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Mean and extreme climate in Europe under 1.5, 2, and 3°C global warming

JRC PESETA IV project – Task 1

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Executive summary

Based on high-resolution regional climate models, the change over Europe in mean climate and extremes, including impact-relevant indicators, are investigated under different levels of global warming (1.5°C, 2°C, and 3°C). A suit of indices describing both hot and cold events are employed and, for precipitation, wet and dry conditions; in particular, we examine the evolution of threshold-based indices, such as the number of frost days or tropical nights, which may be relevant for impact assessment on specific sectors.

Results show that most of Europe is projected to face a robust increase in temperature larger than the global mean one; changes in hot and cold extremes (the hottest day and night and the coldest day and night) are projected to substantially exceed the global mean warming and often the corresponding local seasonal mean warming.

The increase in the temperature of coldest nights in winter, over most of central and northern Europe, is particularly significant, varying from less than 2°C in a 1.5°C world to more than 4°C in the 3°C world. Warming has often a nonlinear effect on the exceedance of non extreme, but potentially impact-relevant indices; for instance, over Poland, the reduction of frost days (i.e., with minimum temperature < 0°C) in winter, compared to the present climate, amounts, on average, to around 8 days in a 1.5°C world, 12 in a 2°C world, and 22 in a 3°C world.

Local precipitation will non-significantly change over most of Europe under either 1.5°C or 2°C warming, compared to 1981–2010. However, a moderate change in mean precipitation may be accompanied by a more marked change in extreme rainfall.

With increasing warming, mean winter precipitation is projected to increase over Northern Europe (NEU) and rainfall will be more frequent and intense. In a 3°C world, nearly 80% of land in NEU will face a robust increase of heavy rainfall in winter.

In summer, an increasing fraction of Southern Europe (SEU) will face reduction of frequency and mean amount of rainfall (and, as consequence, longer dry spells), but, locally (5% of land), also an increase of its intensity in a 3°C world.

According to the indications of the Intergovernmental Panel on Climate Change (IPCC) following the 21st Conference of the Parties in Paris (2015), we specifically assess the the benefits of limiting warming to 1.5°C instead of 2°C. Results show that, compared to 1.5°C world, a further 0.5°C warming results in a robust change of minimum summer temperature indices (both for mean and extremes) over more than 70% of Europe. Robust changes (more than 0.5°C) in maximum temperature affect smaller areas (usually less than 20%).

There is a substantial non-linear change of fixed-threshold indices, with more than 60% increase of the number of tropical nights (i.e., with minimum temperature > 20°C) over southern Europe and more than 50% decrease in the number of frost days over central Europe.

The change in mean precipitation due to 0.5°C warming is mostly non-significant at the grid point level, but, locally, it is accompanied by a more marked change in extreme rainfall.

1 Introduction

At the 21st Conference of the Parties in Paris (2015), signatory countries agreed to keep global warming to below 2°C above preindustrial levels, with the aim of limiting it to 1.5°C.

Although studies assessing the impact of climate change under 1.5°C and 2°C warming are becoming increasingly common, especially at global scale, studies targeting specific regions (including those by King and Karoly (2017) for Europe) are often based on global climate models (GCMs), which, due to their coarse resolution, are unable to simulate fine-scale climate variations, especially in regions of complex topography or coastlines, or with heterogeneous land cover.

The study by Vautard et al. (2014) is based on regional climate models (RCM, i.e., limited-area, high-resolution models forced by boundary and initial conditions by a GCM), but it is limited to the analysis of a +2°C world; in addition, models are forced by A1B emission scenario, rather than Representative Concentration Pathways (RCP), specifically designed for the IPCC Fifth Assessment Report. Pfeifer et al. (2015) used RCMs from the Coordinated Regional-climate Downscaling Experiment over Europe (EURO-CORDEX; Giorgi et al., 2009; Jacob et al., 2013) to assess the robustness of the climate signal at different times in the future, but results were restricted to Germany only. Donnelly et al. (2017) used EURO-CORDEX results to study the impact of different warming levels limited to the hydrological cycle. As a result, a thorough, pan-European assessment of the effect of 1.5°C and 2°C warming on mean and extreme climate events based on state-of-the-art high-resolution RCMs is still missing.

Here we use an ensemble of high-resolution, bias-adjusted RCMs from EURO-CORDEX to investigate the change in mean and extreme climate over Europe under different global warming levels (1.5°C, 2°C, and 3°C). We employ a suit of indices describing both hot and cold events and, for precipitation, wet and dry conditions; in particular, we examine the evolution of threshold-based indices, such as the number of frost days or tropical nights, which may be relevant for impact assessment on specific sectors; future projections of such indices may not be reliable when models' output are used without prior bias-adjustment (Dosio,2016).

2 Data and methods

2.1 Climate Data

Daily mean, minimum (Tn) and maximum (Tx) temperature, and precipitation (Pr) data for the period of 1981–2100 were obtained for an ensemble of RCMs from EURO-CORDEX (Table 1). RCMs were used to downscale the results of GCMs from the Coupled Model Intercomparison Project Phase 5 (Taylor et al., 2012). All RCMs were run over the same numerical domain covering the European continent at a resolution of 0.11°. Historical runs, forced by observed natural and anthropogenic atmospheric composition, cover the period from1950 to 2005; the projections (2006–2100) are forced by two Representative Concentration Pathways (RCP) (Moss et al., 2010; Van Vuuren et al., 2011), namely, RCP4.5 and RCP8.5.

RCMs' outputs have been bias-adjusted (Dosio, 2016) by employing the technique developed by Piani et al. (2010) and the observational data set EOBSv10 (Haylock et al., 2008). Bias adjustment is based on a transfer function such that the marginal cumulative distribution function of the adjusted variable matches that of the observations. A complete discussion of the technique, including validation and effect on climate indices can be found in Piani et al. (2010), Dosio and Paruolo (2011), and Dosio et al. (2012). Dosio (2016) showed that bias-adjustment largely improves the value of present and future threshold-based indices (e.g., the number of summer days): these indices are generally poorly simulated over the present climate, such that the projected climate change may not be reliable. The climate change signal of percentile-based indices and indices related to the duration of an event (e.g., warm spell duration) are not affected by bias-adjustment (Dosio, 2016).

