select periods based on global warming thresholds rather than the more typical approach of selecting time periods (e.g., end of century). The results indicate that the world is likely to pass the +1.5°C threshold in the coming decades. Cross-sectoral dimensions are taken into account to show the impacts of global warming that occur in parallel in more than one sector. Also, impacts differ across sectors and regions. Alongside the negative impacts for certain sectors and regions, some positive impacts are projected. Summer tourism in parts of Western Europe may be favored by climate change; electricity demand decreases outweigh increases over most of Europe and catchment yields in hydropower regions will increase. However, such positive findings should be interpreted carefully as we do not take into account exogenous factors that can and will influence Europe such as migration patterns, food production, and economic and political instability.

Plain Language Summary The Paris Agreement's central aim is to keep global warming below +2°C and avoid dangerous levels of climate change. How will two additional degrees affect Europe and what might be prevented if global warming is limited to +1.5°C rather than to +2°C? The IMPACT_1.5 initiative has explored this future scenario. Seven research institutes from Europe and Turkey integrated their competencies to investigate the potential impacts of +1.5°C on various sectors across Europe. Our results make clear that the world is likely to pass the +1.5°C threshold in the coming decades. A +1.5°C global warming will substantially affect a wide range of economic sectors and regions. For example, heat waves are already nearly twice as likely over southern Europe and the Mediterranean in a +1.5°C world. Alongside the negative impacts, a number of positive impacts are projected for certain sectors and regions. Summer tourism in some parts of Western Europe may be favored by climate change; electricity demand decreases outweigh increases over most of Europe. However, such positive findings should be interpreted carefully as we do not take into account exogenous factors (e.g., migration patterns, food production, etc.) that can and will influence Europe.

1. Introduction

Article 2 of the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) states that it will aim to "strengthen the global response to the threat of climate change" by "Holding the increase in the global average temperature to well below +2°C (hereinafter +2°C) above preindustrial levels and pursuing efforts to limit the temperature increase to +1.5°C above preindustrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (UNFCCC, 2015).

However, nearly 2 years since COP21, it has become apparent that our knowledge of how a +1.5°C world actually appears is severely lacking. To fill this gap the Intergovernmental Panel on Climate Change (IPCC) has been invited to provide a special report in 2018 on the impacts of +1.5°C global warming (hereinafter +1.5°C) above preindustrial levels and related global greenhouse gas emission pathways. Due to the compressed time frame proposed by IPCC, the research on understanding the impacts of a +1.5°C needed to be undertaken immediately (Mitchell et al., 2016).

The research community mobilized to provide scientific content for the IPCC special report mentioned above. *Nature Climate Change*, *Nature Geoscience*, *Nature Communications*, and *Nature* announced regular updates via the "Targeting 1.5°C" Collection. The half a degree additional warming, projections, prognosis, and impacts (HAPPI) experiment was designed to provide a robust framework for the generation of climate data describing how the climate, and in particular extreme weather, might differ from the present day in worlds that are +1.5°C warmer than preindustrial conditions (Mitchell et al., 2017). Furthermore, to assess the impacts of +1.5°C the simulation protocol of the Intersectoral Impact Model Intercomparison Project (ISIMIP2b) has been designed (Frieler et al., 2017). It aims to provide the scientific basis for an aggregation of impacts across sectors and an analysis of cross-sectoral interactions that may dampen or amplify sectoral impacts. The protocol is designed to facilitate consistent projections of the impacts of climate change from a range of impact models across different sectors (water, agriculture, environment, forestry, and fisheries, global and regional coastal infrastructure, energy supply and demand, health, and disaster management).

The Paris agreement also sets long-term goals to guide future mitigation. Policymakers therefore need to be informed by the best available science to assess the potential benefits and uncertainties of mitigation to different warming targets (e.g., +1.5°C and +2°C) and the adaptation needs at different warming levels. In recent years a number of studies have been initiated to discuss the key questions that are relevant in the context of the +2°C goal. In the EU-funded project IMPACT2C (http://www.impact2c.eu) a comprehensive assessment of the climatic changes, impacts and costs of a temperature increase of +2°C (including +1.5°C and +3°C for some cases) on different sectors such as water, energy, agriculture, tourism, infrastructure, and health has been undertaken (Climate Services, 2017).

A dedicated analysis of the key impacts of climate change at warming levels of +1.5°C and +2°C was done by Schleussner et al. (2016) where the ISIMIP Fast Track simulations were applied to the agriculture and water sectors revealing substantial differences in impacts between +1.5°C and +2°C. This analysis was performed using relatively coarse global impact models. The possible changes in regional climate and multisectoral climate impacts at regional scales for Europe have so far not been investigated in detail.

1.1. IMPACT_1.5 Initiative

To increase the scientific knowledge base in regional climate and to investigate the impact of +1.5°C on vulnerable regions the IMPACT_1.5 initiative (1.5CI) was established. Six European research institutes (GERICS, UniRes, TUC, JR, LSCE/IPSL, SMHI) and Iskenderun Technical University in Turkey integrated their competencies to provide an assessment of the potential impacts of +1.5°C on various sectors at a pan-European scale. This work was initiated by the Climate Service Center Germany and developed as an extension of the methods from the EU-funded project IMPACT2C.

We aim at direct comparison of the impacts of climate change on Europe under +1.5°C and +2°C to bring our scientific findings into the context of policy relevant goals and at identifying potential benefits of substantial mitigation efforts. 1.5CI applies the methodology and datasets developed within IMPACT2C.

As it was mentioned before, the impacts of +1.5°C have already been explored as part of IMPACT2C for some specific case studies. For example, Donnelly et al. (2017) compared the impacts of 1.5, 2, and 3°C on water resources in Europe. Their results indicate that +1.5°C will result in increased precipitation over most of Europe except in western regions and increased evapotranspiration across most of Fennoscandinavia and the Alps. Only very localized parts or Europe are projected to have robust increases in mean annual runoff (indicative of increased catchment yields and water availability). High runoff, an indicator of flood risks was shown to increase in many localized regions of Europe, with the highest increases seen along coasts and in mountainous regions, that is, in the Alps, along the Italian, French Mediterranean and Balkan coasts, the southern Norwegian coast, the northwest Spanish coast and the western Irish coast. Note that this analysis does not include potential changes to flash flooding which can be inferred from changes to extreme precipitation at the minute to hourly timescales. Low runoff, indicative of water shortage is only shown to decline in western Ireland and in western mountain regions (Andorra, Western Alps, Western Norway). No robust increases in water shortage were projected. Snowpacks were projected to decrease significantly for all warming levels, across all of Europe, with the exception of some very localized regions of the Alps at lower warming levels.

Comparing these impacts at different warming levels, Donnelly et al. (2017) saw that for precipitation, evapotranspiration, low runoff and snowpack, the changes increase with each warming level. For mean annual runoff, changes at +2°C are greater than at +1.5°C, but the differences are less discernible between +2°C and +3°C (with the exception of projected large decreases in runoff). For high runoff, the changes at +3°C are greater than those at +2°C, but less discernible for +2°C compared to +1.5°C. The general conclusion was that the extent and intensity of all of these changes increases as warming level increases from +1.5°C to +2°C to +3°C.

Tobin et al. (2017) compared climate change impacts on electricity production for different warming levels +1.5°C, +2°C, and +3°C. They found that climate change has an overall negative influence on electricity production from renewables and thermoelectric production. It induces, even for +1.5°C, small changes in solar and wind resources across Europe (0–10%), while hydropower potential increases in Northern Europe and decreases in Southern Europe. Thermoelectric production from power plants using river water as a source for cooling will be constrained by increasing water temperature and declines in summer river flow. They argued that this could induces energy inequity among EU countries. Also, a higher share of renewables not only mitigates climate change but also likely reduces the vulnerability of the energy sector to climate change. They found that the corresponding generation technologies (in particular wind and solar power) are less sensitive to climate change than thermoelectric power production.

The aim of this article is to show how the IMPACT2C methodology can be applied to the +1.5°C warming goal, describe the findings of 1.5CI in detail, and summarize the intersectoral impacts on regional basis. The article is structured around main issues on projected climate changes and their potential impacts on different sectors. The key regional messages on climate impacts in Europe under +1.5°C are summarized and presented at the end.

2. Methodology

In this study, we follow the methodology of IMPACT2C, for example, all available simulations and the methods developed for the analysis of the impact of +2°C were applied. No additional regional climate model or impact model simulations have been performed. The main steps are described in detail in the following subsections.

A novel approach was used to determine the time period when given global warming thresholds, +1.5°C and +2°C, were crossed. The combinations of different global circulation (Taylor et al., 2012) and regional climate (Jacob et al., 2014) models (GCM-RCM) were used to project the future climate under three different representative concentration pathways (RCP) namely, RCP2.6, RCP4.5, and RCP8.5 (van Vuuren et al., 2011). Where possible, multiple impact models were applied to analyze impacts on different sectors. To make the impacts of global warming on different sectors comparable, all impact models were driven by the same set of GCM-RCM (Table 2).

The sources of uncertainties were considered throughout all paths of the modeling chain using the ensemble approach not only for climate but also impact models. This means that through the use of the mandatory scenarios and multiple impact models a wide range of possible developments have been analyzed. Furthermore, our approach is to select periods based on global warming thresholds rather than the more typical approach of selecting time periods (e.g., beginning, middle, end of century). This reduces uncertainty related to climate sensitivity.

Parametrization of socioeconomic relations was induced only in a few models (e.g., for winter tourism, but not for energy).

Table 1.
Definition of the +1.5°C Global Warming Threshold

+1.5°C	Global mean temperature rises to +1.5°C compared to a preindustrial period
Preindustrial period	1881–1910
Reference period	1971–2000
30-year running mean	Both the preindustrial warming until reference period and the future warming since reference period are determined by smoothed time series using a 30-year centered moving average
+1.5°C period	Preindustrial warming until base period +1.5°C; future warming reach +1.5°C the first time

The following subsections detail the methods behind obtaining the ensemble of climate projections, the impact studies and the rationale behind a mandatory set of simulations.

2.1. Climate Projections

2.1.1. Definition of the +1.5°C Global Warming Threshold

To define a period of warming, when global mean temperature rise of +1.5°C, we follow the methodology as described by Vautard et al. (2014). Main definitions are summarized in Table 1.

Here the +1.5°C period is defined as the time when the 30-year average global mean temperature reaches +1.5°C compared to the preindustrial period of 1881–1910.

