European Commission

JRC TECHNICAL REPORTS

PESETA III: Climate change impacts on labour productivity

Gosling S.N., Zaherpour J., Ibarreta D.

2018

Joint Research Centre

EUR 29423 EN

Contact information
Name: Dolores IBARRETA
Address: European Commission, Joint Research Centre, Edificio Expo; C/ Inca Garcilaso, 3, E-41092 Sevilla, Spain
Email: Dolores.IBARRETA@ec.europa.eu
Tel.: +34 9544-88445

EU Science Hub
https://ec.europa.eu/jrc

JRC113740

EUR 29423 EN

PDF ISBN 978-92-79-96912-6 ISSN 1831-9424 doi:10.2760/07911

Luxembourg: Publications Office of the European Union, 2018

How to cite this report: Gosling S.N., Zaherpour J., Ibarreta D., *PESETA III: Climate change impacts on labour productivity*, EUR 29423 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-96912-6, doi:10.2760/07911, JRC113740

Contents

Acknowledgements

This research was funded by the European Commission under research contract JRC/SVQ/2015/J.1/0030/NC "Assessment of global climate change impacts on labour productivity." Andrea Toreti (EC JRC) computed the relative humidity data and processed the daily maximum and minimum temperature. Alessandra Bianchi (EC JRC) re-gridded the population data.

Authors

Simon N. Gosling[1], Jamal Zaherpour[1], Dolores Ibarreta[2]

1. School of Geography, University of Nottingham, Nottingham NG7 2RD, United Kingdom.

2. European Commission Joint Research Centre, Seville, Spain.

Executive Summary

Approach and novelty

This study uses five impact models that describe observed relationships between labour productivity and temperature, with climate model simulations from five climate models under a high emissions scenario (RCP8.5), i.e. 25 climate-impact model combinations, to assess the impact of climate change on outdoor and indoor labour productivity respectively, at the national-scale, across Europe. This is the first assessment to use multiple impact models with multiple climate models and to consider the potential effects of adaptation on lowering the impacts relative to no adaptation taking place.

Impacts are estimated for the end of century (2071-2100) and near-term (2021-2050), relative to present-day (1981-2010). Impacts are also estimated under a mitigation scenario, where global-mean warming is 2°C relative to pre-industrial. Impacts are assessed with and without adaptation respectively. Planned adaptation is represented as an adjustment in work activities following recommendations by the US Occupational Safety & Health Administration to consider the adjustment of work shifts during hot periods – all labour takes place at night instead of day-time, under the adaptation assumption.

Key scientific findings

Without climate change mitigation and adaptation, daily average outdoor labour productivity could decline by around 10-15% from present-day levels in several southern European countries by the end of the century (Bulgaria, Greece, Italy, Macedonia, Portugal, Spain and Turkey; Figure A). Countries in northern Europe could also see declines in daily average outdoor labour productivity but the declines are considerably smaller than for the southern countries, at around 2-4% (Denmark, Estonia, Finland, Norway and Sweden). The magnitude of impact on indoor labour productivity is generally 2-4 percentage points lower than for impacts on outdoor labour productivity, for the three most sensitive impact models, while for the two least sensitive impact models, the differences are smaller.

There is uncertainty in the magnitude of projected climate change impacts on labour productivity due to: 1) differences in the projections of climate between different climate models; and 2) the use of different impact models. Both sources of uncertainty are significant. The range in projected impacts due to using multiple climate models is comparable to the range in impacts from using multiple impact models with only one climate model.

Policy implications

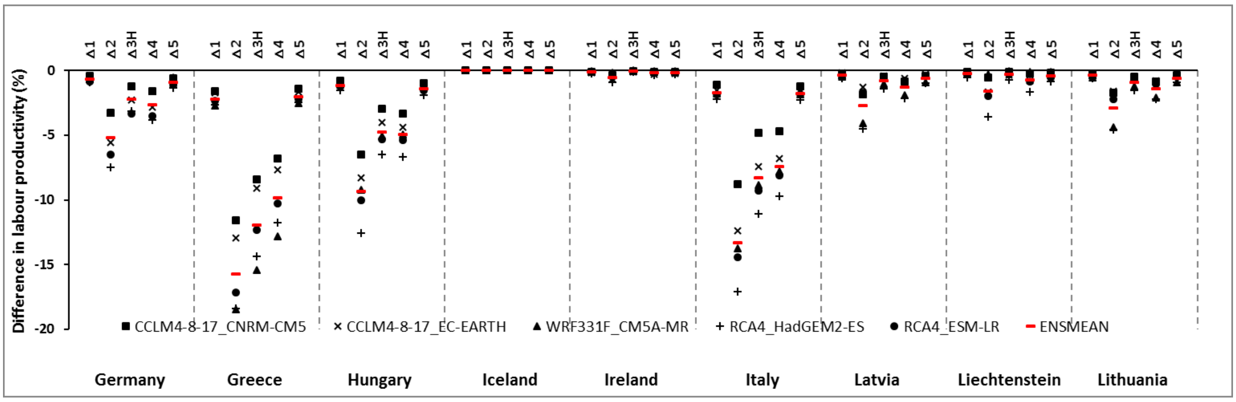
Adaptation and mitigation have the potential to significantly lessen the impacts of climate change on declines in labour productivity across Europe.

For some countries the impacts can be up to around 10 percentage points lower with adaptation than without, for some climate-impact model combinations, at the end of the century under high emissions (e.g. Bulgaria, Croatia, Greece, Italy, Spain and Turkey; Figure A). However, the declines in daily average outdoor labour productivity could still be around 5% relative to present-day in these countries (and up to 10% for Greece, with one climate-impact model combination). Whilst the potential benefits of adaptation are clear from this assessment, it is important to be aware of the caveats associated with the adaptation modelling approach employed. These include an assumption of the entire work force engaged in moderate to heavy labour shifting to night-time working, acknowledgment that night-time working can be associated with negative health effects, and potentially higher costs of night-time working due to energy requirements for lighting and higher wages for working unsocial hours. Such a change in working practices is optimistic, but not implausible, since currently around 20% of workers in Europe are employed on shift work involving night work (Harrington, 2001).

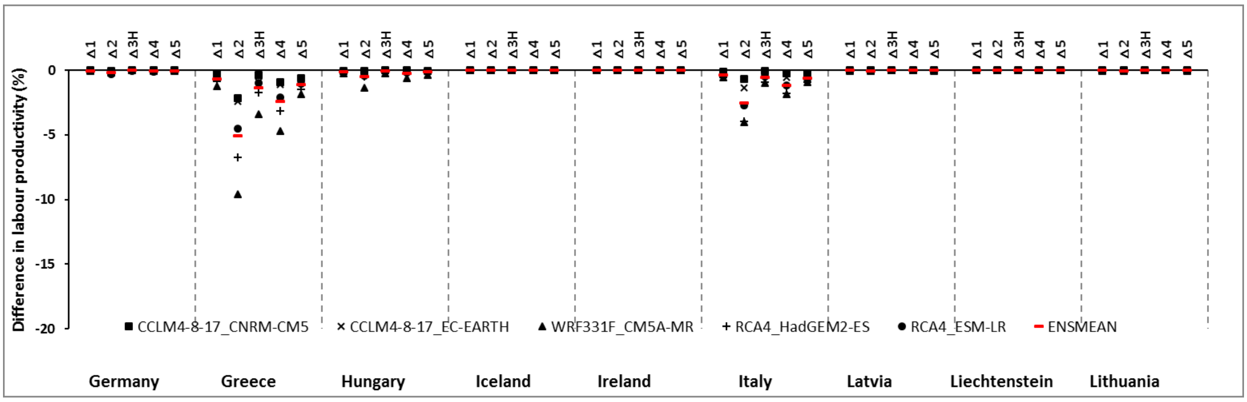
Limiting global warming to below 2°C (and assuming no adaptation) could avoid a substantial proportion of impacts in the European countries that see the largest impacts without mitigation (Bulgaria, Greece, Italy, Macedonia, Portugal, Spain and Turkey). With some climate-impact model combinations the declines in labour productivity can be up to 10 percentage points lower in these countries with mitigation when compared to without mitigation (Figure A).

Figure A. The impacts of climate change on labour productivity in a selection of European countries to demonstrate the spatial heterogeneity of impacts. Impacts are estimated by five impact models (denoted Δ1-5) combined with five climate models (denoted by different markers, ensemble mean in red). Impacts are estimated for: a) end of the century without mitigation and without adaptation; b) end of the century without mitigation but with adaptation; and c) with mitigation that limits global warming to below 2°C relative to pre-industrial but without adaptation.

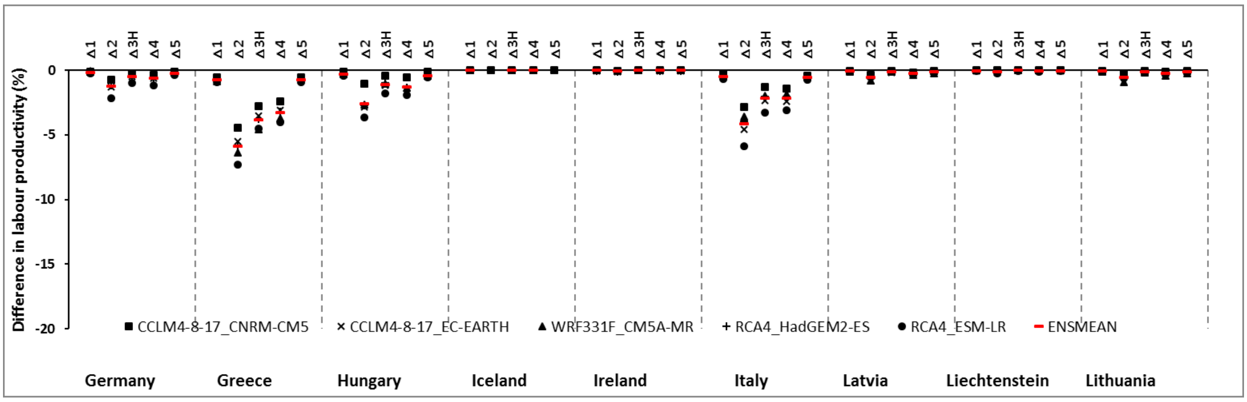
a)



b)



c)



1 Introduction

Empirical evidence from ergonomics studies show that most forms of human performance, hereafter referred to as labour productivity, generally deteriorate under increasing air temperature beyond a threshold (Hancock et al., 2007; Hancock and Vasmatzidis, 2003; Pilcher et al., 2002; Ramsey and Morrissey, 1978; Witterseh et al., 2004). Wet Bulb Globe Temperature (WBGT), instead of dry-bulb air temperature, is normally used when assessing the relationship between temperature and labour productivity (Budd, 2008).