Table 1: List of models runs used in PESETA IV. Runs in bold are the 'core runs', common to all impact models, selected according to the methodology already employed in PESETA III.

RCM	Driving GCM	1.5C RCP4.5	1.5°C RCP8.5	2°C RCP4.5	2°C RCP8.5	3°C RCP4.5	3°C RCP8.5
CCLM4.8-17	**CNRM-CERFACS-CNRM-CM5**	**2035**	**2029**	**2057**	**2044**	**NA**	**2067**
	ICHEC-EC-EARTH	**2033**	**2026**	**2056**	**2041**	**NA**	**2066**
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044	NA	2067
HIRHAM5	ICHEC-EC-EARTH	2032	2028	2054	2043	NA	2065
WRF331F	**IPSL-IPSL-CM5A-MR**	**2023**	**2021**	**2042**	**2035**	**NA**	**2054**
RACMO22E	ICHEC-EC-EARTH	2032	2026	2056	2042	NA	2065
RCA4	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044	NA	2067
	ICHEC-EC-EARTH	2033	2026	2056	2041	NA	2066
	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035	NA	2054
	MOHC-HadGEM2-ES	**2021**	**2018**	**2037**	**2030**	**2069**	**2051**
	MPI-M-MPI-ESM-LR	**2034**	**2028**	**2064**	**2044**	**NA**	**2067**

2.2 Definition of Warming Levels

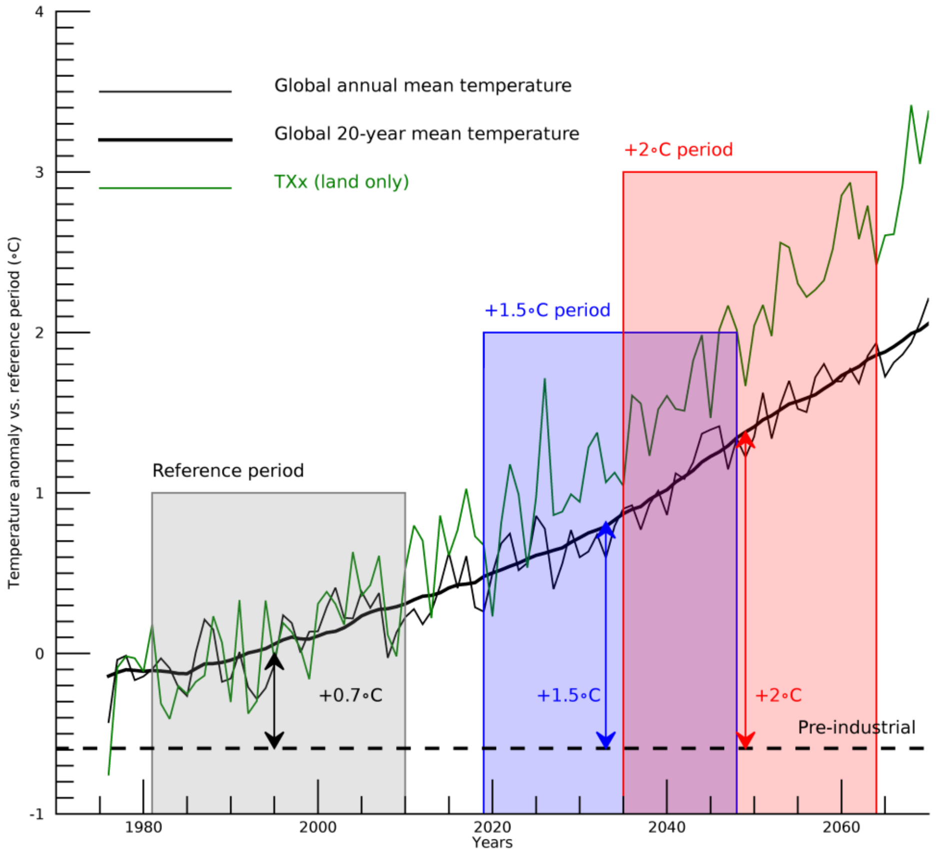
Warming levels (1.5°C, 2°C, and 3°C compared to preindustrial period) are defined following the methodology by Vautard et al. (2014), used in the European Union Seventh Framework Programme project IMPACT2C

(http://impact2c.hzg.de/imperia/md/content/csc/projekte/impact2c_d5.1_fin.pdf).

On the basis of observed temperature (NASA-Goddard Institute for Space Studies (GISS) Surface Temperature Analysis (GISTEMP)) (Hansen et al., 2010) we estimate a global warming of around 0.7°C from the preindustrial period (defined here as 1881–1910) to 1981–2010 (defined as reference period).

For each GCM, we estimate the year when a further 0.8°C global warming is reached, compared to the reference period; the 30 year period around that year is defined as the 1.5°C world; similarly we estimate the timing of the 2°C world (i.e., +1.3°C compared to the reference period) and 3°C world (+2. °C), respectively. The methodology is schematically illustrated in Figure 1.

Figure 1. Time series of global mean temperature and method of estimation of the 1.5∘C and 2∘C levels. Black thick line shows the 20-year running averaged global mean temperature anomaly compared to the reference period (1981-2010) from a GCM. In the 30 year period centred around 1995 the observed warming compared to pre-industrial levels is estimated to be 0.7∘C. We therefore define the year of reaching 1.5∘C with respect to pre-industrial levels as the time when a further 0.8∘C warming is reached with respect to the reference climate. The figure also shows that, over land, the increase of annual maximum temperature (TXx) and its variability is larger than the mean global temperature ones. (modified from Dosio et al., 2018)



As PESETAIV is based on the results of RCMs, the following procedure is further applied:

1. An RCM is defined to project, for example, a 2°C warming when the corresponding driving GCM reaches the 2°C threshold, under either RCP.