Three global observational datasets were analyzed to assess preindustrial warming:

- GISS LOTI (1880–2011) (http://data.giss.nasa.gov/gistemp/);
- HadCRUT3 (1850–2011) (www.cru.uea.ac.uk/cru/data/temperature/);
- NOAA NCDC (1880–2011) (www.ncdc.noaa.gov/cmbfaq/anomalies.php).

First, we consider past preindustrial warming until a predefined reference period of 1971–2000 as calculated from 30-year running means. Three datasets mentioned above exhibit an average warming from the preindustrial period until the reference period of 0.46°C. Second, 30-year running means, starting from the reference period 1971–2000, are calculated for each of the GCMs used. Third the +1.5°C period for each GCM is determined as the +/− 15-year period surrounding the year that the 30-year running mean crosses the +1.5°C threshold (i.e., an additional 1.04 K warming from the reference period).

2.1.2. Multimodel Ensemble of Climate Projections

In the present study climate simulations for impact studies were selected based on the methods developed by Mendlik and Gobiet (2016). Instead of applying the entire ensemble of climate projections for impact assessment, only a few representative members, conserving the GCM spread and accounting for model similarity, were selected. First, principal components analysis for a multitude of meteorological parameters was applied to find common patterns of climate change within the multimodel ensemble. Second, model similarities were detected with regard to these multivariate patterns using cluster analysis. And third, sampling models from each cluster generated a subset of representative simulations (Mendlik & Gobiet, 2016).

In IMPACT2C and the present study, this method was extended to the ensembles of the regional climate models of the EURO-CORDEX initiative (Jacob et al., 2014) with 0.11° horizontal resolution (12.5 km) (EUR-11).

We selected five out of seven EUR-11 runs available at that time. The GCM-RCM matrix used in this study is summarized in Table 2.

In particular the following three criteria were considered as important for this selection:

- RCMs were driven by different GCMs;
- RCMs were developed by different institutions;
- RCMs projected different behavior of climate change signal.

Table 2.
GCM-RCM Ensemble Members Used in This Study

Driving GCM	RCM	GCM-RCM combination (short name)
ICHEC-EC-EARTH_r12i1p1	SMHI-RCA4	SMHI-RCA4/EC-EARTH-r12
ICHEC-EC-EARTH_r12i1p1	KNMI-RACMO22E	KNMI-RACMO22E/EC-EARTH-r1
MPI-M-MPI-ESM-LR_r1i1p1	MPI-CSC-REMO2009	CSC-REMO/MPI-ESM-LR-r1
MOHC-HadGEM2-ES_r1i1p1	SMHI-RCA4	SMHI-RCA4/HadGEM2-ES-r1
IPLS-IPSL-CM5A-MR_r1i1p1	IPSL-INERIS-WRF331F	IPSL.INERIS-WRF331F/IPSL-CM5A-MR-r1

In this case the selected GCM-RCM combinations represented the spread of the EUR-11 ensemble available at that time and were as far as possible independent.

2.1.3. Bias Adjustment

Climate simulations usually contain systematic errors when compared to observations. These arise from inadequate parametrizations of physical processes, coarse resolution, topography, spatial smoothing, and structural errors in the models. Many impact models require input data that is adjusted to remove these model biases, in particular if the model is nonlinearly dependent on the meteorological input.

Consequently, an empirical-statistical technique, called quantile mapping (Gobiet et al., 2015; Wilcke et al., 2013) has been used to adjust biases in standard meteorological variables (temperature and precipitation) of all climate simulations used in IMPACT2C. The adjustment is carried out on the 25-km grid of E-OBS (Haylock et al., 2008) at a daily time-scale. In addition, bias adjusted radiation data has been provided for the hydrological modeling (WFDEI, http://www.eu-watch.org/data_availability; Weedon et al., 2011). The analyses in the following sections were performed using this bias-adjusted data from the GCM-RCM ensemble. Though the bias adjustment was carried out for all available RCPs it was not appropriate to apply the methodology and subsequent analyses for all emissions pathways (see "Selection of an emission scenario of for impacts assessment" below). Therefore, in order to maintain consistency and comparability, we limit our analysis and discussion to the five-member ensemble of RCP4.5 simulations (Table 2).

2.2. Impact Studies

2.2.1. Electricity Demand

Electricity demand changes with climate. In this study, we quantify the impacts of +1.5°C and +2°C on heating and cooling electricity demand for 26 European countries.

Smooth transition regression models are used to estimate the relationship between daily electricity consumption and population weighted temperature. Therefore, E-OBS temperature data (Haylock et al., 2008) has been corrected for altitude effects and aggregated at national level, taking population counts data from 2008 (Eurostat, 2014) as a weight. Data on total daily national electricity consumption was provided by the European Network of Transmission System Operators for Electricity (ENTSO-E, 2014) and corrected for weekday effects, holiday effects, economic effects and time-varying annual effects. For more details on data, methodology and limitations we refer to Damm et al. (2017).

2.2.2. Summer Tourism

In this study, we also use projected climate changes to estimate potential impacts to the tourism in Europe. The widely used Tourism Climatic Index, a summary of ratings of five human comfort indices related to sightseeing tourism developed by Mieczkowski (1985), was employed for comfort rating and also as a predictor for estimating tourism demand in terms of overnight stays for European summer tourism. The index accounts for the monthly climatological conditions that influence long term human comfort. Furthermore, the uniform risk measure of 95% Value at Risk (VaR) is used with an annual time interval over the reference period and +1.5°C and +2°C using total overnight stays as a demand indicator. Here, VaR express the potential loss in overnight stays demand due to changes in climate conditions over the two warming levels for a confidence level of 95%. The concept of 'Weather Value at Risk' is explained in more detail in Prettenthaler et al. (2016).

2.2.3. Winter Tourism

We analyze the impacts of +1.5°C and +2°C on winter tourism demand in European regions dependent on ski tourism. Using partial adjustment models — a specific form of the general autoregressive distributed lag (ADL) model — the relationship between natural snow conditions and monthly overnight stays (November to April) is estimated for 119 NUTS-3 regions (Nomenclature of Territorial Units for Statistics) in 12 selected European countries. The analysis considers all NUTS-3 regions with at least 30 km of total ski slope length in countries that provide an overall length of ski slopes of at least 200 km (Skiresort Service International GmbH, 2013).

Snow data is obtained from the Variable Infiltration Capacity hydrological model (Liang et al., 1994). Daily values of snow water equivalent are available on a grid of 0.5 × 0.5° and for elevation bands with average distances of around 266 m. For calibrating the tourism model on monthly overnight stays, historical snow data for the period 1958–2010 are obtained by forcing the hydrological model with E-OBS gridded data (Haylock et al., 2008) version 9. To aggregate the data from the grid to the NUTS-3 level, we took the weighted mean of those grid cells within a NUTS-3 region in which ski areas are located (matched by the geographic coordinates of the ski areas, if available, or at least of the nearest town), using the total length of ski slopes as weighting factor. We tested in total nine different snow indices: monthly mean snow water equivalents (SWE), and fraction of days per month with at least 4 mm SWE and 120 mm SWE, respectively — each at three different altitudes (minimum, mean, and maximum altitude of the ski resorts). More detailed information on data, methodology and limitations can be found in Damm et al. (2017). GDP and population scenarios of three different Shared Socioeconomic Pathways (SSP1, SSP2, SSP3) (O'Neill et al., 2014) are used to determine the additional climate change impact, which arises from a growing population and changes in GDP. RCP4.5 scenarios are combined with all three SSPs.

2.2.4. Ecosystem Production

Climate change can have powerful impacts on ecosystem productivity through altering water availability, raising/lowering average daily temperatures and daily temperature ranges as well as extremes of heat and drought. To estimate ecosystem production changes, we use the Community Land Model version 4.5 (CLM4.5) to simulate biogeochemical cycles in the terrestrial biosphere under climate change to estimate changes to primary production vulnerability. A detailed description of the model runs can be found in the article Sakalli et al. (2017). The model was run at 25 × 25 km resolution over a pan-European region and forced with the mandatory simulation data described below to estimate the future climate impacts.

We calculated GPP (Gross Primary Production) and NPP (Net Primary Production) vulnerability by using following equation:

$$Vul\,(i) = \frac{\sigma_{P2,i} - \sigma_{P1,i}}{\sigma_{P1,i}} \times 100 \tag{1}$$

where i stands for GPP and NPP, $\sigma_{(P2,i)}$ and $\sigma_{(P1,i)}$ stand for the standard deviation of 30-year periods, that is, reference period, and +1.5°C and +2°C global average temperature increase, respectively.

2.3. Mandatory Simulations

The information from climate modeling and impact assessment studies is complex, therefore the concept of mandatory simulations was applied both in IMPACT2C (Climate Services, 2017) and in the present study. To ensure consistency between different results, all impact models for all impact studies mentioned in the previous subsection were driven by the same climate-input data. This dataset is a bias-adjusted version of the EUR-11 RCP4.5 ensemble (see Table 2 and Section 2.1.3). In this case the impacts of +1.5°C on different regional climate indices and economic sectors are comparable and allow us to highlight consistent cross-sectoral linkages, which provide useful information for development of adaptation and mitigation strategies.

3. Projected Climate Changes and Their Potential Impacts in Europe in +1.5°C and +2°C Worlds

In the context of the Paris agreement with a long-term goal to guide future mitigation, the question of what might be prevented if global warming is limited to +1.5°C rather than +2°C is of major importance.

Table 3.
Summary of the Time Frames, When Corresponding GCM Crosses +1.5°C or +2°C

GCM-RCM combinations	+1.5°C	+2.0°C
RCP2.6		
SMHI-RCA4/EC-EARTH-r12	2028–2057	NA
CSC-REMO/MPI-ESM-LR-r1	2035–2064	NA
RCP4.5		
CSC-REMO/MPI-ESM-LR-r1	2020–2049	2050–2079
SMHI-RCA4/EC-EARTH-r12	2019–2048	2042–2071
SMHI-RCA4/HadGEM2-ES-r1	2007–2036	2023–2052
IPSL.INERIS-WRF331F/IPSL-CM5A-MR-r1	2009–2038	2028–2057
KNMI-RACMO22E/EC-EARTH-r12	2019–2048	2042–2071
RCP8.5		
CSC-REMO/MPI-ESM-LR-r1	2014–2043	2030–2059
KNMI-RACMO22E/EC-EARTH-r1	2012–2041	2028–2057
SMHI-RCA4/HadGEM2-ES-r1	2004–2033	2016–2045
SMHI-RCA4/EC-EARTH-r12	2012–2041	2027–2056

Therefore, we focus not only on the climate impacts in Europe under +1.5°C, but also in direct comparison to the effects under +2°C global warming.