Evidence for the detrimental effects of increasing temperature on labour productivity are largely from studies conducted within specific working environments, involving office, factory, or outdoor workers respectively (e.g. Federspiel et al., 2002; Jeremiah et al., 2016; Lin and Chan, 2009; Link and Pepler, 1970; Niemelä et al., 2002; Niemelä et al., 2001). There has so far been no effort to design a study that provides empirical evidence for changes in labour productivity with temperature across multiple working environments, locations and countries, using a consistent methodology.

Despite the well-known association between increasing temperature and declining labour productivity, there have been few assessments of the impact of climate change on labour productivity, which combine climate projections with exposure response functions (ERFs) that relate changes in labour productivity to WBGT. Some studies have used ERFs derived from empirical studies in distinct locations (Kjellstrom et al., 2009; Kjellstrom et al., 2013), whilst others have used ERFs developed from meta-analyses (Burke et al., 2015; Hsiang, 2010). In the latter case, the ERF was derived from a meta-analysis of 22 ergonomics studies by Pilcher et al. (2002).

With exception to Burke et al. (2015) and Houser et al. (2015), climate model uncertainty has been relatively under-sampled in climate change impact assessments for labour productivity. The number of climate models employed in other assessments include: 1 (Dunne et al., 2013; Kjellstrom et al., 2016; Kjellstrom et al., 2013), 2 (Kjellstrom et al., 2009) and 3 (Kjellstrom et al., 2014). Estimates of the impacts of climate change have been shown to be highly sensitive to the driving climate data from climate models so it is important that this source of uncertainty is adequately accounted for. No previous studies have accounted for impact model uncertainty, however, i.e. the application of multiple impact models/ERFs for estimating impacts – the assessment presented here is the first.

The latest greenhouse gas concentration scenarios (RCPs) have been used in two recent studies (Dunne et al., 2013; Kjellstrom et al., 2016) but no previous work has quantified the impacts associated with prescribed amounts of global-mean warming such as 2°C above pre-industrial temperatures.

Furthermore, no previous climate change impact assessments for labour productivity have explicitly modelled the potential for adaptation to reduce a proportion of the impacts of climate change on labour productivity. This is largely because there is very limited evidence that shows workers have, over time, adapted to warmer working environments. An opportunity exists to investigate how adaptation could reduce the magnitude of impacts through planned adaptation mechanisms such as shifting the hours of working (e.g. working outdoors at night, when temperatures are cooler than during the day).

2 Methods

2.1 Overall approach

The study used simulations of climate variables from 5 different climate models to compute daily indoor and outdoor WBGT respectively, for the period 1981-2100, on a 0.11° grid across Europe. The WBGT estimates were then used as input to five separate labour productivity-WBGT ERFs to compute daily declines in labour productivity for indoor and outdoor workers respectively on the grid. This was done for the following time periods:

- Present-day: 1981-2010
- Near-term: 2021-2050
- End of the century: 2071-2100
- The 30-year time window centred on the point where the driving climate model reaches 2°C global warming relative to pre-industrial.

The difference in labour productivity between the present period and the climate change period was calculated and represents changes in labour productivity attributable to climate change. Data on present-day population for each grid cell was used to calculate the population-weighted mean national difference (from present) in indoor and outdoor daily average labour productivity respectively due to climate change, for each impact model and climate model.

2.2 Climate models

The study provides a comprehensive assessment of the sensitivity of labour productivity impacts to climate model uncertainty by computing impacts with five climate models. Specifically used were daily climate change projections from five Global Climate Model – Regional Climate Model (GCM-RCM) combinations from the CORDEX project for the European region, on a 0.11° resolution (rotated pole) grid:

- CLMcom-CCLM4-8-17-ICHEC-EC-EARTH
- CLMcom-CCLM4-8-17-CNRM-CM5
- IPSL-INERIS-WRF331F-IPSL-IPSL-CM5A-MR
- SMHI-RCA4-MOHC-HadGEM2-ES
- SMHI-RCA4MPI-M-MPI-ESM-LR

Each GCM-RCM combination was run under a high emissions scenario (RCP8.5) for the period 1981-2100.

NetCDF files for daily mean temperature, daily maximum temperature and daily minimum temperature, were downloaded for each GCM-RCM combination from the Earth System Grid Foundation (ESGF), for 1981-2100. Daily maximum and mean relative humidity were calculated empirically from the climate model data.

2.3 Calculating WBGT

WBGT was calculated for indoor (WBGTid) and outdoor (WBGTod) conditions.

Daily WBGTid was calculated for every 0.11° grid cell from the psychrometric wet bulb temperature (Tw) and daily maximum temperature (Tmax), following the method described by Lemke and Kjellstrom (2012):

$$WBGTid = 0.67Tw + 0.33Tmax$$

Climate models do not routinely output Tw so it was estimated empirically from Tmax and daily maximum relative humidity (RHmax), following Stull (2011):

$$Tw = Tmax\ atan[0.151977(RHmax + 8.313659)^{1/2}] + atan(Tmax + RHmax) - atan(RHmax - 1.676331) + 0.00391838(RHmax)^{3/2}\ atan(0.023101\ RHmax) - 4.686035$$

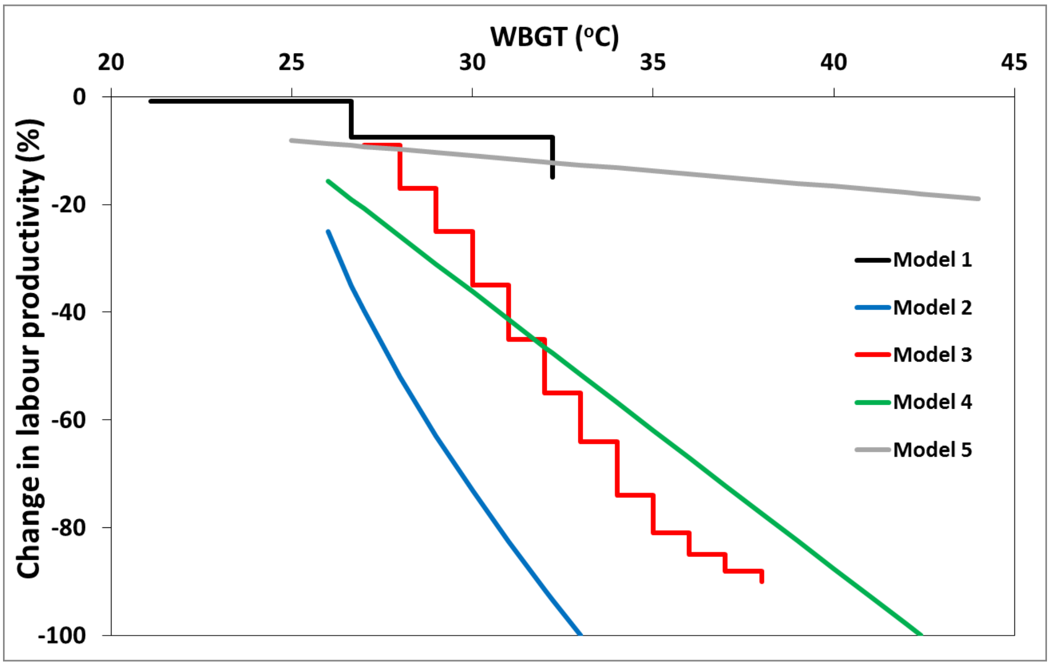
WBGTod was calculated by the approximation described by Kjellstrom (2014):

$$WBGTod = WBGTid + 3^{o}C$$

2.4 Impact models

A unique element of this study is that it brings together several impact models previously used in climate change impacts assessments, but separately. The impact models are ERFs that describe relationships between labour productivity and WBGT. The application of different impact models for the first time provides a demonstration of the uncertainty in impact projections that can arise from using different ERFs. Five impact models were employed in the study. There is significant heterogeneity in the five impact models (Figure 1).

Figure 1. The five impact models used in the present study. The threshold temperatures above which labour productivity starts to decline are where the lines begin on the left. At the end of each line on the right, it is assumed that the line becomes horizontal with increasing WBGT.



The first impact model is an ERF developed by Pilcher et al. (2002), which has been used in two recent climate change impact assessments (Burke et al., 2015; Hsiang, 2010). The ERF is a step-function (Figure 1) developed from a meta-analysis of 22 studies that report associations between labour productivity and WBGT. A more recent meta-analysis (Hancock et al., 2007) was consulted but crucially it does not present the results as an ERF.