2. For each GCM-RCM run, the e.g. 2°C period is defined as the 30 year period centered around the year when the 2°C global warming is first reached (Table 1).

This "time sampling" methodology (James et al., 2017) may be not suitable for not time-invariant impacts (e.g., sea level rise); however, Maule et al. (2017) showed that the effect over Europe is small compared to the model's variability.

2.3 Indices of mean and extreme climate

For each variable, several indices (Table 2) from the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang et al., 2011) were calculated on every land grid point of each model. Indices include absolute-threshold indices (e.g., the number of summer days), percentile-based indices (e.g., TX90p), and indices based on the duration of an event (e.g., consecutive dry days).

Table 2: List of ETCCDI indices

Index	**Name**	**Definition**
SM	Seasonal mean	Average over the season
TX10p	Cold days	Percentage of days where maximum daily temperature (TX) is lower than the calendar 10th percentile (centred on a 5 day window) of the reference period
TX90p	Warm days	Percentage of days where TX is higher than the calendar 90th percentile (centred on a 5 day window) of the reference period
SU	Summer days	Number of days where TX > 25°C
ID	Ice days	Number of days where TX < 0°C
TXx	Max TX	Maximum of daily maximum temperature in a given period (e.g. season or year)
TXn	Min TX	Minimum daily maximum temperature in a given period
WSDI	Warm spell duration	Number of days per period when, in intervals of at least six consecutive days, TX is higher than calendar 90th percentile (centred on a 5 day window) of the reference period.
TN10p	Cold nights	Percentage of days where daily minimum temperature (TN) is lower than the calendar 10th percentile (centred on a 5 day window) of the reference period
TN90p	Warm nights	Percentage of days where TN is higher than the calendar 90th percentile (centred on a 5 day window) of the reference period
FD	Frost days	Number of days where TN < 0°C
TR	Tropical nights	Number of days where TN > 20°C
TNx	Max TN	Maximum daily minimum temperature in a given period
TNn	Min TN	Minimum daily minimum temperature in a given period
CSDI	Cold spell duration	Number of days per period when, in intervals of at least six consecutive days, TN is lower than calendar 10th percentile (centred on a 5 day window) of the reference period.
TOTPREC	Total precipitation	Total precipitation in a given period
SDII	Simple daily intensity	Mean daily precipitation over wet days (i.e., when precipitation > 1 mm)

RR1	Number of wet days	Total number of days when precipitation >1mm
R10mm	Heavy precipitation days	Total number of days when precipitation > 10 mm
RX1day	Max 1 day precipitation	Maximum daily precipitation in a given period
CDD	Consecutive dry days	Largest number of consecutive days where precipitation <1mm
CWD	Consecutive wet days	Largest number of consecutive days where precipitation >1mm

2.4 Statistical Analysis

The significance of the change of an index, on the basis of the RCMs' ensemble, is assessed with a methodology proposed by Tebaldi et al. (2011), depicted schematically in Figure 2a.

First, for each land point and for each model run, we test the statistical significance of the change of the time series of an index under, for example, the reference period and the 2°C period, by means of a two-sample Kolmogorov-Smirnov test with the null hypothesis that the discrepancies between the two distributions are only due to sampling error. A significance level of 5% indicates that the null hypothesis can be rejected statistically.

Second, we classify the change as follows:

1. The change is considered robust if more than 50% of the RCMs show a statistically significant change and, at the same time, more than 80% of them agree on its sign.

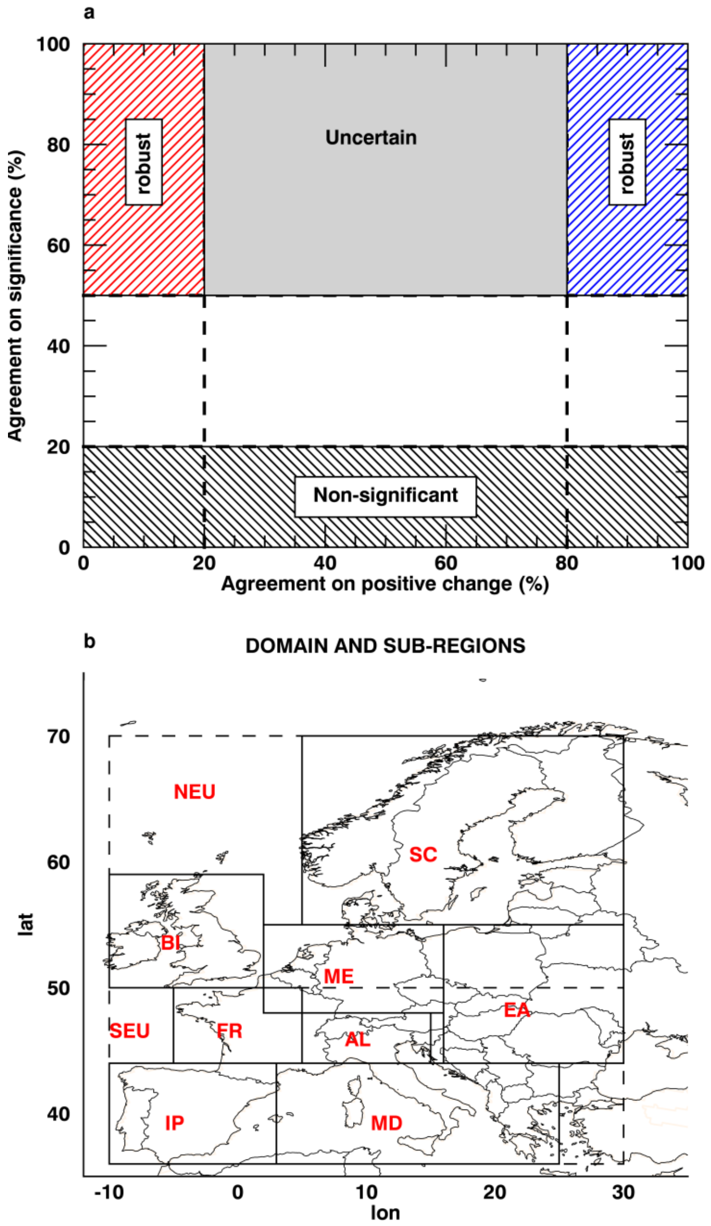
2. The change is considered uncertain, or unreliable, if more than 50% of the RCMs show a statistically significant change but less than 80% of them agree on its sign.