In contrast to the traditional approach with well-defined future time-slices (e.g., 2021–2050 or 2071–2100), we consider the future periods when driving GCMs have reached +1.5°C or +2°C. Table 3 summarizes the time frames when 11 GCM simulations, including those selected for IMPACT2C, pass the warming thresholds of +1.5°C and +2°C. They cover a large range of possible greenhouse gas concentration trajectories and are characterized by radiative forcing ranging from +2.6 to +8.5 W/m^2.

While global warming exceeds +1.5°C within the next two decades for RCP4.5 and RCP8.5 (2030 and 2026, respectively), +1.5°C will be crossed in the time frame around 2045 for the low emission RCP2.6. For RCP4.5, selected GCMs already reach +2°C threshold by the 2030s and do not exceed +2°C at all for RCP2.6. For RCP4.5 and RCP8.5 the central estimates lie in a range between 2036 and 2056.

The advantage of this approach over the more classical approach using ensembles at a given, fixed, period, is that it removes some of the uncertainty resulting from the GCMs climate sensitivity (Vautard et al., 2014). Other forms of uncertainty such as that related to internal variability are still present and are readily apparent in the spread shown in, for example, the climate impacts detailed in Section 3.1 (see also Deser et al., 2012).

Also, in reality, different systems, such as the ocean, land cover and biogeochemical cycles might take longer to adjust to +1.5°C or +2°C depending on the speed of the warming. Donnelly et al. (2017) investigated the effect of choice of the ensemble (e.g., the RCP scenarios) by comparing the impacts at +2°C using either low (RCP2.6 and RCP4.5) or high (RCP8.5) emissions scenarios. While there were some differences in the impacts on European hydrology for the two different methods, these differences were in most cases smaller than the differences between different warming levels. This result places some confidence in using this methodology for defining the climate at different warming levels.

Furthermore, Fox Maule et al. (2016) investigated the effect of the pathway to +2°C global warming on the regional temperature change of Europe. They found that the different time-slices and scenarios taken from the simulations in IMPACT2C can be concatenated into an ensemble representing Europe in a +2°C world. There is a small but significant difference in the regional temperature change. However, the effect is small compared to internal variability on the timescales involved in reaching +2°C for the investigated emission scenarios.

In the present study, however, differential impacts for +1.5°C and +2°C were investigated for RCP4.5 only, since +2°C is not exceeded for RCP2.6. RCP8.5 represents high-end climate change with steep temperature increase (Collins et al., 2013). For this reason, we omit the RCP8.5 simulations.

In the following subsections, we present initial results of 1.5CI and focus on changes in the mean climate indices, canonical extreme indices and the impacts of a temperature increase of +1.5°C and +2°C on electricity demand, summer and winter tourism and ecosystem production. The analyses add to the growing body of knowledge of the +1.5°C impacts on Europe for water (Donnelly et al., 2017) and electricity production (Tobin et al., 2017) from the related IMPACT2C study using a similar methodology to describe the 1.5°C and 2°C warming periods. Due to the consistency of the forcing dataset the results can then be combined to examine cross-sectoral and region-specific impacts.

3.1. Climate Indices

3.1.1. Mean Surface Air Temperature

Assessing changes in climate indices is the basis for investigating their impacts. Annual and seasonal mean near surface temperature is one of the basic quantities used to assess climate change. Changes in temperature directly affect the human comfort and well-being as well as the living conditions of animals and plants. Most economic sectors are affected directly or indirectly by mean temperature changes. For example, the tourism sector is affected when an increase in mean temperature reduces the snow cover for skiing in winter. Increasing temperatures can also influence the energy sector via changing electricity demand for heating and cooling. Temperatures also influence health and agriculture. Thus, annual as well as seasonal mean temperature is of importance.

In this analysis, one has to keep in mind that climate change signals are defined with respect to the reference period of 1971–2000 whereas +1.5°C and +2°C refer to global warming with respect to the preindustrial period. Thus, the warming of 0.46 K between the preindustrial period and the reference period is not included in the figures of climate change signals here.

In Figure 1, mean temperature is depicted as yearly and seasonal averages. The ensemble exhibits an increase in yearly and seasonal mean temperatures for all parts of Europe. In most regions of Europe, the yearly averaged projected regional warming is more pronounced than the respective global mean warming of +1.5°C and +2°C. Under both +1.5°C and +2°C the strongest annual warming occurs in North-Eastern Europe. This is due to the strong warming in these areas in the winter season. In summer, mountainous areas like the Alps and the Pyrenees show stronger warming compared to other parts of Europe and compared to the global average. Stronger warming can also be observed in the interior of the Iberian Peninsula, the Balkans, and parts of Turkey. The same pattern can be found for springtime under both warming thresholds.

All simulations agree in projecting an increase in temperature under +1.5°C and +2°C for Europe in all seasons with the exception of one model projecting a decrease for Central Western Europe in spring under +1.5°C global warming (not shown).

3.1.2. Mean Precipitation

Changes in precipitation have the potential affect to almost all economic sectors. Water, energy (e.g., hydropower production), health, agriculture (e.g., crop yields) and tourism are all affected by reductions or increases in water availability.

In Figure 2 the change in annual and seasonally averaged precipitation for +1.5°C and +2°C is depicted for annual and seasonal averages. Our results for both +1.5°C and +2°C show an increase in the annual mean precipitation over Northern and Eastern Europe and a slight decrease over the Mediterranean area, especially over the Southern part of the Iberian Peninsula. The precipitation increase is more pronounced for +2°C and exceeds more than 15% in Northern Europe. All simulations agree on the described increase in precipitation. The precipitation decrease in the Iberian Peninsula is projected by four of the five simulations. Altogether, this indicates a robust climate change pattern.

In winter and in spring, mean precipitation over North-Eastern Europe is projected to increase more strongly than in other parts of Europe under +2°C. In summer, only the Northern part of Scandinavia shows

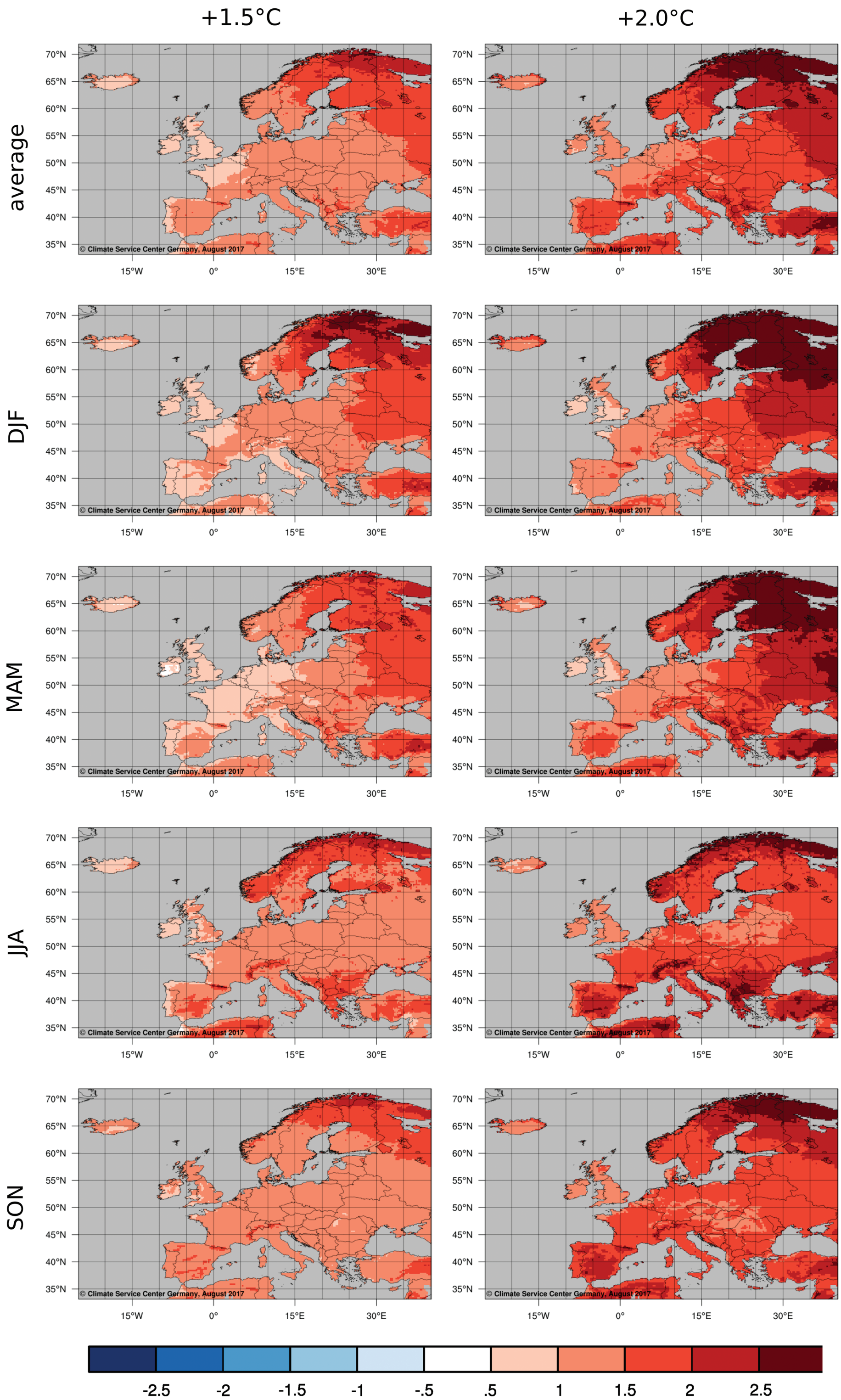

Figure 1. Changes (°C) in near-surface air temperature between the reference period of 1971–2000 and for +1.5°C (left panel) and +2°C (right panel) periods.