The ERF described by Pilcher et al. (2002) does not differentiate between the intensity of work being undertaken by the worker – other ERFs do, e.g. the third model used in this study (Kjellstrom et al., 2014). This is because the meta-analysis only considered how certain types of task were effected by increases in WBGT. The ERF covers four types of tasks: reaction time tasks, attentional or perceptual tasks (e.g., vigilance, tracking or acuity tasks), mathematical tasks (e.g., multiplication or adding tasks, identifying lower versus higher numbers), and reasoning, learning, or memory tasks (e.g., logic tasks, word recall tasks). Therefore the first ERF is quite different from the other four used in this study, because the other four have been created to specifically describe the relationship between WBGT and physical labour. Nevertheless, the ERF defined by Pilcher et al. (2002) is used in this study because of its application in two recent prominent assessments of the impacts of climate change on labour productivity (Burke et al., 2015; Hsiang, 2010). Moreover, it is the only ERF used in this study that is derived from a systematic meta-analysis of empirical evidence published in the peer-reviewed literature.

The second impact model is an ERF developed by Dunne et al. (2013), which is based upon National Institute for Occupational Safety and Health (NIOSH) standards and combines light, moderate and heavy labour into a single metric by a non-linear regression equation along a continuum from 25°C to 32.2°C (Figure 1). The decline in labour productivity is calculated as:

$$\text{Decline in labour productivity (\%)} = 100 - (100 - (25 \times \max(0, \text{WBGT} - 25)^{2/3}))$$

If WBGT is less than 25°C then there is no loss in labour productivity. If WBGT is greater than 33°C, then the decline in labour productivity is 100%.

Dunne et al. (2013) notes that the ERF derives from a comprehensive attempt by NIOSH (1986) to synthesize available knowledge on the effect of temperature on productivity in hot and humid conditions, to yield a single recommendation on work limits with general applicability. This resulted in the establishment of safety thresholds applicable to healthy, acclimated labourers, sustainable over an 8-hour work period.

The ERF displays the highest sensitivity of all the impacts models employed in this assessment (Figure 1). Beyond the 33°C limit, the threshold implies that no amount of labour can be safely sustained over a typical 8 hour work period. Dunne et al. (2013) explains that this has been observed in several studies described by NIOSH (1986) including a study of iron, ceramics, and quarry workers (Nag and Nag, 2009) that showed beyond the exercise regime of around 1 hour, the threat of heat exhaustion and other medical effects requires a switch in the mode of labour, away from the sustainable thresholds they define in the ERF, and towards a focus on more short-term thermal stress accumulation where the labourer is closely monitored and allowed to actively dissipate accumulated heat stress over long periods of recovery. As far as can be ascertained, the original ERF applied by Dunne et al. (2013), and the method by which it was derived, is not described in a peer reviewed journal.

The third impact model (Figure 1) uses one of three ERFs developed by Kjellstrom et al. (2014), which are based upon three ISO standard work intensity levels (Parsons, 2006): 200 W (assumed to be office workers in the service industry, engaged in light work indoors), 300 W (assumed to be industrial workers, engaged in moderate work indoors) and 400 W (assumed to be construction or agricultural workers, engaged in heavy work outside), and three studies that report observed declines in labour productivity with increasing temperature (Nag and Nag, 1992; Sahu et al., 2013; Wyndham, 1969). Whilst Kjellstrom et al. (2014) calculated declines in labour productivity for light and moderate activity using indoor WBGT and heavy activity with outdoor WBGT, the present study assumes that all work intensities can occur either inside or outside because it is plausible that, for instance, heavy work activity can take place indoors (e.g. lifting heavy machinery in a factory) as well as outdoors (e.g. construction work. The ERF for heavy work only is used in this assessment because it corresponds to the type of work conducted by the study participants that were used to develop all the other impact models (except the first model).

There are two limitations with this ERF. The first is that the ISO standard document (Parsons, 2006) referred to by Kjellstrom et al. (2014) contains no empirical evidence to support the recommendations for the hourly work/rest ratios at specific work intensity levels that were used to inform the exposure-response functions presented by Kjellstrom et al. (2014). Secondly, although the incorporation of empirically based evidence into the ERF in part addresses the above limitation, the empirical evidence is from studies in highly distinct locations, including a gold mine (Wyndham, 1969), 124 rice harvesters in

West Bengal in India (Sahu et al., 2013), and six women observed in a climatic chamber (Nag and Nag, 1992).

To explore how impacts estimated from one of the ERFs that informed the third impact model, compares with estimates from it, and the other impact models, the fourth impact model is based upon empirical evidence reported by Sahu et al. (2013) (Figure 1). The authors investigated high heat exposure during agricultural tasks in India. They observed that worker productivity reduced by approximately 5.14% for each 1°C increase in WBGT above 26°C. Sahu et al. (2013) developed a linear regression model that is applicable for workers who have worked for 5-hours or more. The loss in productivity can be calculated for all WBGT values greater than or equal to 26°C and less than 42.4°C (above 42.4°C the decline is 100%). The decline in labour productivity is calculated as:

$$\text{Decline in labour productivity (\%)} = 100 - ((-5.14 * \text{WBGT}) + 218)$$

The fifth impact model uses some of the latest empirical evidence on how labour productivity is affected by high temperatures. Li et al. (2016) observed a 0.57% decrease in productivity for every 1°C rise in WBGT above 25°C, for re-bar workers (heavy labour) in China. The decline in labour productivity can be calculated for all WBGT values greater than or equal to 25°C as:

$$\text{Decline in labour productivity (\%)} = 100 - ((-0.57 * \text{WBGT}) + 106.16)$$

Whilst the fourth and fifth impact models are derived from empirical evidence, reported in peer reviewed journals, they are specific to certain types of heavy labour, within distinct climates, and with particular workers. In contrast, the first and third impact models were derived from multiple sources of empirical evidence.

The present assessment assumes that relationships between WBGT and labour productivity observed at the local scale, for distinct locations, types of labour and specific individuals (e.g. 16 rebar workers in China (Li et al., 2016)), can be scaled-up for all types of labour, the general population, and across Europe. Thus it is assumed that the estimated impacts for outdoor and indoor labour productivity are applicable to all economic sectors that involve moderate to intense indoor or outdoor working, including agriculture, construction, and factory working.

2.5 Population data

Present-day population, for the year 2006, is available at 100 m resolution across Europe from Batista e Silva et al. (2013). The projection system is ETRS89 / ETRS-LAEA (EPSG:3035). This was re-gridded to the climate model grid that was on a rotated pole with 0.11° resolution by converting the climate model grid to a point shapefile using WGS84 longitude and WGS84 latitude. This was then projected from WGS84 (EPSG: 4326) to ETRS89 / ETRS-LAEA (EPSG:3035). From the projected shapefile was created a gridded map at 100 m resolution snapped to the population map where each cell takes the ID of the nearest point (Euclidean Allocation). The values of the population map within each ID zone were then summed to yield population at 0.11° resolution. In line with some past climate change impact assessments for labour productivity (e.g. Dunne et al., 2013), population remained stationary at present-day levels under the climate change scenarios.

2.6 Modelling adaptation

Changes in labour productivity due to climate change were first calculated from WBGTid and WBGTod using daily Tmax and RHmax (see Section 2.3). This means that the WBGT estimates are representative of working conditions during the hottest part of the day, i.e. during day-time hours. This represents the no adaptation case.

Adaptation was modelled by assuming an adjustment in work shifts from the day-time to night-time. Such an adjustment in work activities follows recommendations by the US

Occupational Safety & Health Administration (OSHA, 2016) to consider during hot periods the adjustment of work shifts to allow for earlier start times, or evening and night shifts. Currently, around 20% of workers in Europe are employed on shift work involving night work (Harrington, 2001), so such a change in working practices is not implausible.

Tmax was replaced with Tmin (the daily minimum temperature) in the calculation of WBGTid and WBGTod. RHmax was also replaced with mean daily relative humidity. This yielded estimates of WBGT for night-time, since minimum temperatures usually occur during the night. Night-time WBGT was calculated for present-day and future time periods.

It is often assumed in climate change impact assessments that the adaptation mechanism is implemented instantaneously at some point in the future, often at the same time during which future impacts are calculated (Gosling et al., 2017). However, such an instantaneous deployment of adaptation is unrealistic and unlikely to occur. Instead, therefore, when estimating the impact of climate change on labour productivity for cases where there is adaptation in the future, the impacts are calculated relative to labour productivity as if all labour is conducted at night-time in the present-day. This is equivalent to assuming that a shift to night-time working occurs now, as opposed to instantaneously at an arbitrary point in the future. This avoids inflating the potential benefits of adaptation in the calculation, which would occur if instantaneous future adaptation is assumed and impacts estimated relative to present-day day-time labour productivity. The estimates of the impacts of climate change with adaptation assumed, are, therefore, an upper estimate of the impacts under such a scenario. If the impacts with adaptation were estimated relative to present-day day-time working, the potential benefits of adaptation would likely appear larger and in some cases might result in a net increase in labour productivity relative to present-day. The approach employed means that for any given location, if night-time WBGT increases in the future relative to present-day, the most positive benefits of adaptation that can occur, is that future labour productivity remains at present-day levels – it cannot exceed present-day levels of labour productivity. Thus whilst the latter situation of an increase in labour productivity in the future is possible with a cooling climate in the future (and would be represented in the modelling approach employed in this assessment) *adaptation alone* cannot result in an increase in future labour productivity relative to present-day (which would be an over-optimistic assumption).