In addition to these two classes we also distinguish the case where more than 80% of RCMs show a non-significant change (independently of the agreement on the sign): this is a meaningful and useful information, often overlooked, as it indicates areas where the change simulated by most of the models is robust, but small compared to the variability, or nearly zero.

Results are presented either as maps of the RCMs' ensemble median, or as spatial average over sub-regions (Figure 2b), defined as Mediterranean (MD), Eastern Europe (EA), Scandinavia (SC), Alps (AL), France (FR), Mid-Europe (ME), British Islands (BI), Iberian Peninsula (IP), Northern Europe (NEU), and Southern Europe (SEU).

Figure 2: a) Illustrative method used to assess robustness: the change is considered robust if more than 50% of the models runs show a statistically significant change and, at the same time, more than 80% of them agree on the its sign. If less than 20% of models indicate a positive change of e.g. precipitation, this means that 80% indicate a negative one. The change is considered uncertain, or unreliable, if more than 50% of the RCMs show a statistically significant change but less than 80% of them agree on its sign.
In addition to these two classes, defined in Tebaldi et al. (2011), we also distinguish the case where more than 80% of RCMs show a not statistically significant change (independently of the agreement on the sign).

b) Geographical sub-regions used in the analysis; in addition to the regions defined in e.g., Christensen and Christensen (2007), we defined two macro-regions, Northern Europe (NEU) and Southern Europe (SEU), defined as land points with latitude greater (lower) than 50° north. Source (Dosio and Fischer, 2018)



3 European climate under different warming levels

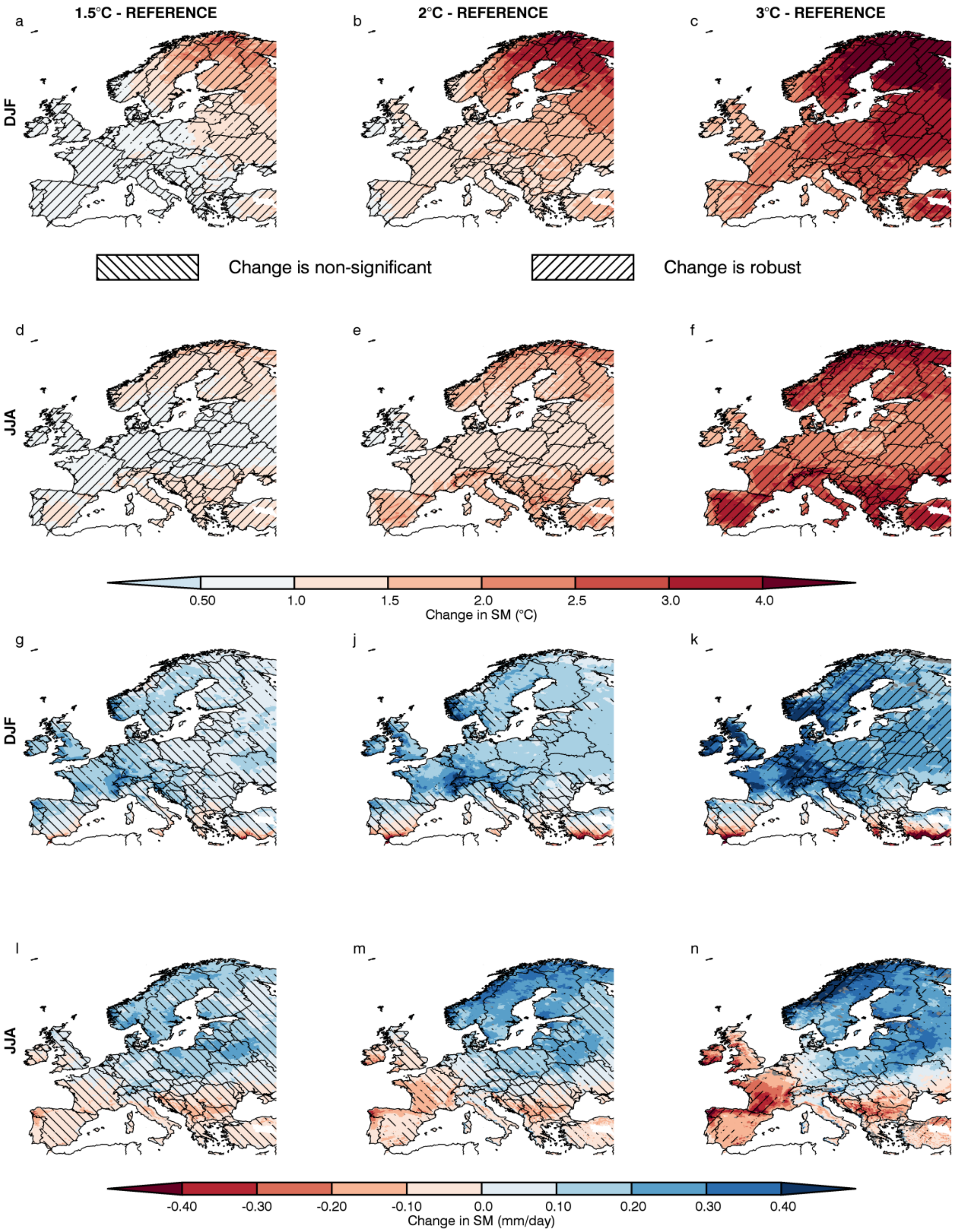
3.1 Mean climatology

Europe is projected to warm more than the global average; compared to the reference period, a robust change in mean temperature in both winter (December–February, DJF) and summer (July–August, JJA) is expected for all warming levels (Figure 3). Even at 1.5°C global warming (0.8°C with respect to 1981– 2010), a large fraction of Europe is projected to face a robust increase of mean temperature of more than 1°C (Figure 3a), both in DJF and JJA, which is larger than the global annual mean one.