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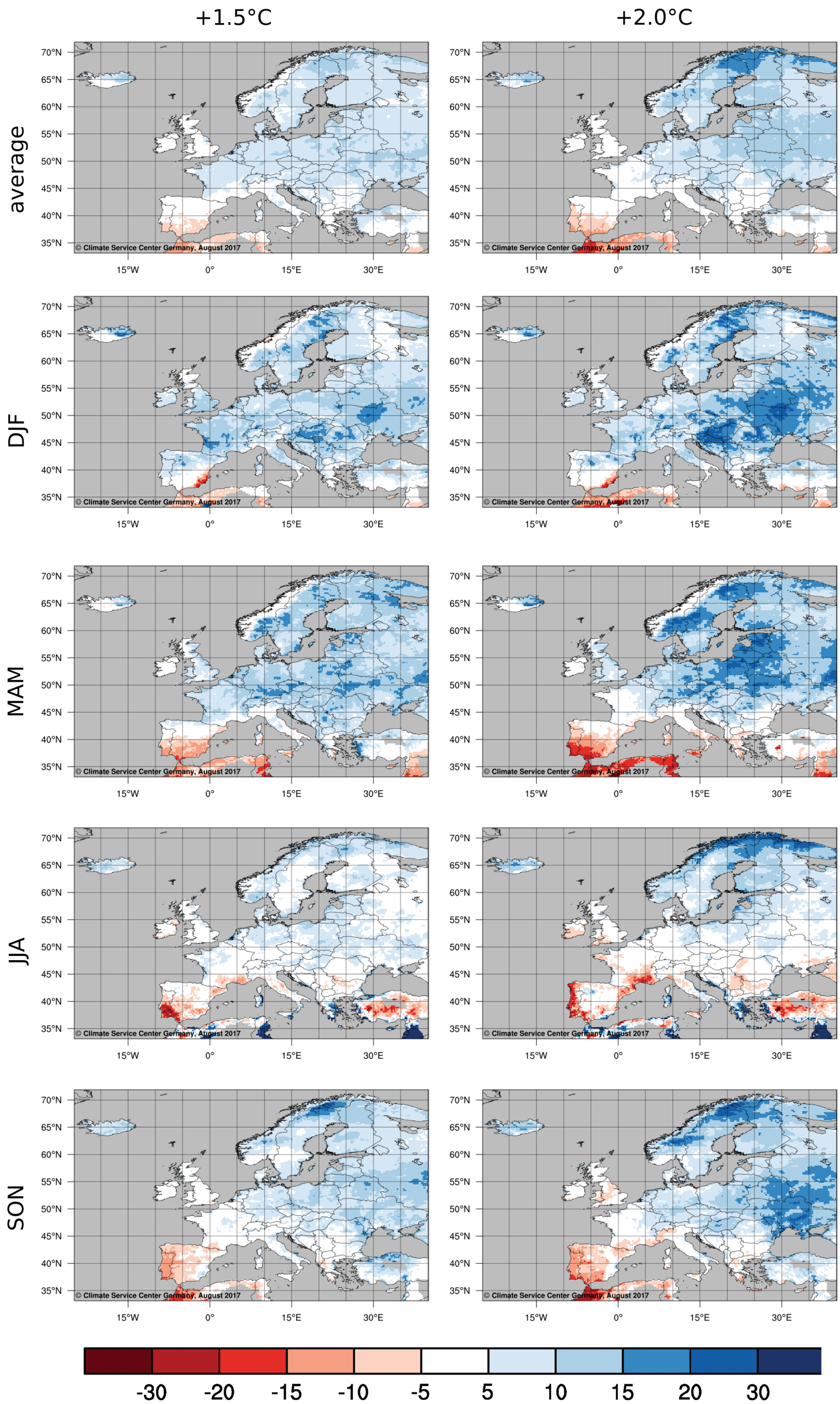

Figure 2. Changes in total precipitation (%) between the reference period of 1971–2000 and for +1.5°C (left panel) and +2°C (right panel) periods.

a strong increase in precipitation. While in most parts of Europe summer precipitation is not projected to change, there are some hotspots areas in the Mediterranean region for which a strong decrease of precipitation is projected. These areas comprise the Iberian Peninsula (especially the southwest), Southern France and parts of the Balkans and Turkey. Under +1.5°C, similar patterns can be observed but with a lower magnitude of the climate change signals. Most of the models agree on the described increases in precipitation for the different seasons. Furthermore, in most regions where a strong decrease in precipitation is projected, all or most of the models agree in the sign of the climate change signal (not shown). The spatial distribution of changes is comparable to the results in Donnelly et al. (2017) using slightly different ensembles of GCM-RCM combinations. Further details can be found in the IMPACT2C Atlas (http://www.atlas.impact2c.eu).

3.1.3. Extreme Events

Under global warming, a European-wide increase in the frequency of some types of extreme events such as extreme daily or subdaily precipitation and heat waves is expected (European Environment Agency, 2017). Those which are linked most closely to the thermodynamic response of the system are the most robust (e.g., heat waves, maximum/minimum temperatures, cold snaps, heavy precipitation, etc.) while those linked to the more uncertain dynamical response are generally less robust but show clear directions of change over particular regions (e.g., dry spells, persistent weather patterns, wind storms).

Heat waves are among the most profound risks human populations face as the climate warms. Already nearly a third of the world's population faces increased exposure to deadly heat conditions, a number set to increase over the coming decades (Mora et al., 2017). As the deadly heat wave of 2003 showed, Europe is

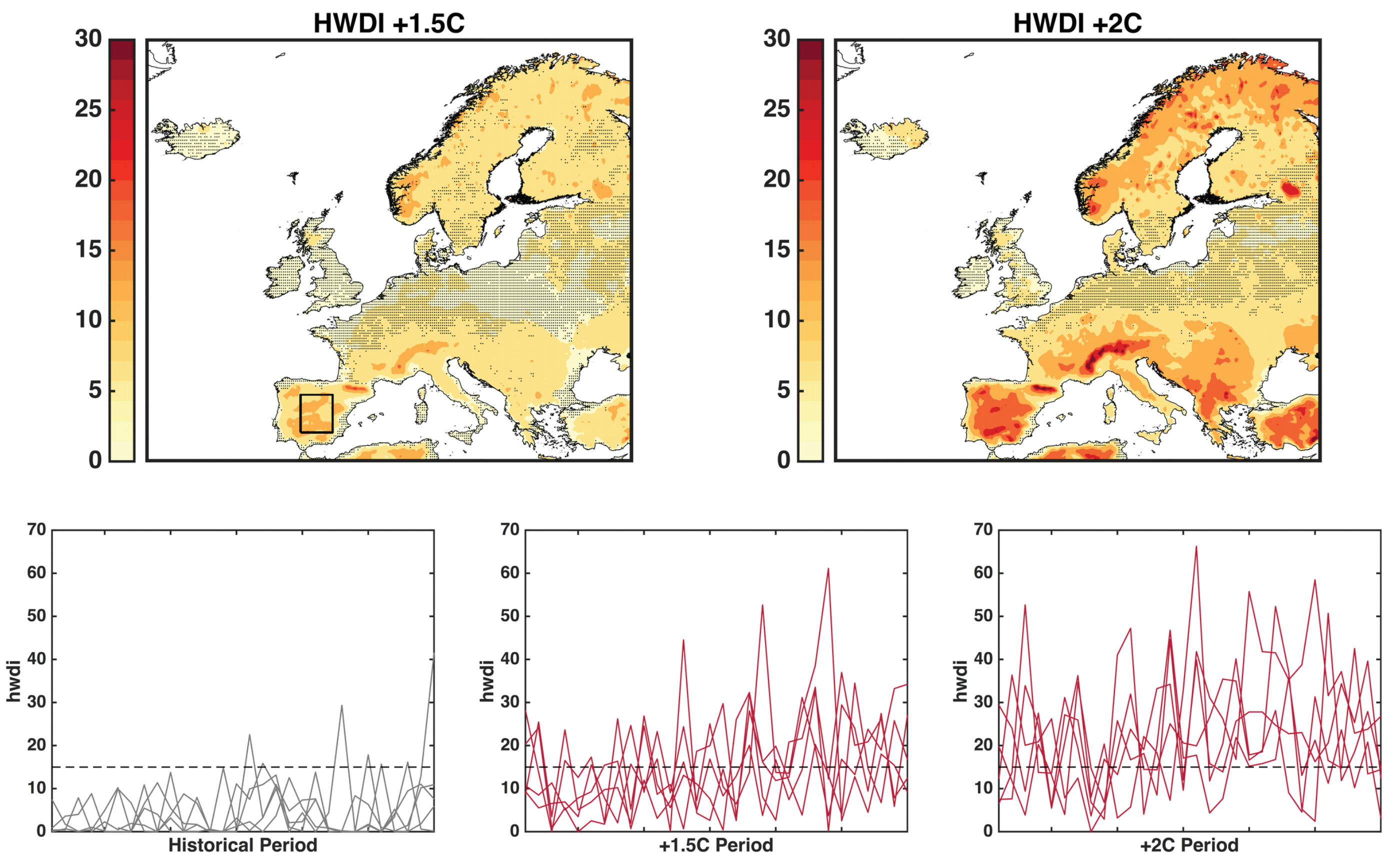

Figure 3. The top panels show the bias-adjusted five-member RCP4.5 ensemble mean response in heat waves under +1.5°C (left) and +2°C (right). Areas that are not stippled are regions where at least four of the five ensemble members exhibit changes that are statistically significant as determined by a Wilcoxon-rank-sum test (95% level). Heat waves in the box over central Spain in the upper left panel are examined in greater detail in the lower panels. In the lower panels the area averaged heat wave time series for are shown each ensemble member for the historical (left), +1.5°C (middle) and +2°C (right) periods. The historical 95th percentile (dashed line) is shown across all three panels for reference.

not immune to these risks. Heat waves can be defined and analyzed in a number of different ways and there is as yet no universally accepted definition (see e.g., Fischer & Schär, 2010; Coumou & Robinson, 2013; Pal & Eltahir, 2016). Here two definitions are used in order to illustrate the consistency and robustness of this particular response over Europe, irrespective of method. The first approach employs the European Climate Assessment's heat wave duration index (HWDI) as defined by the Expert Team on Climate Change Detection and Indices (ETCCDI). The ETCCDI spent over a decade constructing a comprehensive overview of extreme statistics focused mostly on precipitation and temperature (Karl & Easterling, 1999; Klein Tank et al., 2009; Sillmann et al., 2013). The HWDI is defined as the number of days from May–September where, in intervals of 6 days, the maximum daily temperature exceeds the climatological daily maximum temperature of a reference period, by at least 5°C. In the current context, the reference period corresponds to 1971–2000. The second approach defines heat waves using the so-called block maxima approach. Heat waves are calculated as the yearly maximum mean 5-day temperature period. Results are then presented as the change in return periods of the historical 1:20 year 5-day heat wave event. It should be noted that a 1:20-year event represents a moderately extreme event or summer. Very extreme events at the very tail of the distribution (such as the 2003 heat wave) are not investigated here. Both approaches have their strengths and weaknesses and using them jointly helps build a consistent storyline around the projected changes in these high impact events.