2.7 Impact model evaluation

The five impact models are based upon empirical evidence of associations between labour productivity and WBGT, and/or safety thresholds for conducting work in hot and humid environments. Thus they are conceptually different from physically based impact models such as hydrological models and crop yield models, which tend to be based upon model parameters that represent physical processes and therefore require calibration and evaluation for tuning model parameters. The labour productivity models are synonymous with other human health impact models that are not generally evaluated, such as temperature-mortality models, which are constructed from empirical data for specific locations, using established epidemiological statistical techniques (Baccini et al., 2008; Gasparrini et al., 2015). Moreover, the labour productivity models cannot be evaluated for the locations where they were derived because this would involve evaluating the models against their training data. Furthermore, the original datasets from which the models were derived are not readily available, which precludes an evaluation of the impact models with techniques such as split-sample evaluation.

3 Results

3.1 Outdoor labour productivity – without adaptation

Figure 2 shows, for the end of the century, the mean national differences (from present) in daily average outdoor labour productivity due to climate change, assuming no adaptation. Figure 3 and Figure 4 shows the results for near future and 2°C respectively.

The end of century projections are for RCP8.5 (high emissions), which means that without climate change mitigation, daily average outdoor labour productivity could decline by between 10-15% from present-day levels in several southern European countries by the end of the century (Bulgaria, Greece, Italy, Macedonia, Portugal, Spain and Turkey), as a result of increases in WBGT. These impacts are around 10% points greater than seen in the near-term under the same scenario for the same countries. The impacts under the 2°C scenario are comparable to the impacts in the near-term. Limiting global warming to below 2°C could avoid a substantial proportion of impacts in the European countries that see the largest impacts without mitigation (Bulgaria, Greece, Italy, Macedonia, Portugal, Spain and Turkey). With some climate-impact model combinations the declines in labour productivity can be up to 10 percentage points lower in these countries with mitigation when compared to without mitigation.

Countries in northern Europe also see declines in daily average outdoor labour productivity with climate change, but they are considerably smaller than for the southern European countries, at around 2-4% at the end of the century (Denmark, Estonia, Finland, Norway and Sweden).

Figures 2-4 highlight that there is uncertainty in the magnitude of projected climate change impacts on labour productivity, due to differences in the projections of climate between different climate models and the use of different impact models. The magnitude of both sources of uncertainty is largest at the end of the century. Both sources of uncertainty are significant. The range in projected impacts due to climate model uncertainty and impact model uncertainty is comparable for most countries. For example, for Croatia at the end of the century, for one impact model (Model 2) the decline in labour productivity ranges between 8-15% across climate models; whilst for one climate model (RCA4_ESM-LR), the range in impacts is 2-15% across different impact models.

Figure 2: End of century mean national differences (from present) in daily average outdoor labour productivity due to climate change (*no adaptation*)

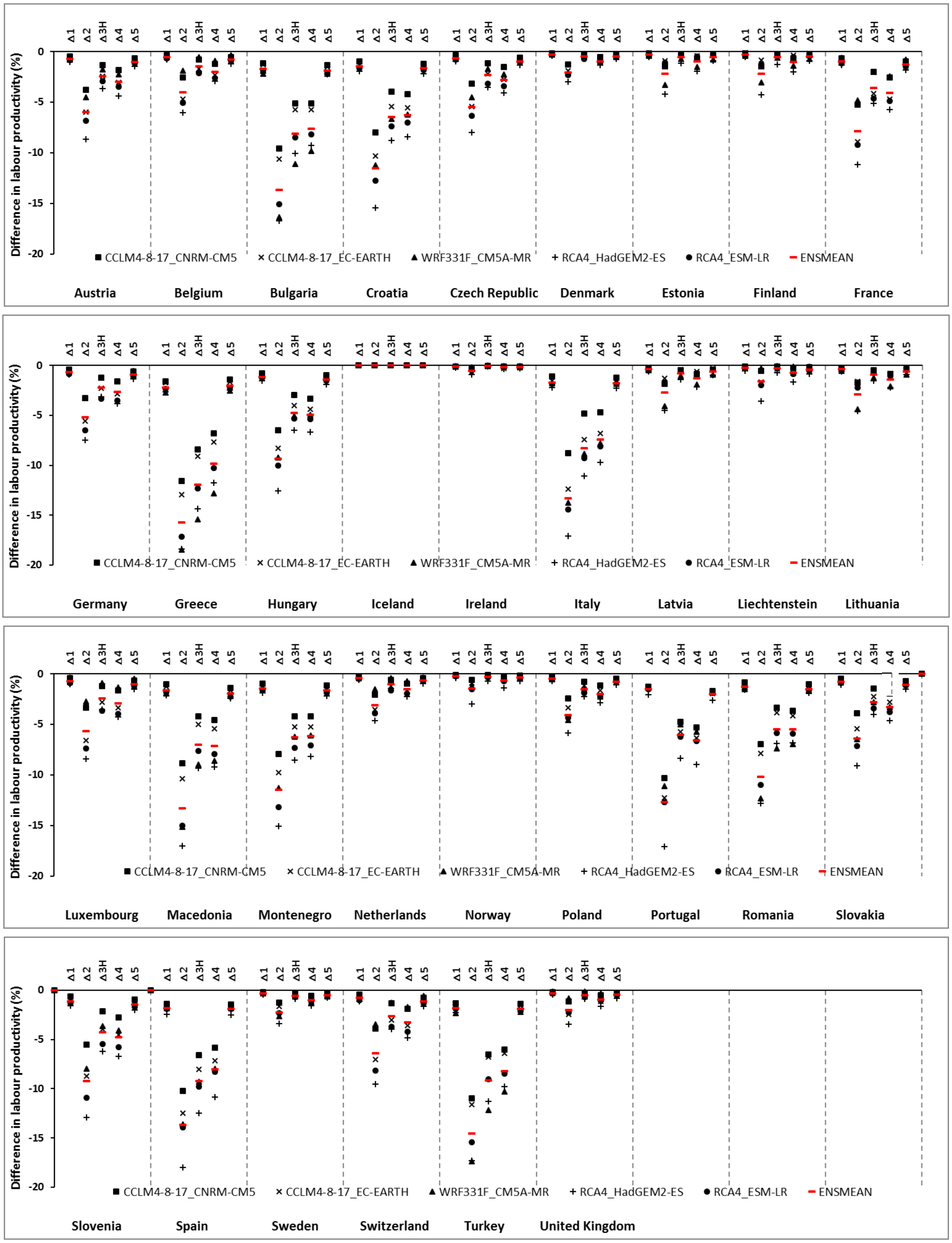


Figure 3: Near future mean national differences (from present) in daily average outdoor labour productivity due to climate change (*no adaptation*).