The change in precipitation is less pronounced; for both 1.5°C and 2°C worlds, the change in both winter and summer over most of Europe is non-significant (at the grid point level), if compared to the reference period. Where the change is significant, the models' agreement in both sign and intensity of change is high (although models' disagreement on sign can be larger when the change is non-significant): in fact, there are no regions where the change is uncertain or unreliable (as defined in the methodology; see Figure 2a).

Under 3°C warming a robust increase of precipitation is expected over most of central and northern Europe in winter, and a robust decrease is expected over part of Spain, France, and Turkey in summer.

Figure 3. Change (compared to the reference period 1981-2010) of (a-f) seasonal mean temperature and (g-n) daily precipitation for winter and summer at different warming levels (1.5°C, 2°C, and 3°C). Regions where the change is robust or non-significant are highlighted. Source (Dosio and Fischer, 2018)



3.2 Indices of extreme temperature

Under global warming, the temperature Probability Distribution Function (PDF) of temperature is expected to change, with an increase of the mean value and broadening of its width (increase of variability). This results in an increased probability of extreme events (Fischer & Schär, 2010; Schär et al., 2004). However, the tail of the PDF (i.e., hot and cold extremes) can change, at increasing levels of warming, differently than the mean value.

Figure 4 shows the change of selected temperature indices under different warming levels; Figure 5 shows the fraction of land where this change is either robust or non-significant, for NEU and SEU in both winter and summer. TXx, TXn, TNx, and TNn are a measure of hot and cold extreme temperature events, whereas the number of frost days and tropical nights are examples of threshold-based indices that may be relevant for impact assessment studies.

Here we describe in detail only few, most representative examples:

1. Under 1.5°C warming, ~85% of NEU in DJF is projected to face an increase of mean Tx (SM, Figure 5a). However, the fraction of land affected by a robust change of other indices is smaller. This can be either due to a change in the temperature distribution (PDF) or due to a higher year-to-year variability of, for example, TNn and TXx with respect to the mean: even if the absolute change of TNn and TXx is large, the significant fraction would be smaller due to the higher noise component in the extreme indices (Ballester et al., 2010; Fischer & Schär, 2010). The increase of TNn in winter, over most of central and northern Europe, is particularly significant, varying from less than 2°C in a 1.5°C world to more than 4°C in the 3°C world (Figures 4g–4k).

2. In summer over SEU (Figure 5m) nearly 80% of land is subject to a robust change of all indices of minimum temperature even in a 1.5°C world: this indicates a marked shift of the PDF toward higher temperatures, with consequent increase of both minimum (TNn) and maximum (TNx) extremes.

3. Compared to a 1.5°C world, under 2°C warming, there is a marked increase in the fraction of land affected by robust changes of ETCCDI indices (TXn over SEU in JJA, Figure 5l, but also TXn and TNn over SEU in DJF, Figures 5d and 5e, and SU and TXx over NEU in JJA; Figure 5g). Under 3°C warming, nearly all temperature-related indices show a robust change, compared to the reference period, over the entire continent.

4. Warming has often a nonlinear effect on the exceedance of non extreme, but potentially impact-relevant, fixed-threshold indices; for instance, over Poland, the reduction of frost days in winter, compared to the present climate, amounts, on average, to around 8 days in a 1.5°C world, 12 in a 2°C world, and 22 in a 3°C world (Figures 4o–4q).

Figure 4. Change (compared to 1981–2010) of selected temperature ETCCDI indices for winter and summer at different warming levels (1.5°C, 2°C, and 3°C). Regions where the change is robust or non-significant are highlighted. Changes of TXx, TXn, TNx, and TNn are shown in °C, whereas those of TR and FD are shown in days/season (Dosio and Fischer, 2018).