Changes in HWDI are shown in Figure 3 for +1.5°C and +2°C and are given in days. These changes are positive everywhere and can come about through the number of heat waves over 6 days, the length of heat waves over 6 days or both. Additionally, time-series of individual simulations are examined for a region over central Spain, which shows significant, spatially coherent and robust changes in both time periods (Figure 3, bottom panels). The changes at +1.5°C in this metric are already robust over large parts of central and southern Europe and the Mediterranean (Figure 3 upper left). At +1.5°C the HWDI increases by up to 15 days over the May–September summer period for many parts of southern Europe and the Mediterranean. Under +2°C many regions experience increases in HWDI of almost a month compared to the historical period. If we zoom in on a region covering central Spain (see upper left panel for outline) we can examine the time series from the individual ensemble members (lower panels). The increase in HWDI with increased global warming is clear. At +1.5°C (+2°C), the historical one-in-20-year summer is exceeded every 2.5 (1.5) years. In other words, at +1.5°C global warming, 8 out of every 20 years experience conditions that are currently experienced only once every 20 years, on average. These increases in HWDI are mainly due to an increase the number of heat waves each summer rather than the length of the individual heat waves, which only increase by a day or so on average. The lower panels in Figure 3 also show that, despite the increases in HWDI there remains considerable interannual variability and that the variability increases with increasing warming. This increase in variability has implications for the most extreme events. Even though present methodology is not able to capture these very rare events, findings indicate that due to increases in year-to-year variability they may indeed become more likely (Schär et al., 2004). The projected increases in HWDI even at +1.5°C represent substantial risks given the already established links between anthropogenic climate change and recent extreme heat events over Europe, such as the 2003 heat wave (Robine et al., 2008; Mitchell et al., 2016). At +2°C many regions in southern Europe and the Mediterranean exhibit changes such as those shown in the lower panels of Figure 3, such that today's moderately extreme summers become the new normal.

Examining the results from the block maxima approach, which focuses only on one heat wave event per year as opposed to the HWDI approach that counts all events that exceed a particular threshold, a similar story line emerges (Figure 4). Heat wave increases in this instance are measured by the changes in return periods for each of the global warming periods.

In Figure 4, we have selected 10 European cities in different European subregions, and calculated how the return period of a 1:20 year heat wave event changes. We took less rare events than extreme heat waves in order not to make assumptions on the temperature distribution tails and avoid a parametric method to calculate return periods. Instead, return periods of the maximum yearly 5-day mean were calculated by pooling all models and simulated years for each corresponding warming case. This provided statistics of at least 150 years. We find that in general, return periods decrease from 20 years to at most 7 years in the +1.5°C case and 5 years for the +2°C case. However, in the majority of the cases the likelihood of a 1:20 year event is increased by a factor ranging from 5 to 10 depending on the city and the assumed global warming. While

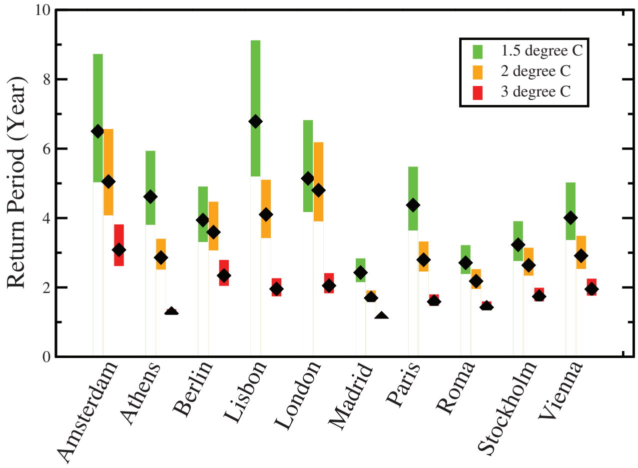

Figure 4. Return periods, and their 5%–95% range, of the return periods of 1:20 year historical 5-day heatwave events, calculated as the yearly maximum 5-day mean temperature period with pooled bias-adjusted EURO-CORDEX simulations for three warming scenarios. Confidence intervals are estimated using a bootstrap method.

the difference between +1.5°C and +2°C is relatively small in these cities, the increases over the historical period are substantial. It should also be noted that Madrid, which lies in the middle of the box selected in Figure 3 shows results that are quite consistent with those from the HWDI approach.

We have further calculated equivalent numbers for cold spells (not shown). In this case it was not possible to calculate the return period change of one-in-20-year events from the historical period as they have become extremely rare in the warming scenarios and the nonparametric approach could not be applied. The spatial patterns, however, show robust decreases in cold snaps across Northern Europe and Scandinavia.

It is well established that dynamics and phenomena that are largely determined by dynamical processes such as rainfall, are among the most uncertain of climate change impacts (Shepherd, 2014). However, storylines can be developed around multiple lines of evidence such as consistency with physical understanding and theory, trends, and model results (Bony et al., 2015). As with heat waves there are many indices that have been developed to examine different characteristics of *extreme precipitation*. In the present study we chose the annual maximum 5-day total precipitation amount. The general finding from previous work on the end-of-the-century scenarios is that extreme precipitation increases over Europe with warming but the patterns vary by season and region (see e.g., EEA, 2017; Fischer & Knutti, 2015; Jacob et al., 2014). It should be noted that we are not able to examine subdaily extremes, which can have high impacts. Indications are that these types of extremes also increase over Europe in a warming climate (e.g., Ban et al., 2015).

In Figure 5 we show the change in annual maximum 5-day precipitation over Europe in mm for each warming period. Despite the fact that the response has not fully emerged from background variability, already by +1.5°C warming there is consistent agreement in the direction of change over much of Europe. This is especially apparent over areas with complex topography (the Alps and western Norway) and some coastal areas (the Balkan coast, northwest Spain). Similar to the heat wave analysis the lower panels focus on an important region that exhibits robust changes under +1.5°C and +2°C warming. In this case we choose the western Alps. The increases are less dramatic than those of heat waves but it is still apparent even under visual inspection that the magnitudes of extreme precipitation events increase in a +1.5°C warmer world. The change in frequency is also clear and results in today's one-in-20-year event are being exceeded on average once every 5 years in both the +1.5°C and the +2°C periods. The regions of greater change in annual maximum 5-day precipitation correspond with robust increases in annual maximum (high) runoff in Donnelly et al. (2017), indicating the usefulness of this indicator in predicting changes to flood risk.

3.2. Electricity Demand

Assuming present demographic and economic structures, global warming by +1.5°C reduces electricity consumption in most European countries (Figure 6). The reduced heating electricity demand outweighs the

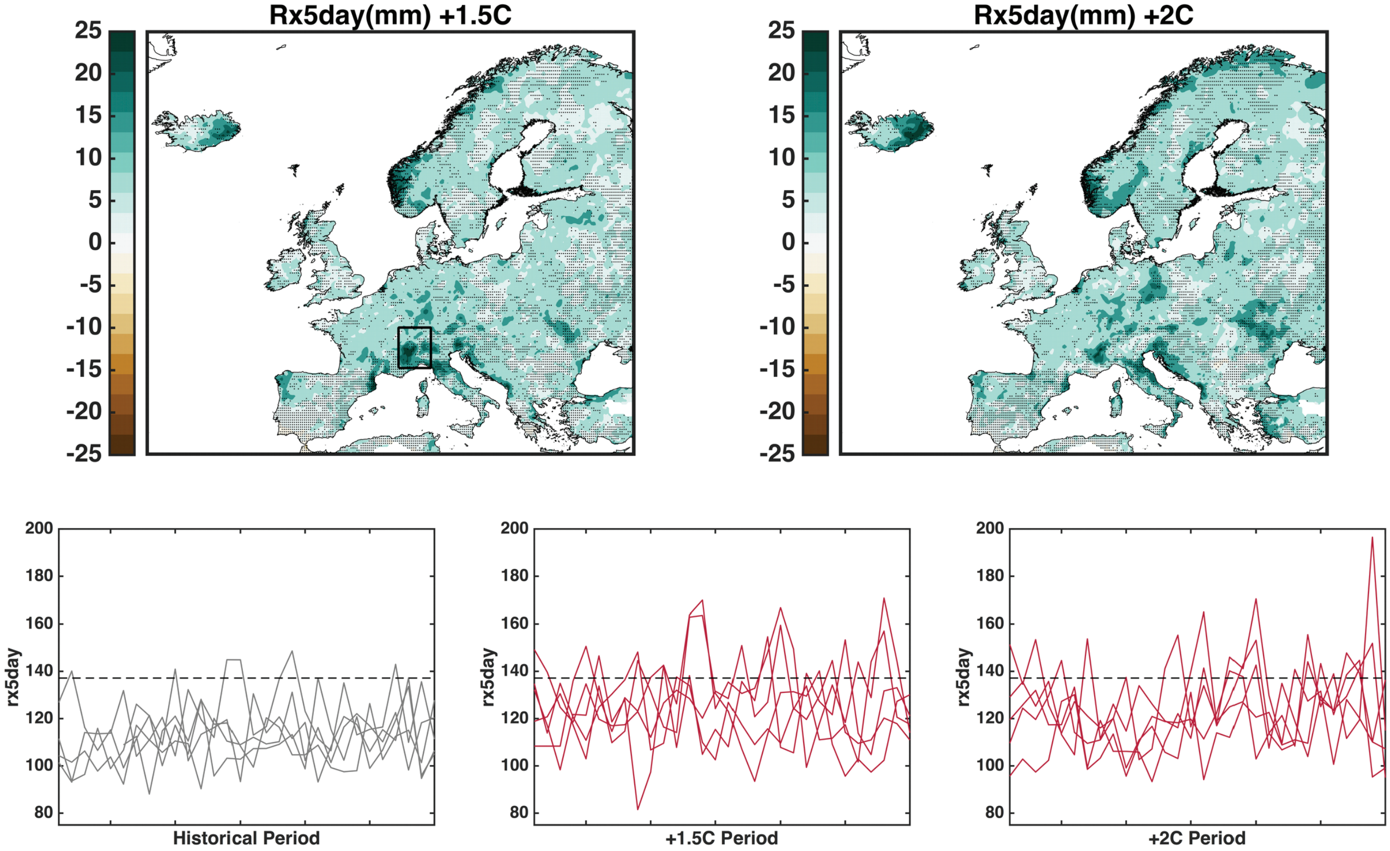

Figure 5. The top panels show the bias-adjusted 5-member RCP4.5 ensemble mean response in maximum 5-day total precipitation (Rx5day in mm) under global +1.5°C (left) and +2°C (right). Areas that are not stippled are regions where at least 4 of the 5 ensemble members agree on the sign of the change. Rx5day changes in a box over central the southwest Alpine region in the upper left panel are examined in greater detail in the lower panels. In the lower panels the area averaged Rx5day time series are shown each ensemble member for the historical (left), +1.5°C (middle) and +2°C (right) periods. The historical 95th percentile (dashed line) is shown across all three panels for reference.

increase in cooling demand. The highest decrease in relative terms is found for Norway (−3.6%), followed by Sweden, Estonia, Finland, and France. Italy is the only country for which an overall increase in electricity demand is projected. The decrease of electricity demand in absolute terms is projected to be by far the highest in France (−11 TWh p.a.).