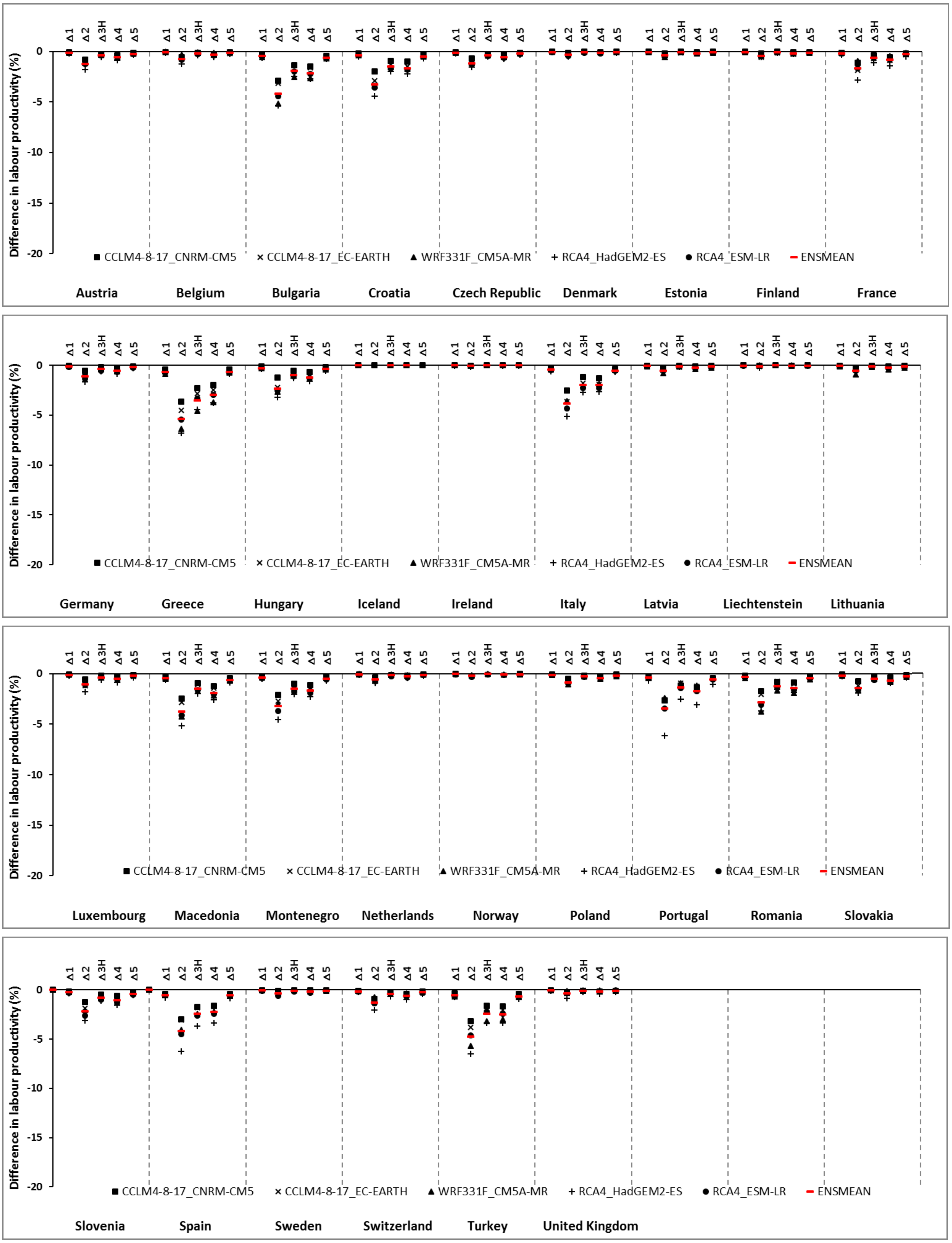
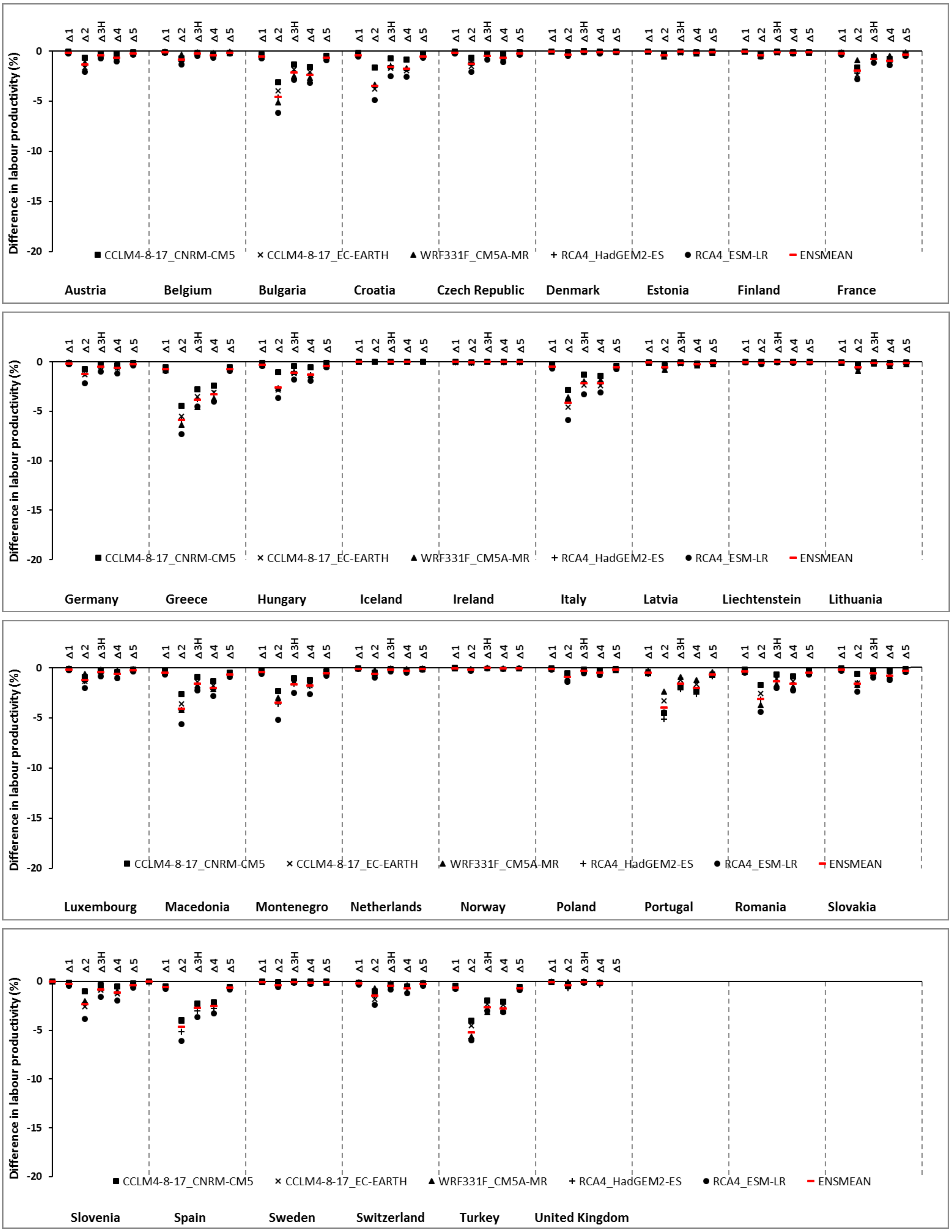


Figure 4: 2⁰C mean national differences (from present) in daily average outdoor labour productivity due to climate change (*no adaptation*).



3.2 Outdoor labour productivity – with adaptation

Figures 5-7 show the same as Figures 2-4, except: 1) it is assumed that all outdoor labour occurs at night, as a result of planned adaptation that imposes a European-wide adjustment of work shifts from day-time to night-time; and 2) the declines in labour productivity attributable to climate change are relative to as if all present-day labour is conducted during the night-time in present-day (i.e. assuming a shift to night-time working now, as opposed to an arbitrary time in the future).

If planned adaptation is implemented in the present-day, i.e. outdoor workers started working at night now, then adaptation could avoid significant declines in labour productivity that are attributable to climate change, which would otherwise occur in the absence of adaptation. For some countries, specifically those where impacts are largest across Europe without adaptation, the impacts can be up to around 10% points lower with adaptation than without (e.g. Bulgaria, Croatia, Greece, Italy, Spain and Turkey).

By the end of the century, night-time working could mean that daily average outdoor labour productivity remains at, or very close to, present-day levels in many European countries. However, for some southern European countries (Bulgaria, Croatia, Greece, Italy, Spain and Turkey), at the end of the century the declines in daily average outdoor labour productivity attributable to climate change could still be around 5% (and up to 10% for Greece, with one climate model), even when shifting to night-time working, due to night-time temperatures exceeding threshold temperatures.

Figure 5: End of century mean national differences (from present) in daily average outdoor labour productivity due to climate change (*with adaptation*).

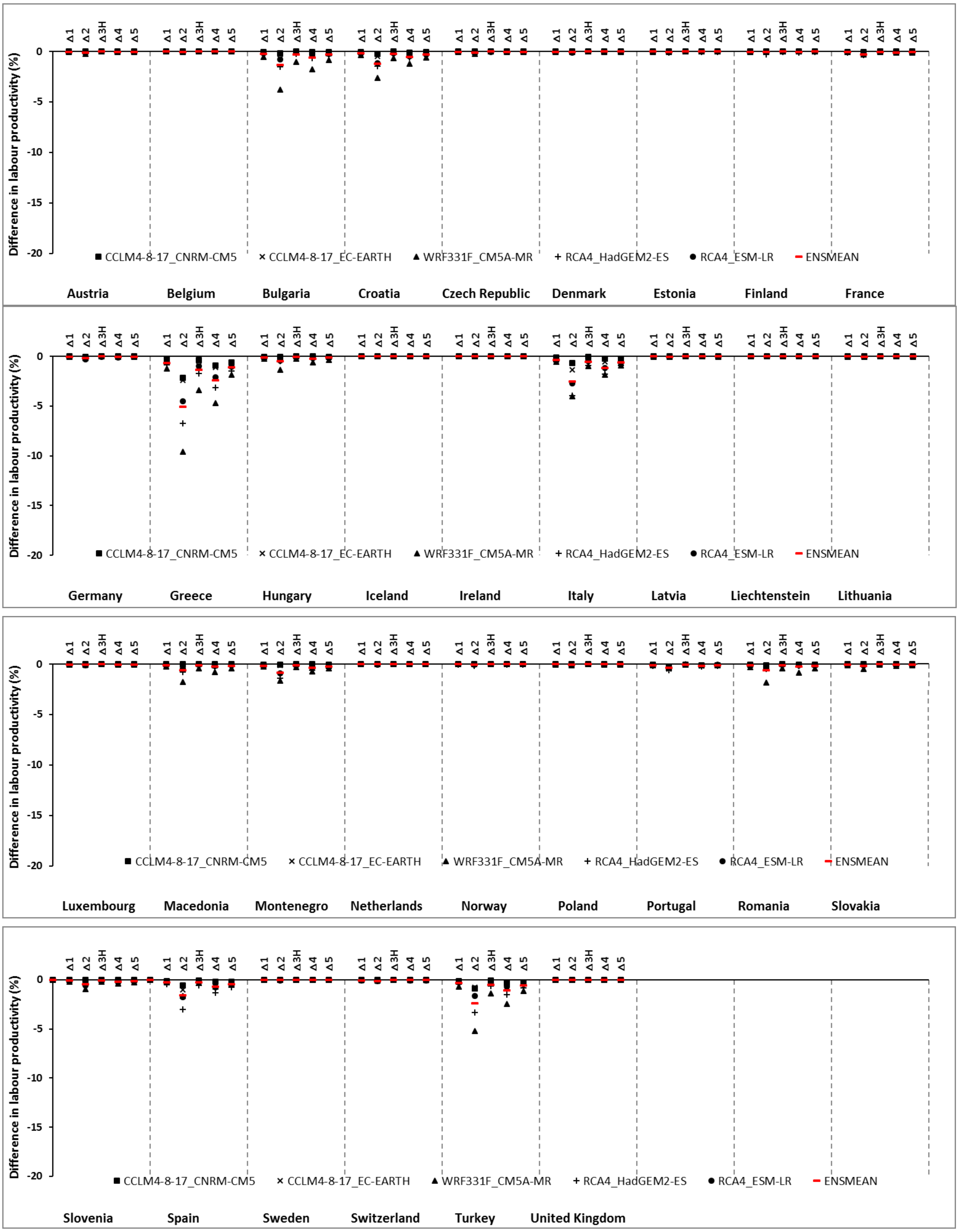


Figure 6: Near future mean national differences (from present) in daily average outdoor labour productivity due to climate change (*with adaptation*).