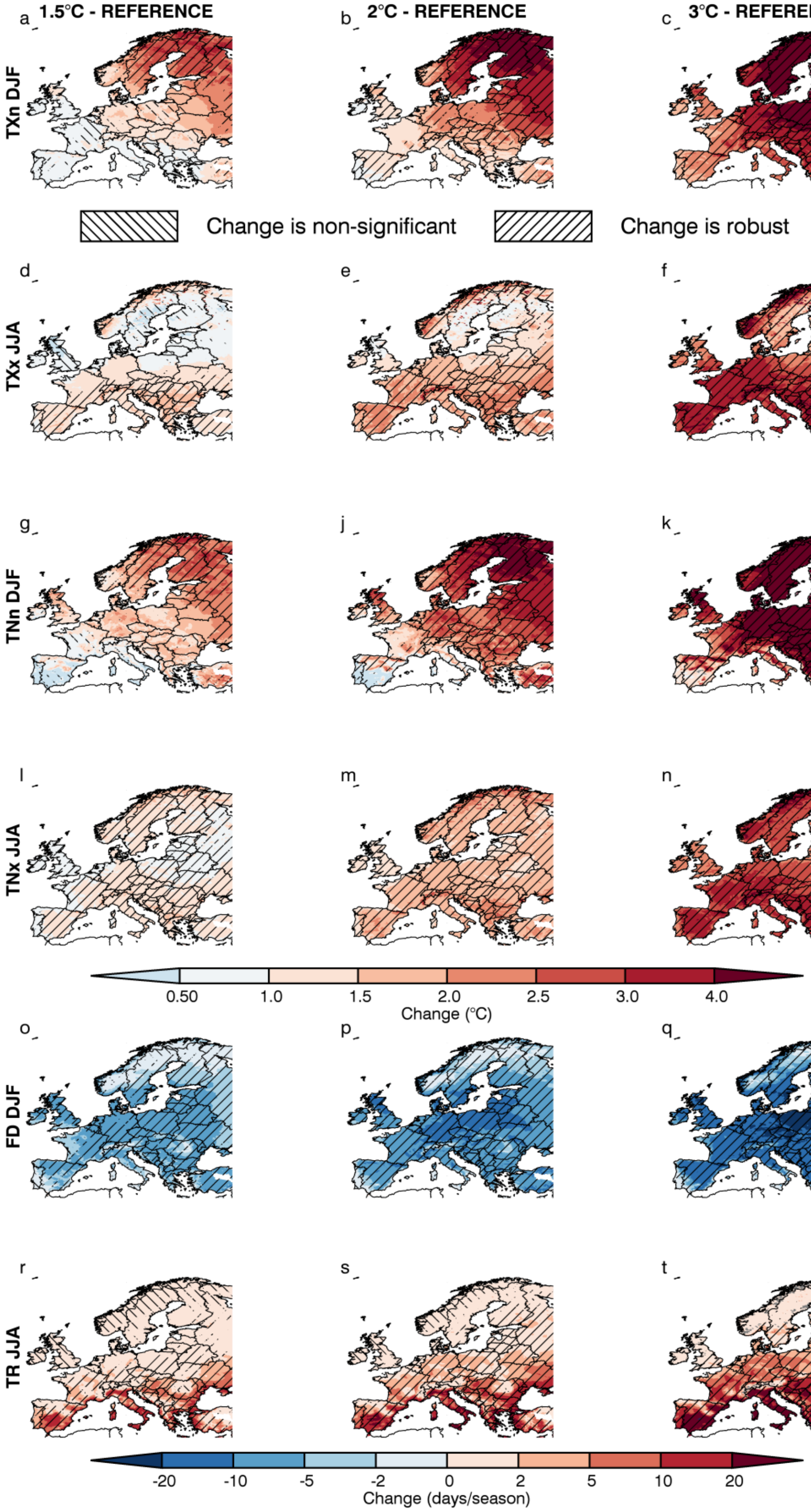
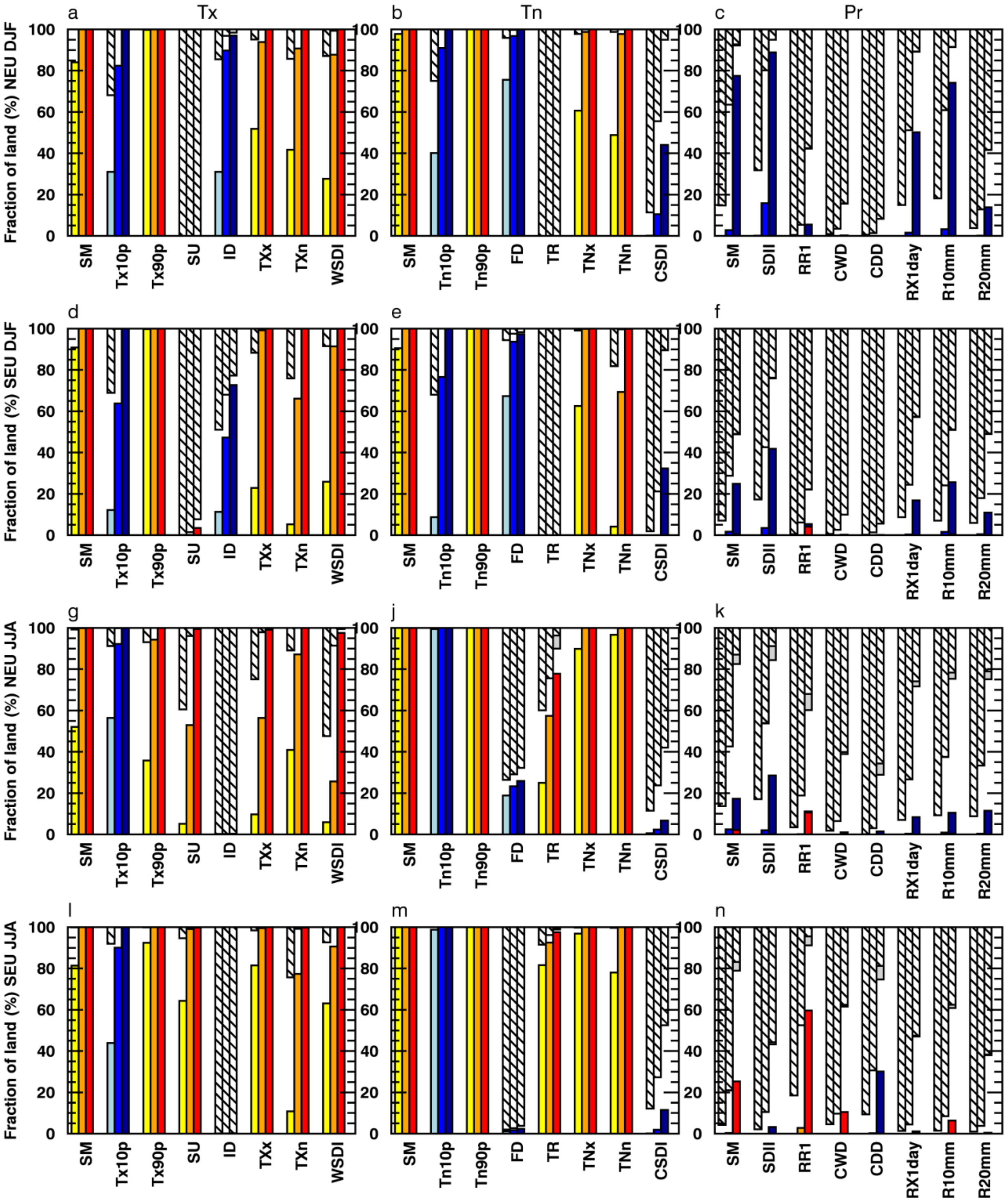


Figure 5. Fraction of land (%) experiencing a robust (colored bars) or non-significant (hatched bars) change compared to the reference period of some ETCCDI indices, under different warming levels. Columns show results for indices based on Tx, Tn, and precipitation, respectively. Rows show results for NEU and SEU in DJF and in JJA, respectively. For temperature indices, the yellow, orange, and red colors indicate a robust positive change, under 1.5°C, 2°C, and 3°C warming, respectively; the blue colors indicate a robust negative change. For precipitation indices, blu colors indicate a robust positive change; red colors a robust negative change (Dosio and Fischer, 2018).