Under +2°C, a further increase in electricity demand by 0.2%-points (0.7 TWh p.a.) is to be expected in Italy. In Norway, a further decrease in electricity demand by 0.9%-points (1.2 TWh p.a.) is determined. Overall, a further decrease in electricity demand by 8 TWh p.a. is projected when limiting global warming to +1.5°C instead of +2°C.

3.3. Summer Tourism

Tourism is an extremely important part of the European economy, especially for the Mediterranean countries and is highly dependent on climatic conditions (Grillakis et al., 2016). The largest share of European tourism activity takes place during summer and the Mediterranean region can be characterized as ideal in terms of climate comfort especially during the peak period (June–August; Grillakis et al., 2016).

The impact of the climatic change by roughly half an additional degree temperature increase from the reference period 1971–2000 (Figures 7a and 7b) will have an impact on summer tourism comfort (Figures 7c and 7d) especially in the core summer period (July to August). For the May to October period marginal positive changes are projected over the majority of the European region, while for the June to August period a negative effect over southern Spain and Cyprus and also for the most coastal regions of the Mediterranean is projected. Comfort changes from half an additional degree will probably have direct impact on the

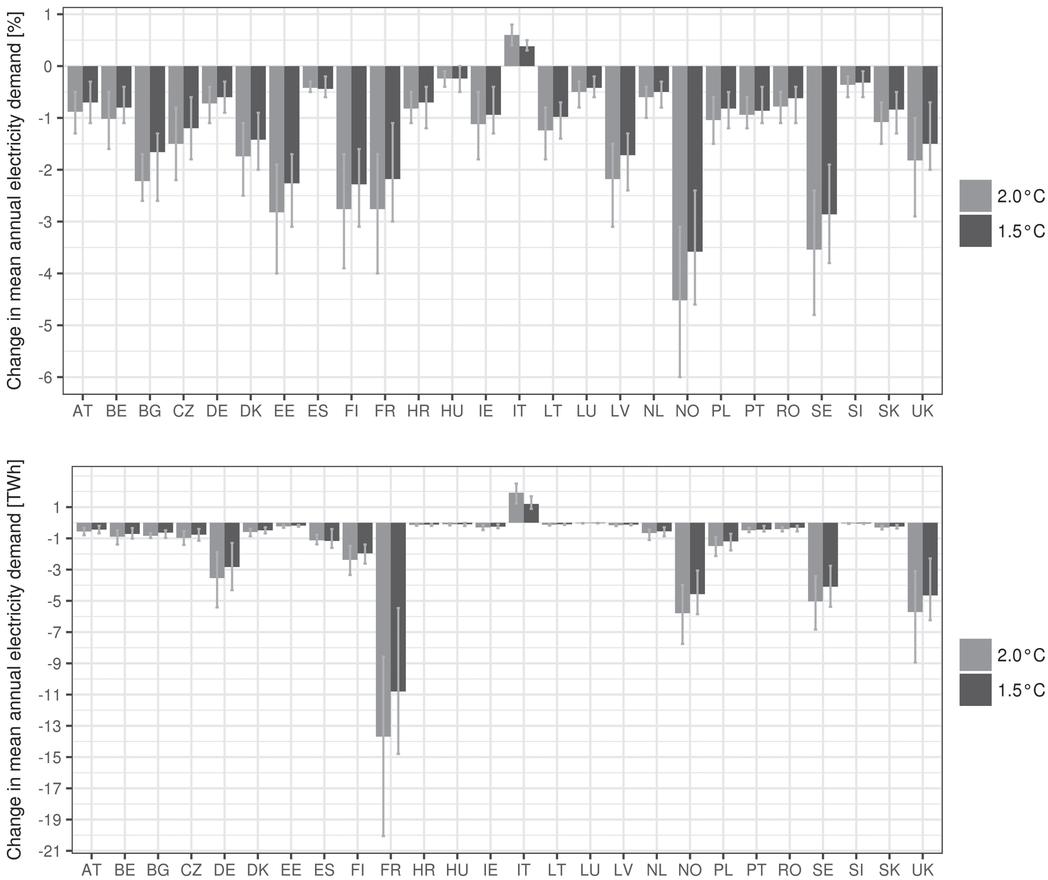

Figure 6. Change in mean annual electricity demand between +1.5°C and +2°C and the reference period 1971–2000, in relative terms (top) and absolute terms (bottom) using the mean over five RCP4.5 runs.

overnight stays (Figures 7g and 7h). Negative impacts are projected for Cyprus and Greece with a potential decrease of 8% and 2%, respectively, while for Spain and Italy the decrease in the comfort over the southern regions of the countries could be compensated by an increase to the north, with a possible northward shift of tourism activity. The rest of the European countries are expected to benefit from the changing climate. This could also have a direct impact on the risk, which is projected to change slightly or not at all (Figure 7k) for the May to October period and strongly increase for most of the European countries for the June to August season (Figure 7l).

From a different perspective, several conclusions can be drawn regarding what the impacts avoided by keeping global warming at +1.5°C compared to a further increase up to +2°C. Marginal comfort changes for most of Europe, improved conditions for Western Europe between 40 and 50°N and the Balkans are projected for the May to October period (Figure 7e). On the other hand, a deterioration is foreseen for the summer tourism intensive regions of southern Spain, Cyprus and coastal parts of Greece and Italy for the June to August peak season (Figure 7f). This pattern can also be seen in the overnight stays that are expected to increase for the May to October period (Figure 7i) and also during June to August (Figure 7j) except Cyprus and Greece. Despite the overall improvement, a notable increase is foreseen in the Value at Risk (Figures 7m and 7n as a combined effect of increased exposure due to more overnight stays and higher probability of loss associated to extreme climatic events affecting tourism activities. High (but less) risk is also projected for Portugal (+4%) and Italy (+3%), while, on the other hand, UK could have 17% reduced risk at +2°C compared to +1.5°C.

3.4. Winter Tourism

Figure 8 shows the changes in winter overnight stays between +1.5°C and +2°C, respectively, compared to reference period of 1971–2000. In the right plot, the climate-induced changes in winter overnight stays are

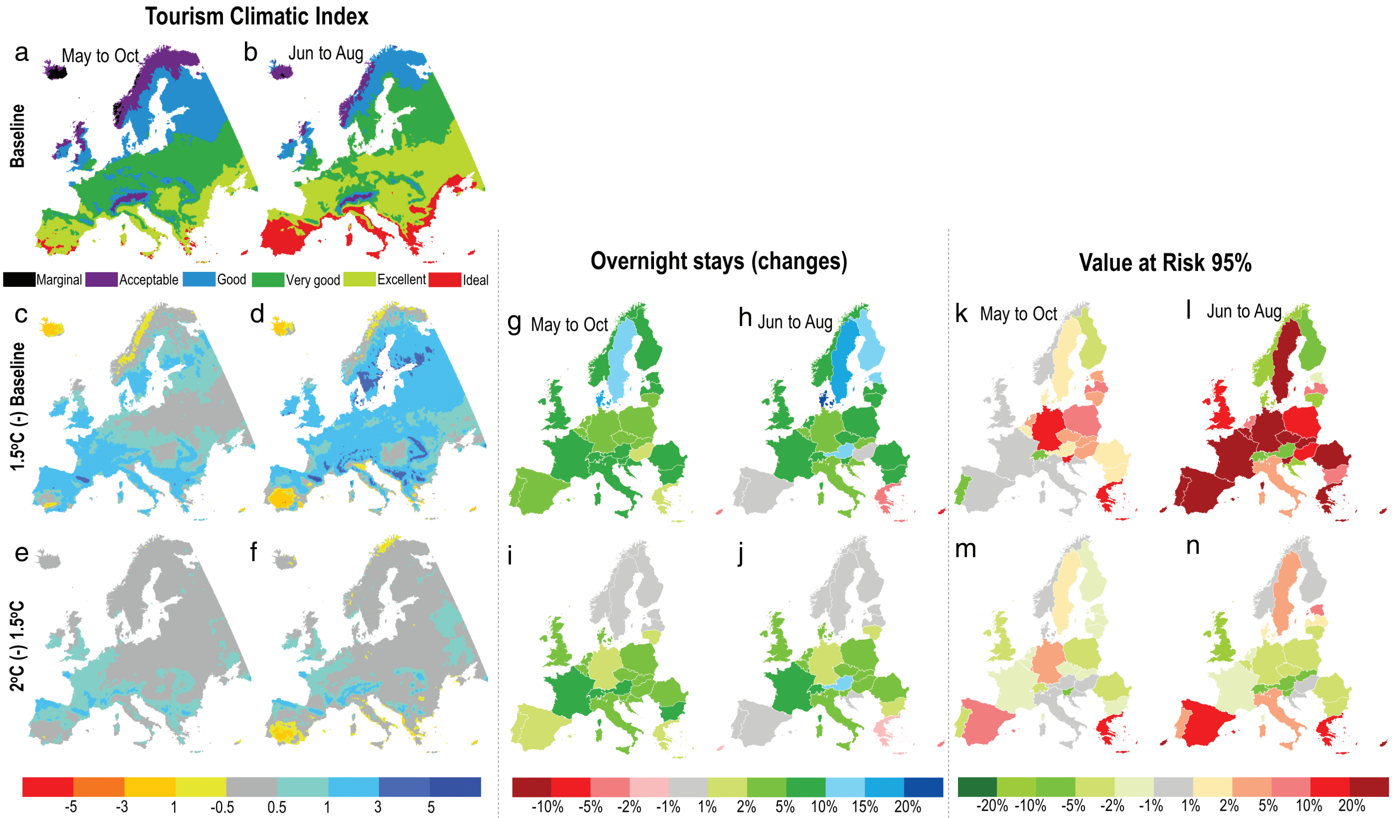

Figure 7. Tourism Climatic Index (left), overnight stays (middle) and Value at Risk (right) for May to October and June to August periods. Changes are estimated for +1.5°C level relative to reference climate and for the "avoided" impacts by keeping +1.5°C relative to the +2°C global warming levels.

shown in relative terms. The left plot presents the changes in absolute terms, where the values are split into the solely climate-induced impact and the additional climate impact due to socioeconomic changes.