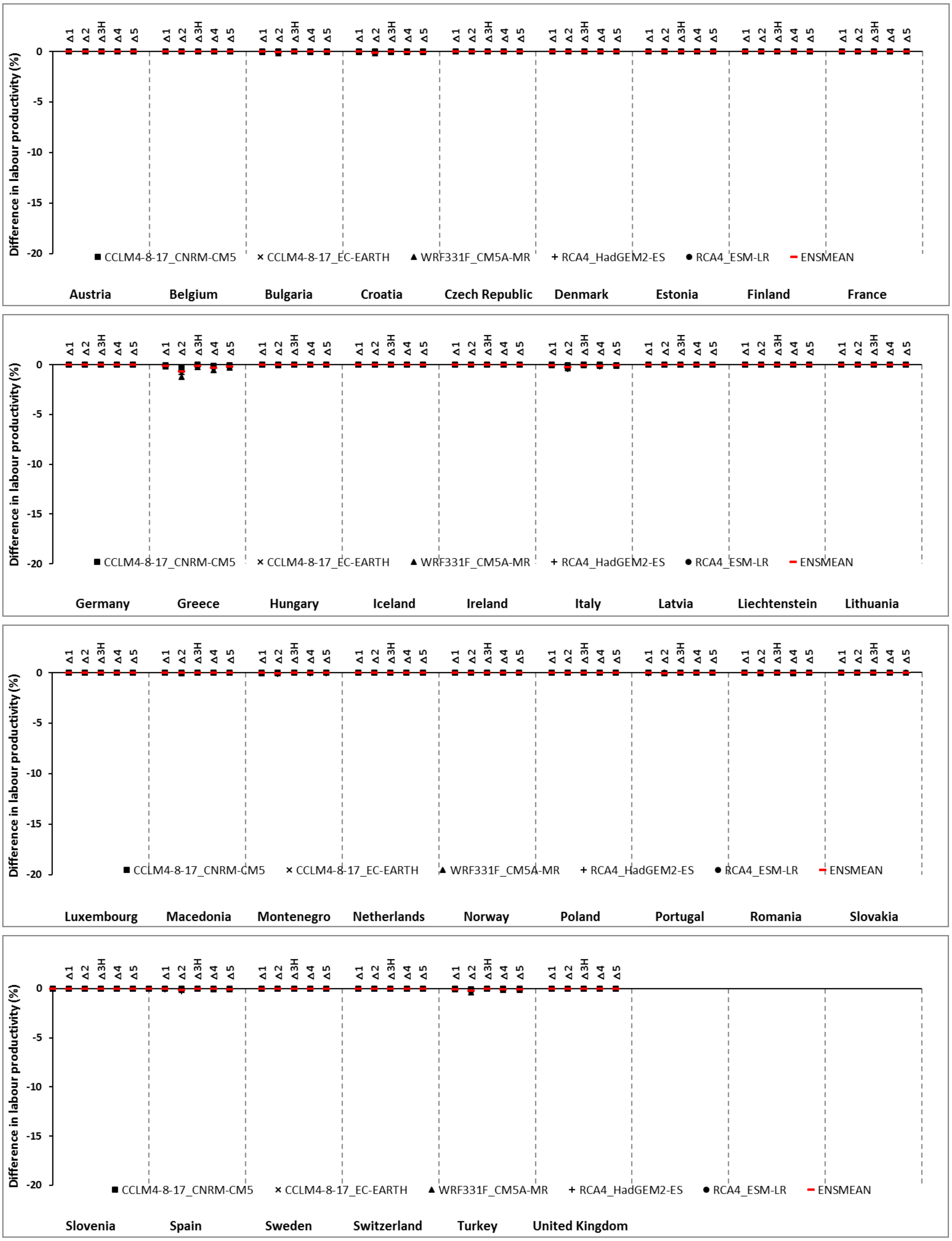
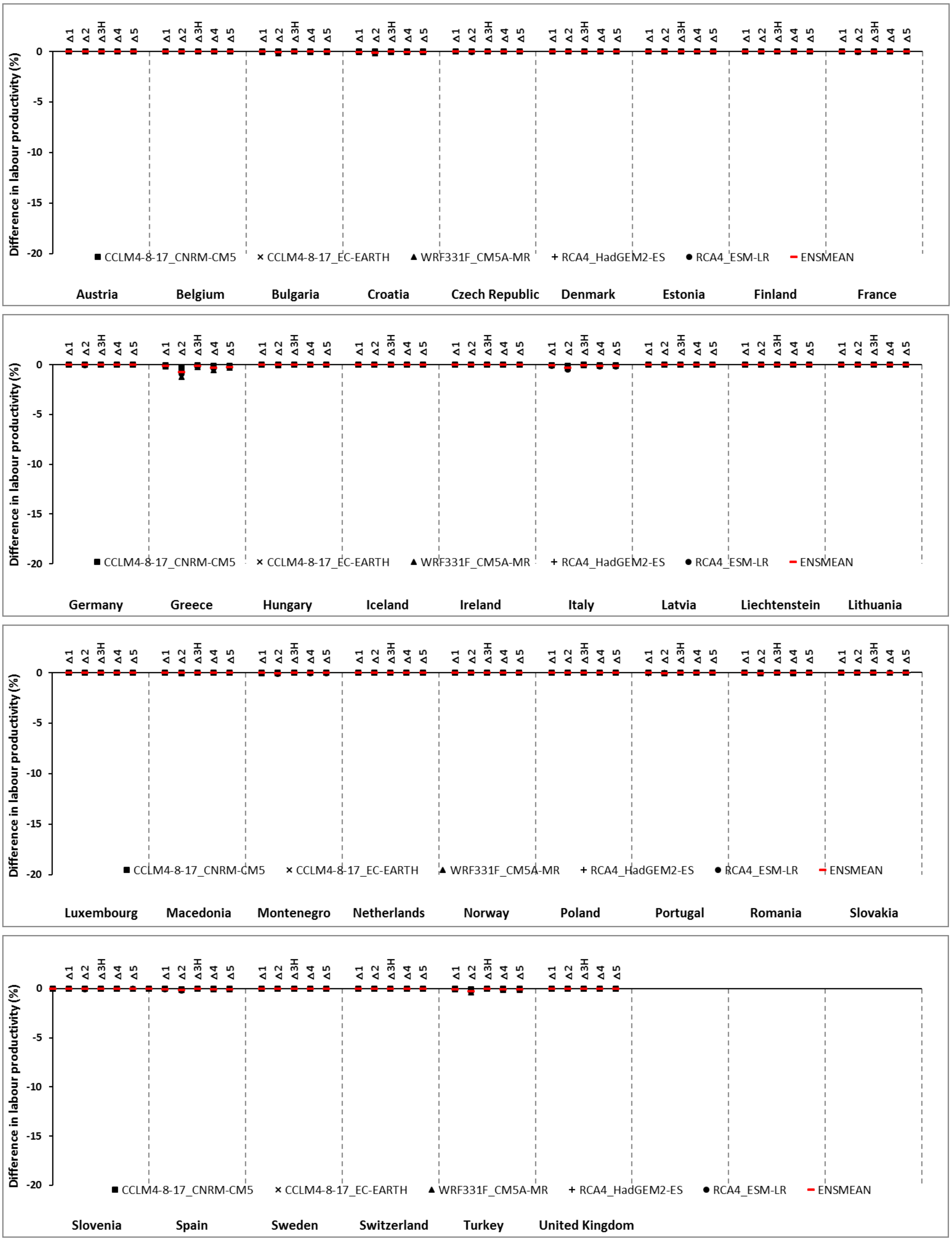


Figure 7: 2°Cmean national differences (from present) in daily average outdoor labour productivity due to climate change (*with adaptation*).



3.3 Indoor labour productivity – without adaptation

Figures 8-10 show the mean national differences (from present) in daily average indoor labour productivity due to climate change, assuming no adaptation, for end of the century, near term and 2°C respectively. The magnitude of impact is generally 2-4 percentage points lower than for impacts on outdoor labour productivity, for the more sensitive impact models (2, 3 and 4), while for the least sensitive impact models (1 and 5), the differences are smaller.

The largest impacts on indoor labour productivity are observed in the same countries where impacts are largest on outdoor labour productivity: Bulgaria, Greece, Italy, Macedonia, Portugal, Spain and Turkey. For these countries, climate change mitigation that limits global warming to below 2°C results in impacts that are between 3-6 percentage points lower than they would be at the end of the century under RCP8.5.

In common with the outdoor projections, the magnitudes of climate model and impact model uncertainty is largest at the end of the century, and both sources of uncertainty are significant in magnitude. The range in projected impacts due to climate model uncertainty and impact model uncertainty is comparable for most countries.

Figure 8: End of century mean national differences (from present) in daily average indoor labour productivity due to climate change (*no adaptation*).