3.3 Precipitation Indices

Local precipitation will non-significantly change over most of Europe under either 1.5°C or 2°C warming, compared to 1981–2010. However, a moderate change in mean precipitation may be accompanied by a more marked change in extreme rainfall, as the change in precipitation frequency distribution is not uniform (Dosio, 2016).

With increasing warming, mean winter precipitation is projected to increase over NEU (Figure 3), and rainfall will be more frequent (RR1; Figure 5c) and intense (simple daily-precipitation intensity index (SDII); Figure 5c). In a 3°C world, nearly 80% of land in NEU will face a robust increase of heavy rainfall in winter (such as R10mm).

On the other hand, in summer, an increasing fraction of SEU will face reduction of frequency (RR1; Figure 5n) and mean amount of rainfall (and, as consequence, longer dry spells, CDD), but over some areas also an increase of its intensity (SDII, although over only 5% of land) in a 3°C world.

4 Assessing the Differences Between 1.5°C and 2°C Worlds

The complete summary of the fraction of land subject to a robust change in ETCCDI indices between 2°C and 1.5°C worlds is shown, for each sub-region and season, in Figures 6a–6f. In addition, we show the absolute value of the change averaged over the points where this change is robust (Figures 6g–6n).

A 0.5°C warming will affect mostly minimum temperature indices in summer: a robust change in mean Tn, and the exceedance of its extremes (Tn10p and Tn90p) is expected over more than 70% of land in most sub-regions. Robust changes in other temperature indices and seasons are also expected over most of the sub-regions, although the fraction of land affected is usually small (less than 20%). There are some exceptions, however, such as Tx90p in winter, whose change is robust over more than 50% of IP, FR, AL, and MD. Also, the Iberian Peninsula and the Mediterranean will face, in summer, a robust change of mean Tx and Tx90p over more than 50% of land.

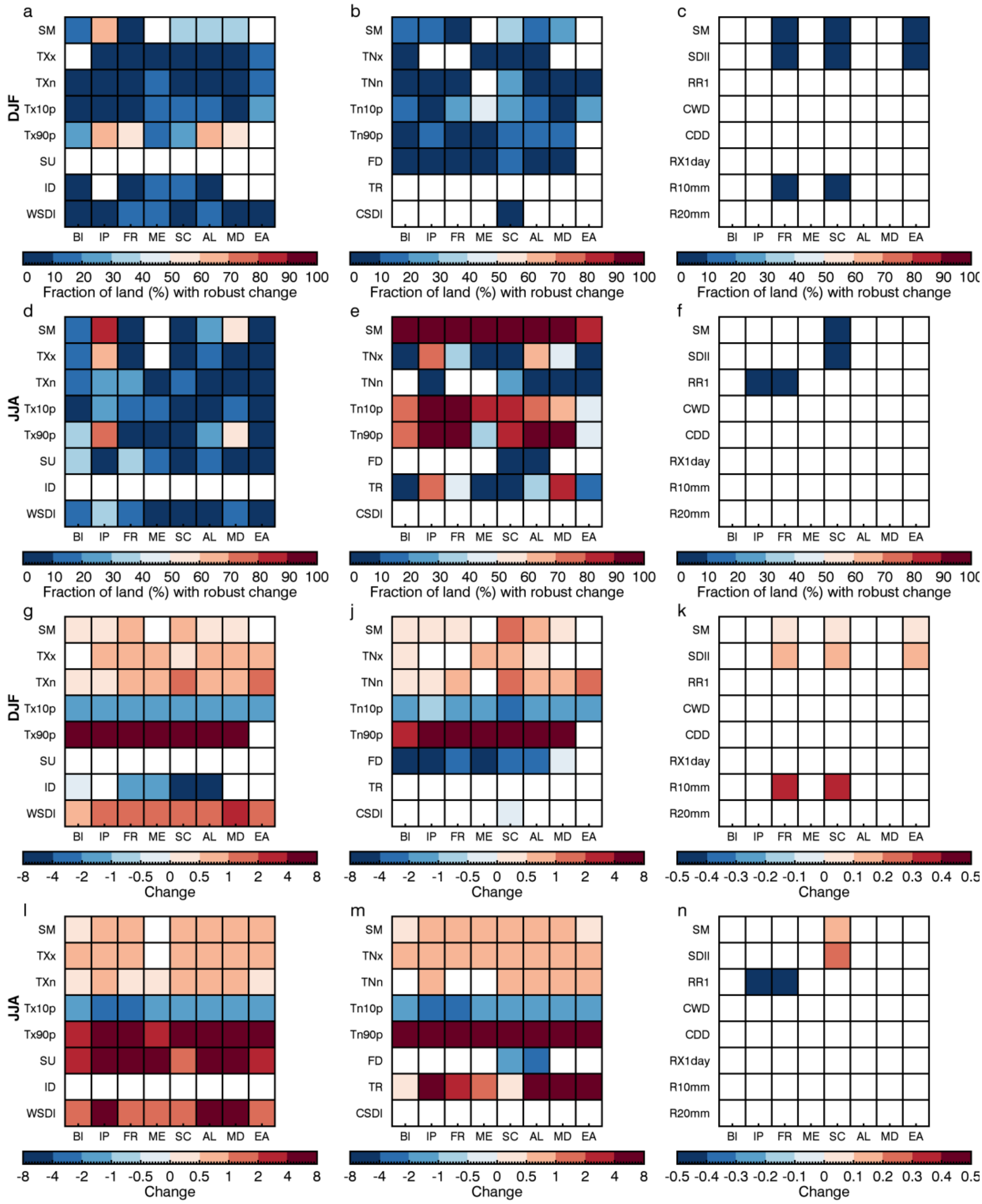
It is important to note that the change between 2°C and 1.5°C worlds, over the fraction of land where it is robust, is substantial. For instance, in summer, both hot and cold extremes (TXx, TNx, and TNn, and, to a lesser extent, TXn) increase more than 0.5°C (although the fraction of land where this change is robust is usually less than 10%). In winter, the change will be larger than 0.5°C mostly for TXx, TXn, and TNn.