Skiing tourism in Europe is dominated by the four Alpine countries Austria, France, Italy and Switzerland, which account for 83% of the total length of ski slopes (data base from Skiresort Service International GmbH, 2013). The highest absolute changes in winter overnight stays—under +1.5°C as well as +2°C—are found in Austria, followed by Italy. Austria and Italy account for the largest fraction of skiing related winter overnight stays in the selected NUTS-3 regions, both currently and in future periods.

In relative terms, a decrease in winter overnight stays of about 2% is to be expected in Austria under +1.5°C. Similar relative changes in winter overnight stays are found for Italy (−1.7%) and Slovakia (−1.8%) under +1.5°C.

Under +2°C, a further decrease of about 1% is estimated for Austria (0.9 million overnight stays) and Italy (0.5 million overnight stays), which is the highest change in relative terms among the countries under consideration. In other words, these losses in overnight stays can be avoided when limiting global warming to +1.5°C instead of +2°C. Overall, this amounts to 1.9 million annual winter overnight stays in Europe being saved by limiting global warming to +1.5°C.

3.5. Ecosystem Production

Impacts of climate change on CO_2 uptake by primary producers (i.e., plants) have been intensively studied due to the increase in greenhouse gases in the atmosphere since the industrial revolution. A change in CO_2 uptake capacity of an ecosystem can directly affect the carbon sink/source ratio, which also directly influences the atmospheric CO_2 concentration. Gross Primary Production (GPP) is mainly the amount of fixed CO_2 by primary producers in an ecosystem in a certain time, where Net Primary Production (NPP) is the amount of stored net energy into biomass (i.e., NPP = GPP − respiration of the primary producers).

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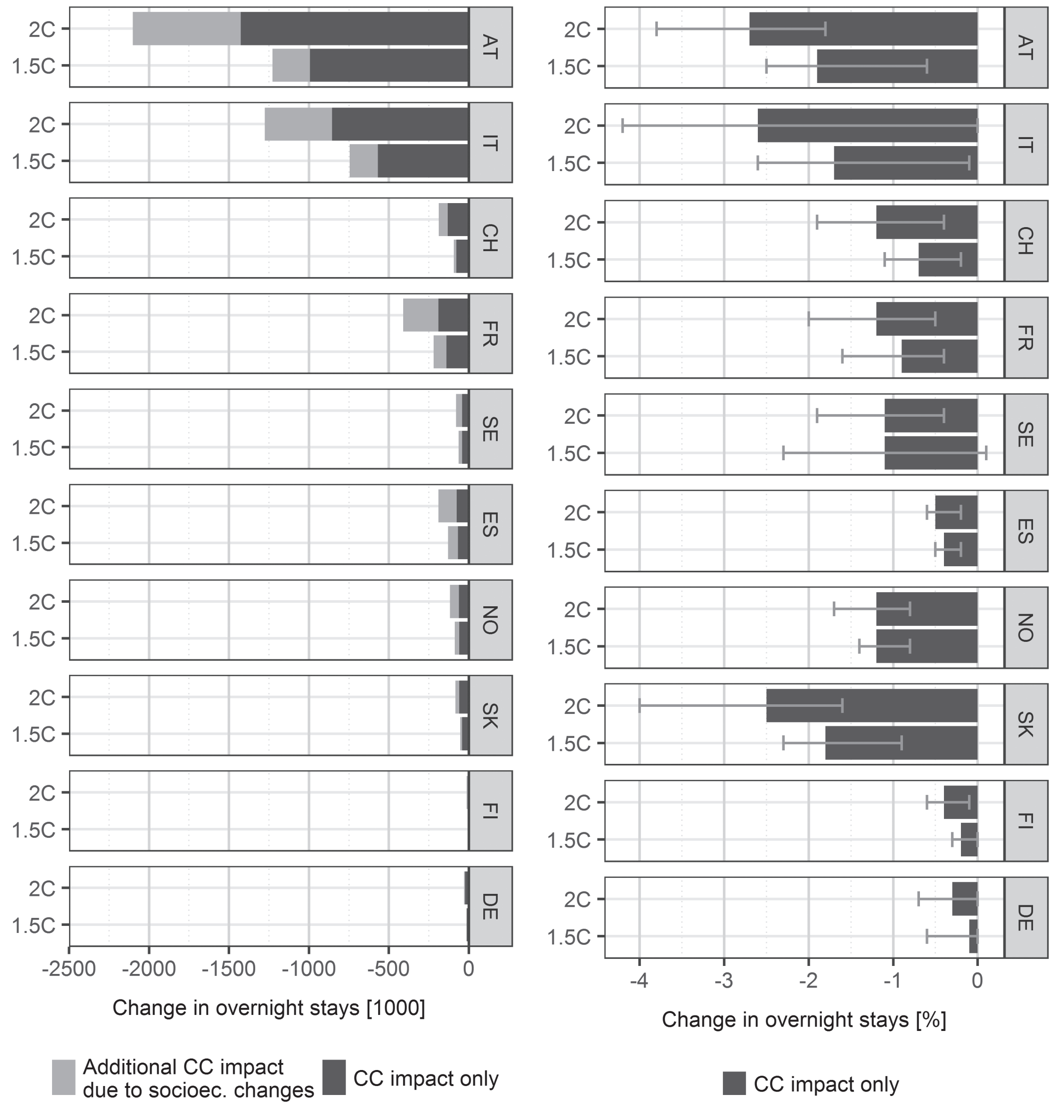

Figure 8. Average change in winter overnight stays between the +1.5°C/+2°C periods and the reference period 1971–2000, in absolute terms (left plot) and relative terms (right plot). Mean over five RCP4.5 runs.

In this study, we simulated two of the most important CO_2 uptake processes in the terrestrial ecosystem, that is, GPP and NPP. In Figure 9, we plotted spatial distribution of GPP and NPP modeled for the baseline period (1971–2000). In general, cold-deciduous broad-leafed forests can take up most of the CO_2, that is, up to ca. 1400 gC/(m^2 year) in the baseline from the atmosphere (see Figure 9a). The spatial distribution of simulated NPP was also quite similar to GPP in the three periods (see Figure 9b). In general, approximately 50% of the fixed CO_2 was used for respiration by the plants.

We also investigated vulnerability of the GPP and NPP under climate change. Results of this study are illustrated is Figure 9 rows 2 and 3. The vulnerability maps are important for developing strategies for ecosystem conservation. For GPP and NPP, the most vulnerable areas were in Northern Europe and Scandinavia, Spain and Greece. In those regions decreases in GPP and NPP can cause an increase of up to 60% in vulnerability under +1.5°C increase in global average temperature (see Figures 9c and 9d). Under +2°C more regions exhibit increased vulnerability for both GPP and NPP. GPP and NPP vulnerability increases by up to ca. 80% over almost all of Europe except Scandinavia and northeast France (see Figures 9e and 9f). Generally, NPP exhibits greater vulnerability extent than GPP under both warming periods.

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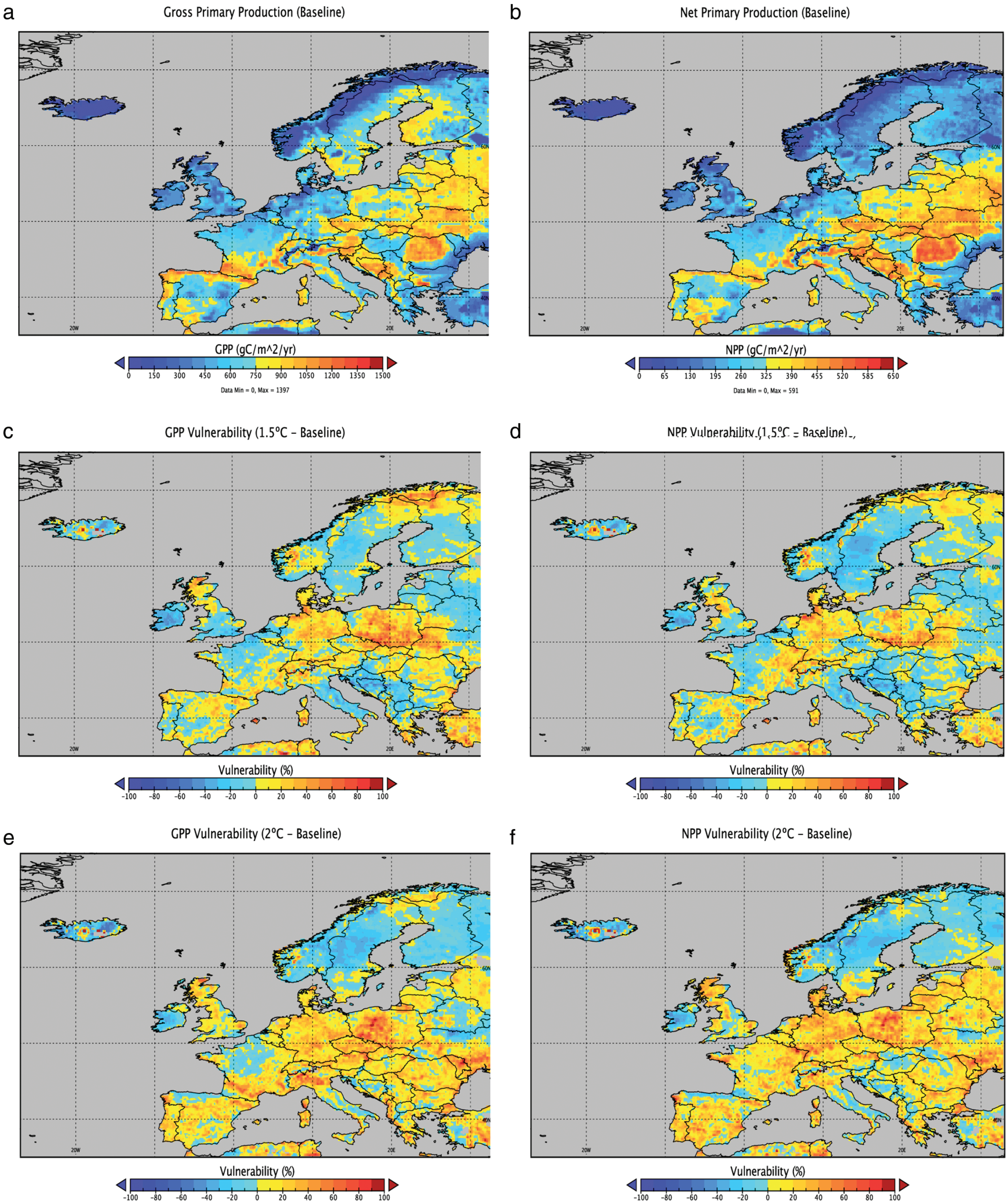

Figure 9. Climate change signal for GPP and NPP (in columns), and baseline, +1.5°C and +2°C periods (in rows), respectively.