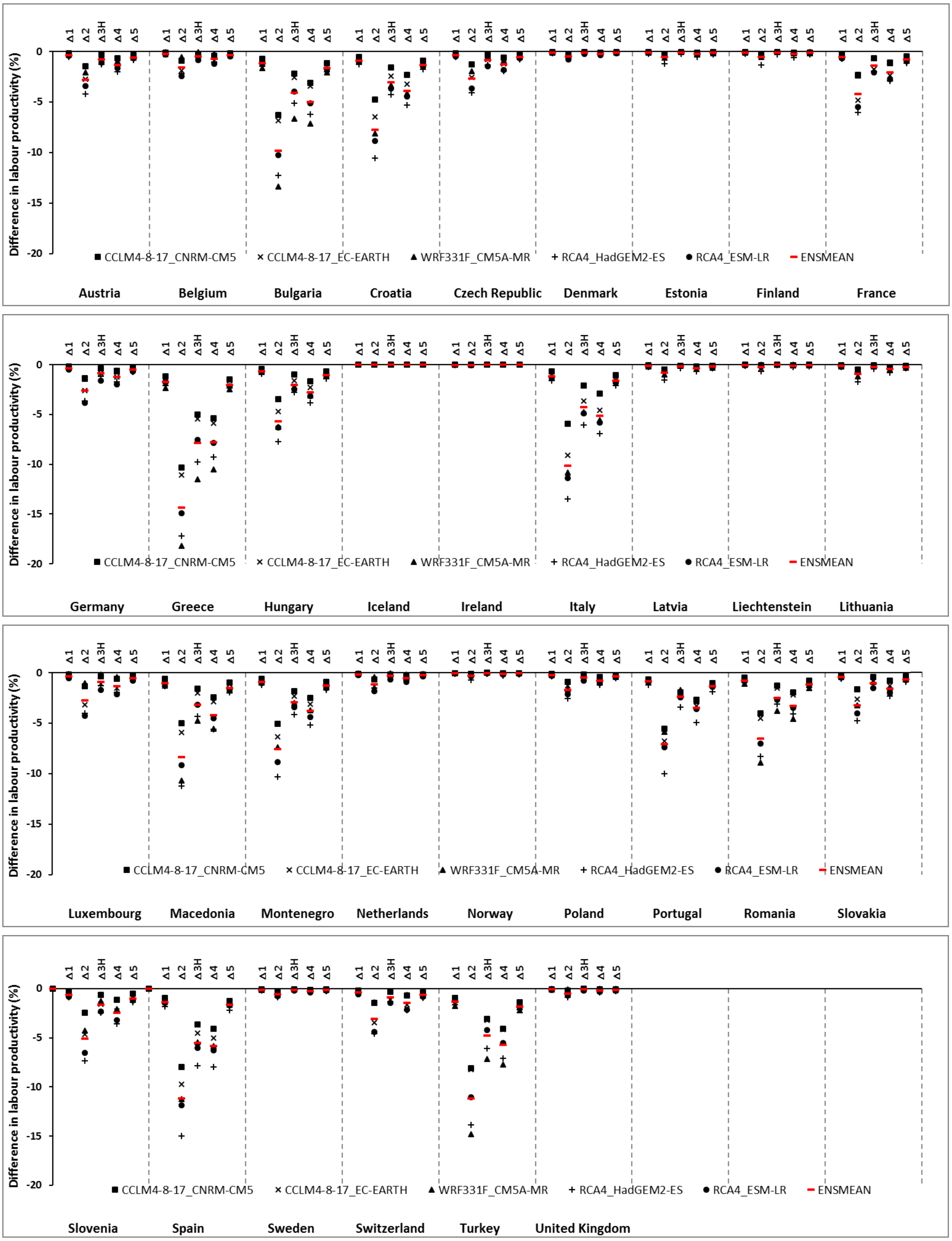


Figure 9: Near-term mean national differences (from present) in daily average indoor labour productivity due to climate change (*no adaptation*).

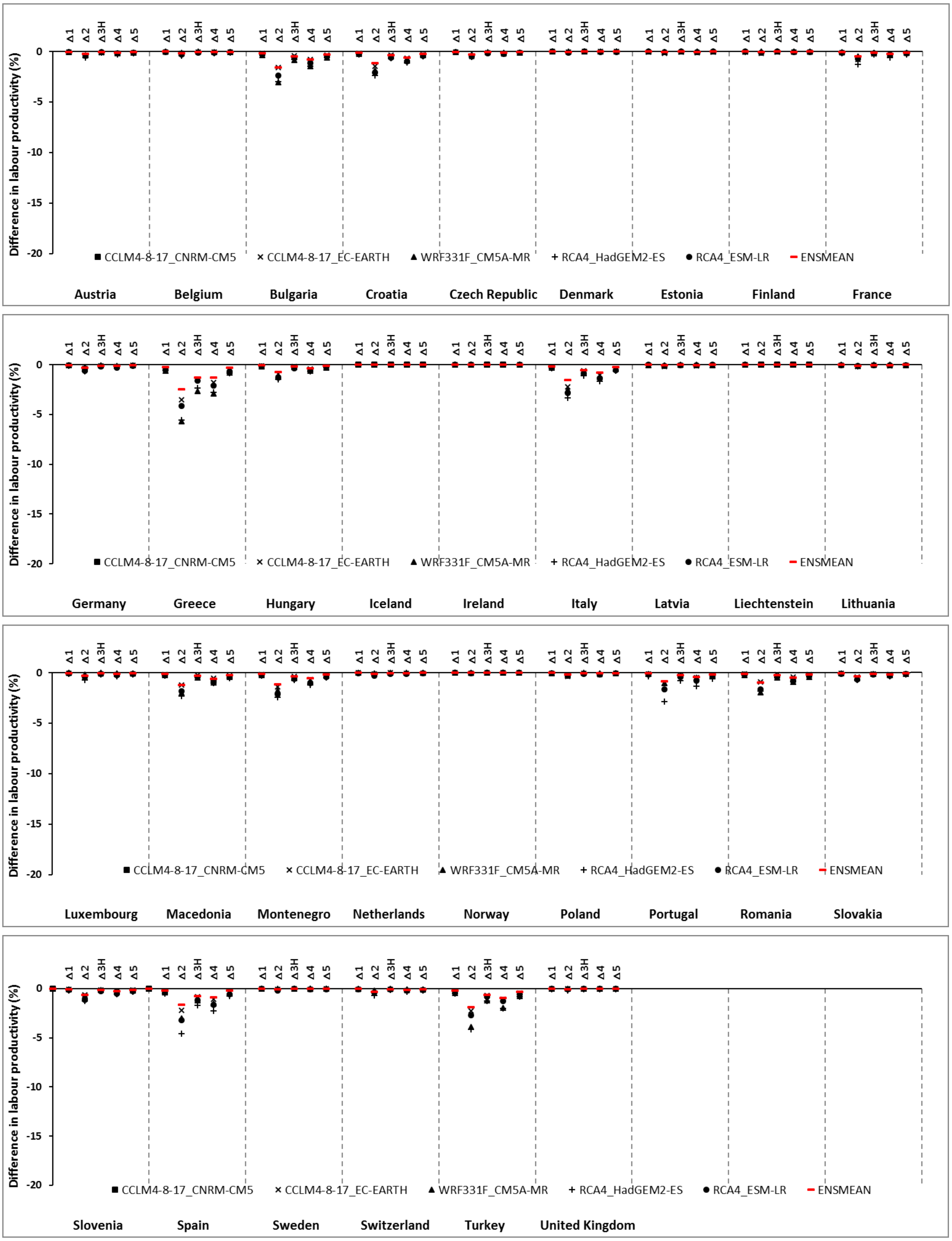
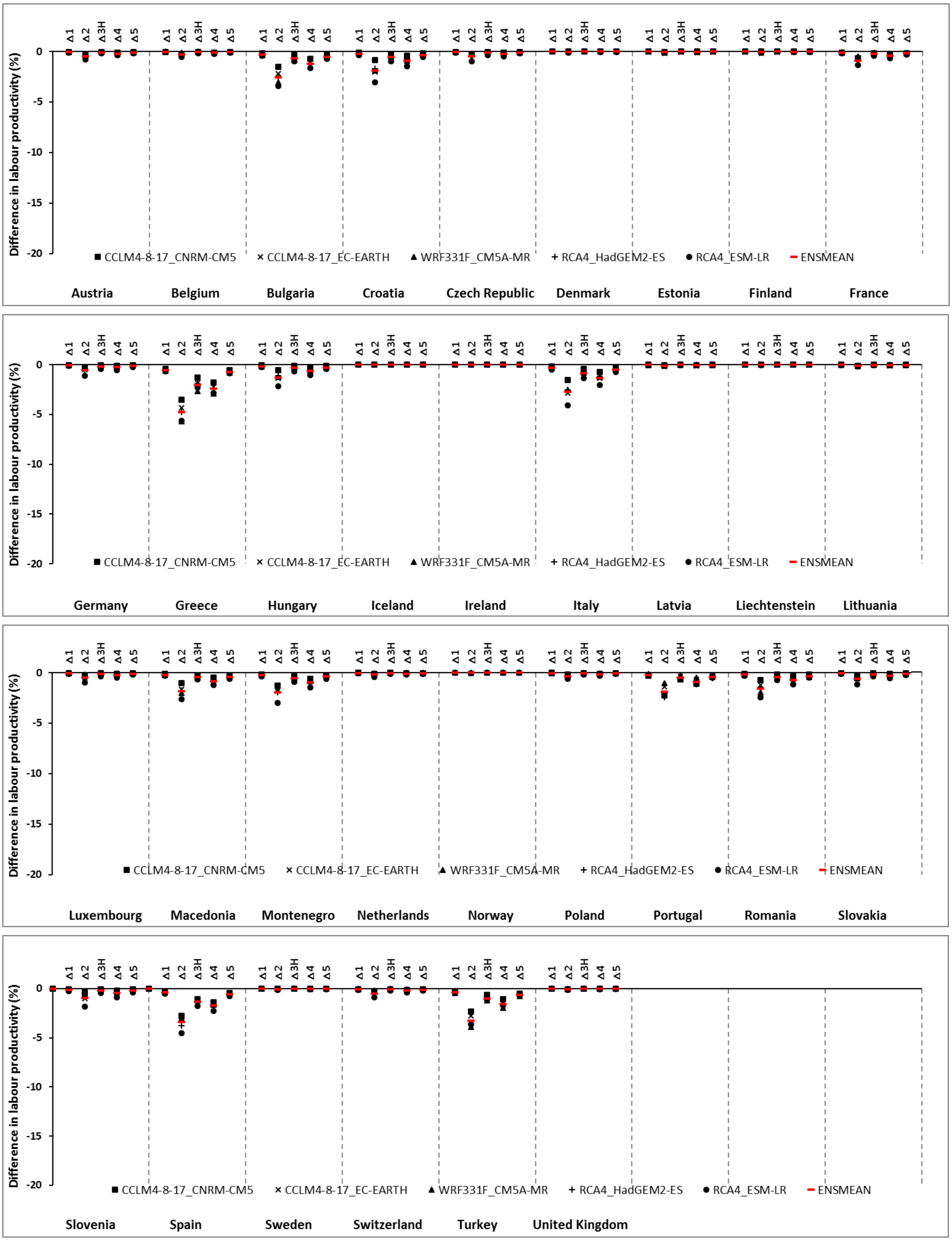


Figure 10: 2°C mean national differences (from present) in daily average indoor labour productivity due to climate change (*no adaptation*).