There are substantial nonlinear changes in fixed-threshold indices between 1.5 and 2°C worlds: over north- central Europe, particularly Germany and Poland, the reduction in frost days is more than 50% larger for 2°C than 1.5°C world, with potential impacts on ecosystems and agriculture including the spread of pests (Figures 4o–4q). Likewise, the increase in the number of tropical nights is more than 60% larger in many places in southern Europe and the Mediterranean (where TR increases, on average, from around 10 to 17 days/season; Figures 4r–4t). In particular, the increase is more than 5 days per season over some densely populated regions, which may have potential adverse effects on public health.

Asymmetry between the change in cold and hot extremes is also evident from the percentile-based indices; whereas Tx10p is, in most regions, expected to decrease by 1–2 days/season (Figures 6g, 6j, 6m, and 6l), Tx90p will increase by more than 3 days/season nearly over every region, both in DJF and JJA.

Finally, only a small fraction of land (less than 10% over only few sub-regions) is affected by robust changes in precipitation when comparing 2°C and 1.5°C worlds. However, a robust increase in precipitation intensity (SDII) and extremes (and R10mm) is expected over a small (less than 10%) part of France and Scandinavia in winter, whereas in summer precipitation will decrease (in frequency, RR1) over some areas in IP and FR, and increase (in mean and intensity, SDII) over around 10% of Scandinavia.

Figure 6. (a–f) Fraction of land expecting a robust change in temperature and precipitation indices between 2°C and 1.5°C worlds for each sub-region in DJF and JJA. (g–n) Value of the change spatially averaged only over the land points where the change is robust. Note that units depend on the index (see Table 2). The white areas denote regions where less than 1% of land is expected to face a robust change in the index. First column refers to maximum temperature indices, second column to minimum temperature indices, and third column to precipitation indices (Dosio and Fischer, 2018).



5 Conclusions

Most of Europe is projected to face a robust increase in temperature larger than the global mean one; changes in hot and cold extremes (the hottest day and night TXx and TNx and the coldest day and night TNx and TNn) are projected to substantially exceed the global mean warming and often the corresponding local seasonal mean warming.

Compared to 1.5°C world, a further 0.5°C warming results in a robust change of minimum summer temperature indices (mean Tn, and exceedance of its extremes, Tn90p and Tn10p) over more than 70% of European land areas. Robust changes in maximum temperature, in both winter and summer, affect smaller areas (usually less than 20% of land) but the change will be substantial (more than 0.5°C,) especially for extreme temperature.

There are substantial nonlinear changes in fixed-threshold indices, such as FD in winter and SU and TR in summer, between 1.5 and 2°C worlds. In particular, north-central Europe is projected to be affected by a reduction of more than 50% of the number of frost days, and part of the Mediterranean will face an increase of more than 60% in the number of tropical nights, with potential adverse effects on public health. It must be noted that the change of these fixed-threshold-based indices cannot be properly assessed unless the climate projections are bias-adjusted: however, bias adjustment relies on the assumption stationarity of the error, and its results may be influenced by the chosen method and, most importantly, by the observational data set used as reference (Dosio, 2016).

The difference in mean precipitation between 1.5°C and 2°C worlds is mostly non-significant at the grid point levels. Robust changes in mean precipitation and extremes are limited to a small area (less than 10%) of Scandinavia (both in winter and summer), and, locally, France and Spain in summer. However, despite the higher variability, the fraction of land where the differences in extreme rainfall are significant between the two warming levels is larger than for the mean, especially in winter.

Some caveats to our study need to be mentioned.

1. The statistical significance of the change may depend on (a) the period chosen as reference (Hawkins & Sutton, 2016) and (b) the length of the sampling period (Sippel et al., 2015). Although choosing earlier periods (e.g., 1971–2000) and a different sampling length may alter the results (e.g., the fraction of land with significant change) of some indices at lower warming levels (1.5°C), our choice is consistent with the WMO Guide to Climatological Practices indicating 1981–2010 as the current standard for calculating climatological standard normal. Moreover, the results for the difference between 1.5°C and 2°C worlds are independent of the reference period. Fischer et al. (2013) argued that even if changes are non-significant at individual grid points, spatially aggregated results provide robust evidence even for extreme indices.

2. We assume that the results for different warming levels are independent of the underlying RCPs (RCP4.5 and RCP8.5), i.e., the time it takes to reach, for example, 2°C. While this method (defined as "time sampling" by James et al., 2017) may have some drawbacks (notably, its non applicability to not time-invariant impacts such as sea level rise), and, in addition, results for, for example, TXx may depend on the different temperature trend in the two RCPs, Maule et al. (2017) show that the effect over Europe is small compared to the models variability (especially the GCMs one), especially on the time scales needed to reach 2°C.

3. This findings agree qualitatively with previous studies (Donnelly et al., 2017; King & Karoly, 2017 ; Vautard et al., 2014) although there are notable differences in the robustness of the signal especially for precipitation, due to the different methodologies used, specifically, the different reference period (being 1971–2000 in Vautard et al., 2014, and Donnelly et al., 2017), and, more importantly, the definition of robustness.

Despite those limitations, this study demonstrates that half a degree warming will indeed make a difference over Europe, especially for minimum temperature indices in summer, which are projected to affect large areas of Europe (up to 90% of land for mean minimum temperature, Tn10p and Tn90p). The impact on other temperature indices and seasons is less pronounced (usually limited to less the 10% of land), although, where the change is robust, it is substantial, especially for impact relevant indicators such as the number of frost days or tropical nights.

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