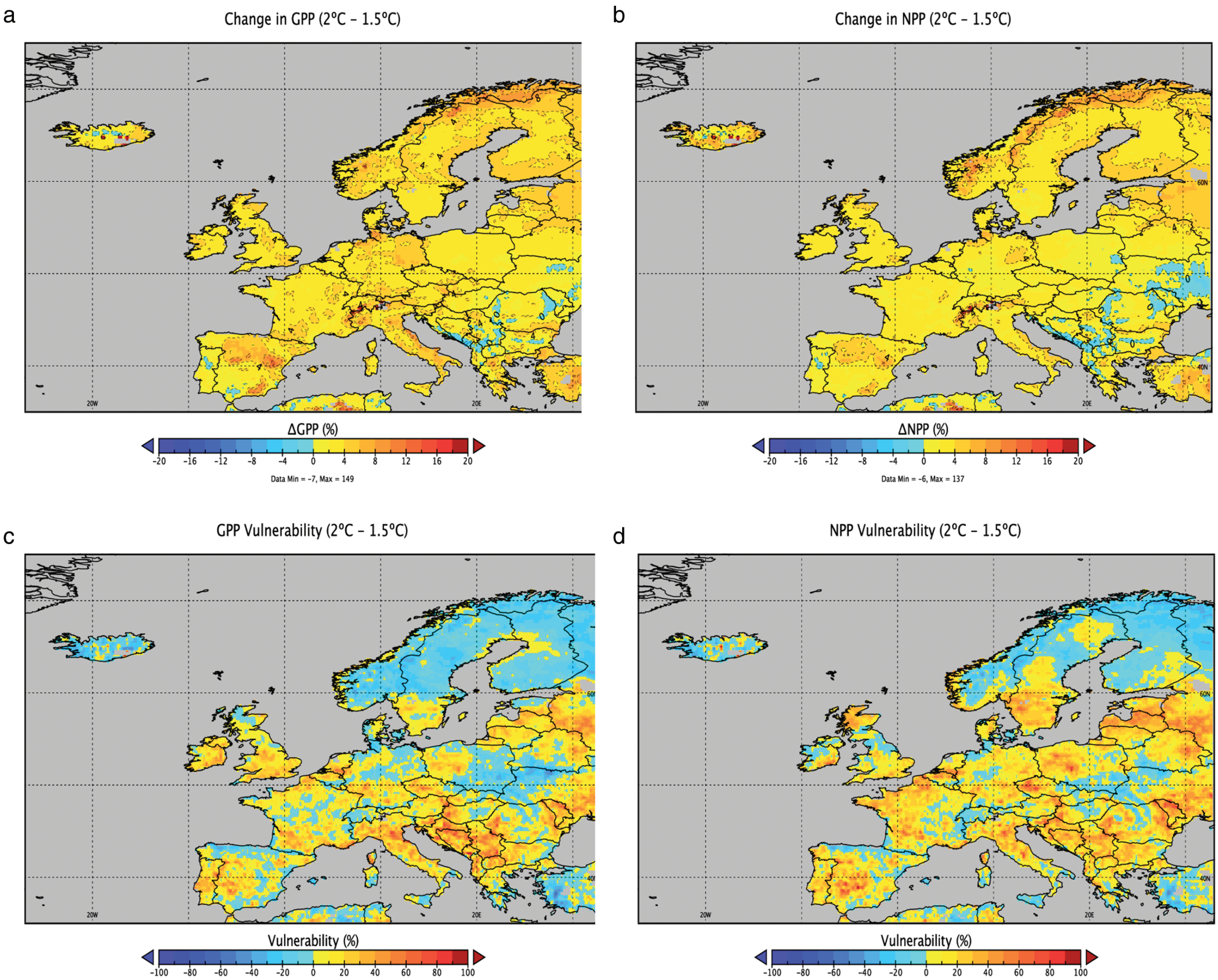

Figure 10. Differences in vulnerability between +2°C and +1.5°C periods.

The impacts of half a degree additional warming, that is, the difference between +1.5°C and +2°C on GPP and NPP, are shown in Figures 10a and 10b. This gives an indication of the risks avoided if warming is limited to the lower threshold. The +0.5°C increase affected GPP and NPP by up to 2% in most of European regions, by up to 4% in Central Europe and Northern Europe, and by up to 8% in the high-altitude and cold regions of Europe and by up to 2% in most other European regions. Furthermore, GPP and NPP slightly decreased in some European regions, that is, in central Portugal, southern Spain, and Eastern Europe with sub-Mediterranean cold deciduous broad-leafed plant formation.

Most critically, limiting warming to +1.5°C instead of +2°C avoids an increase in ecosystem vulnerability of 40–50% over much of Europe (see Figures 10c and 10d). Under the additional +0.5°C temperature increase, the most vulnerable regions are ecosystems in the Balkans, Italy and Eastern Europe.

4. Key Messages on Climate Impacts in Europe in a +1.5°C World

The key messages of our research can be summarized in the following section in which impacts are gathered spatially by subregions of Europe and a few key messages detailed for each. We analyzed the climate projections for RC4.5 to estimate when global mean warming might exceed the +1.5°C and +2°C.

The results indicate that the world is likely to pass the +1.5°C threshold within the next two decades, for example, around 2026 for RCP8.5. However, these are mean estimates, and there is a considerable range of projections from different climate models. Nevertheless, for the intermediate RCP4.5 pathway the central estimates lie in the relatively narrow window around 2030. In all likelihood, this means that a +1.5°C world is imminent.

We present our results taking into account cross-sectoral dimensions to show the impacts of global warming that occur in parallel in more than one sector. Taken with the climate indices one can also see how, barring methodological assumptions and shortcomings, many sectors respond to the climate changes less intensely than extreme events or ecosystem productivity, for example. The benefits of limiting the warming to the lower level are also clear, even if there are some benefits (e.g., summer tourism and electricity demand). That said, a +1.5°C global warming will substantially affect a wide range of economic sectors and regions throughout Europe:

In Europe generally, the impacts are more pronounced for +2°C than for +1.5°C for the climate system as well as a number of sectors, including water, electricity demand, summer and winter tourism and ecosystem production. Vulnerability to global warming of +1.5°C and +2°C differs across sectors and regions. Together with negative impacts for certain sectors and regions, a number of positive impacts are projected, for example, summer tourism in some parts of Western Europe may be favored by climate change. Likewise, the decreases in electricity demand could be seen as beneficial.

(a) Scandinavia
- Warming is generally much higher than the global mean warming for both thresholds with highest levels seen inland for the cold season;
- Extreme precipitation exhibits locally robust increases mostly along the western Norwegian coast;
- Evapotranspiration increases but water availability also increases due to increased runoff in an already high-runoff region;
- Electricity demand decreases substantially, mainly due to reduced heating demand.

(b) UK and Ireland
- In London, the historical one-in-20-year heat wave occurs once every 5 years;
- Positive conditions for summer tourism are expected to increase;
- Annual electricity demand decreases.

(c) Western Europe
- Forested regions become highly vulnerable due to decreasing productivity;
- Historical one-in-20-year heat waves frequency increases by factor of 5–10 in some cities;
- The region and especially the coastal areas could benefit from a modest increase in summer tourism climate comfort and a parallel decrease over the Mediterranean.

(d) Eastern Europe
- Temperature increases are well above the global average especially in the winter season;
- Mean precipitation increases are largest for the shoulder seasons;
- Forested regions become highly vulnerable due to decreasing productivity.

(e) Mediterranean
- Surface water availability is not predicted to increase except in small, localized regions on the Spanish/French border and southern France;
- Heat waves increase throughout the region with today's one-in-20-year event/summer becoming commonplace;
- Electricity demand is projected to decrease with the exception of Italy, but this assumes present demographics and economic structures;
- Climatic favorability for summer tourism is foreseen to deteriorate in the southernmost tourism-intense regions of Spain, Greece, Italy, and Cyprus enhancing vulnerability.

(f) The Alps
- Exhibits increases in extreme precipitation and heat waves;
- Snowpack declines everywhere with the only exception being very localized, high elevation areas of the Alps;

- Winter overnight stays decrease by 2% in Austria under +1.5°C. Similar relative changes in winter overnight stays are found for Italy (−1.7%) and Slovakia (−1.8%); In absolute terms, Austria and Italy are most affected.

5. Conclusions

We investigated the impacts of +1.5°C global warming that could be experienced in Europe and provided compared impacts under +1.5°C and +2°C with respect to changes in climate indices. In addition, an exploration of some climate impacts under different possible future worlds was presented for a number of sectors including water, electricity demand tourism and ecosystems.

These results will have major implications for the speed and urgency of current policy discussions. While climate impacts are only one of many factors, which influence policy decisions they inextricably link many of the most important issues confronting European society such as poverty, inequality, security, migration, etc. It also indicates that early adaptation is likely to be needed to address the changes anticipated over upcoming decades.

This work is continuing; we aim at broadening our analysis to include additional essential climate variables and expand the investigation of impacts into other economic sectors.

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