3.4 Indoor labour productivity – with adaptation

Figures 11-13 show the same as Figures 8-10, except it is assumed that all indoor labour occurs at night, as a result of planned adaptation that imposes a European-wide adjustment of work shifts from day-time to night-time. In the same way as planned adaptation could avoid impacts for outdoor labour productivity, relative to no adaptation, there could also be impacts avoided for indoor labour productivity. By the end of the century, night-time working could mean that daily average indoor labour productivity remains at, or very close to, present-day levels in almost all European countries except Greece. Thus the potential benefits for adaptation are greater for indoor labour productivity than for outdoor labour productivity. This is because indoor WBGT increases less with climate change than outdoor WBGT.

3.5 The role of extremes

The approach to estimating the impacts of climate change on labour productivity inherently accounts for the occurrence of extreme events. This is because daily climate data was used to estimate daily labour productivity. Therefore an extreme event, such as a heatwave, would be associated with large declines in projected labour productivity on the days of the heatwave. These in turn will be reflected in the national mean annual changes in labour productivity that are presented in this report.

Figure 11: End of century mean national differences (from present) in daily average indoor labour productivity due to climate change (*with adaptation*).

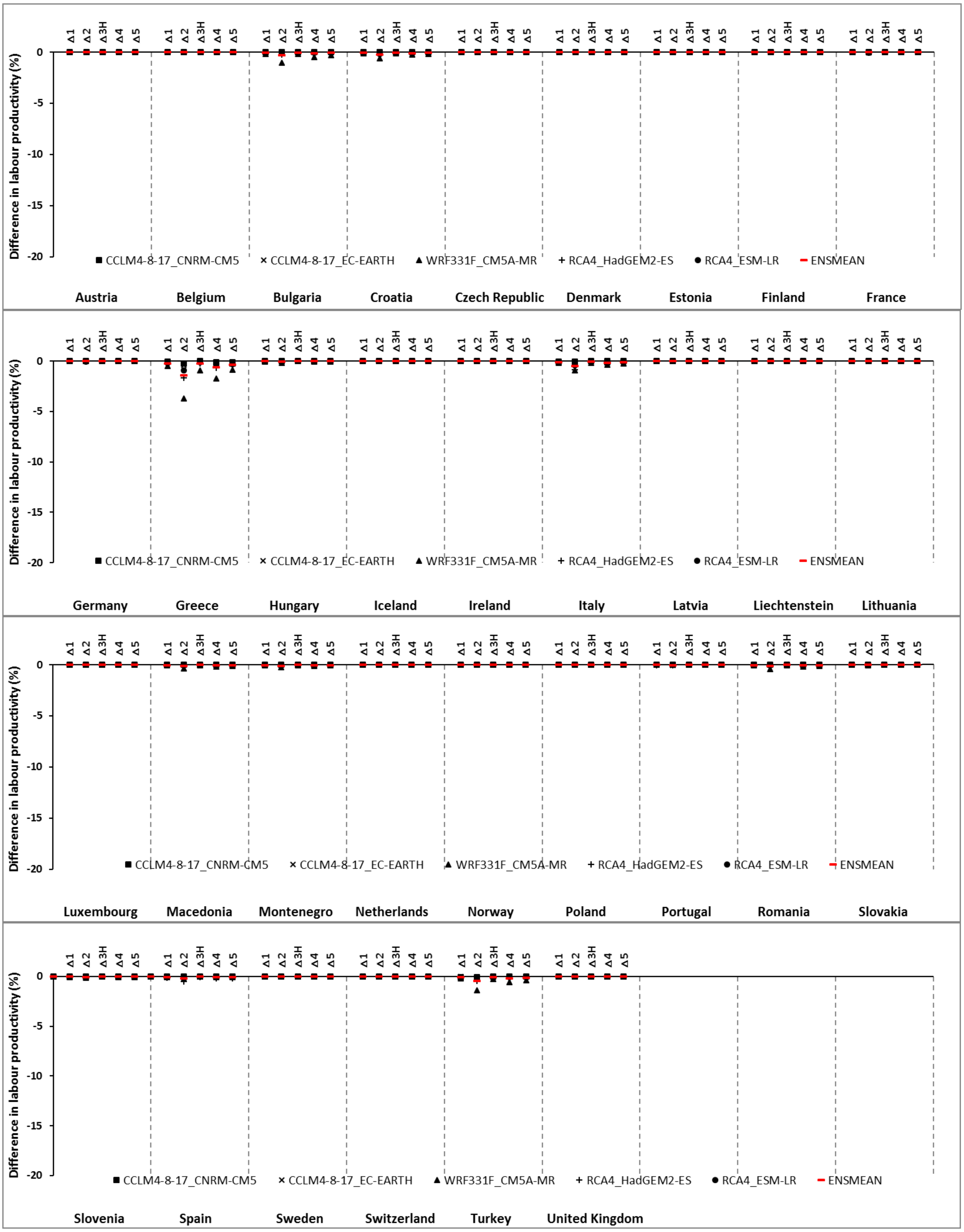


Figure 12: Near-term mean national differences (from present) in daily average indoor labour productivity due to climate change (*with adaptation*).

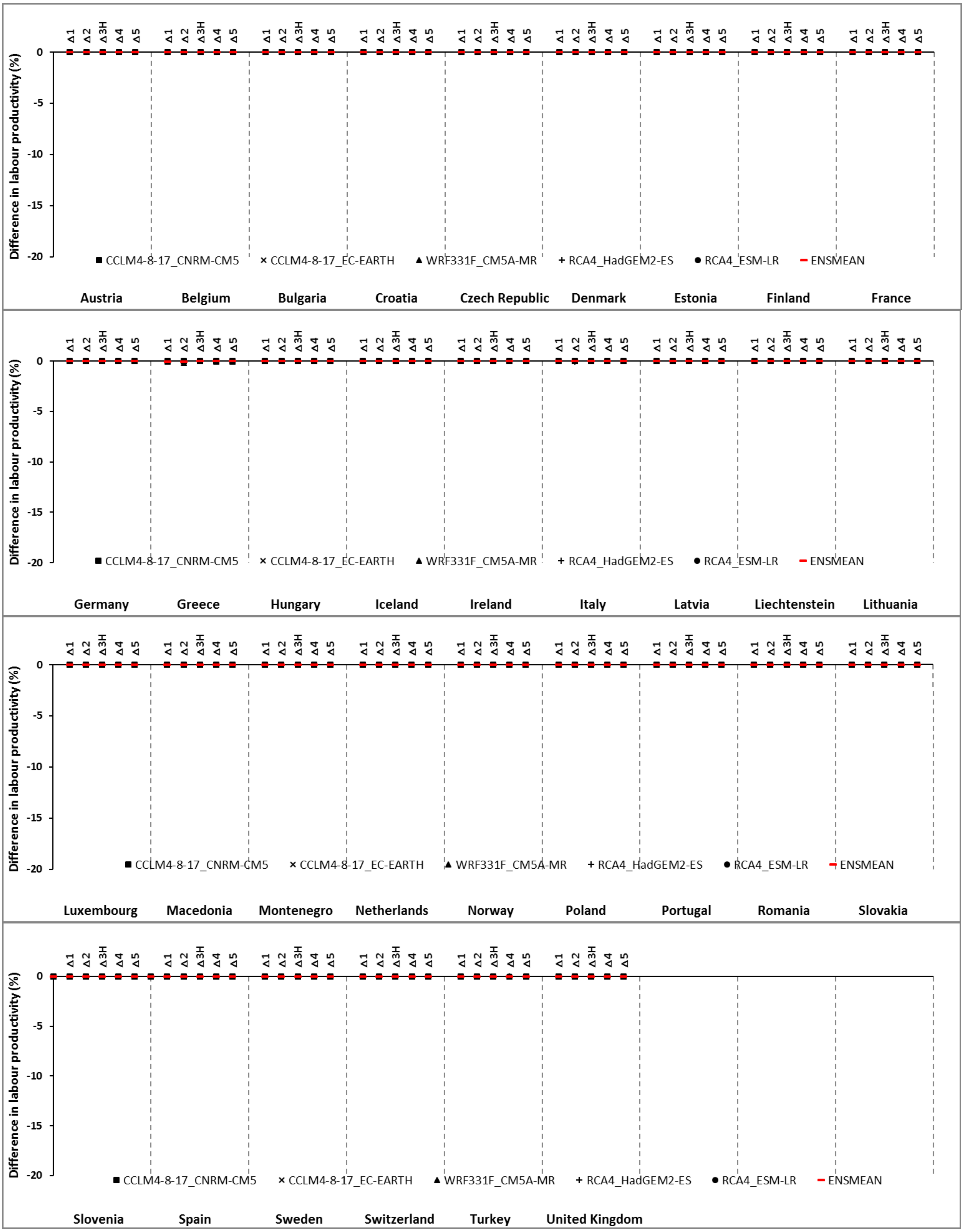
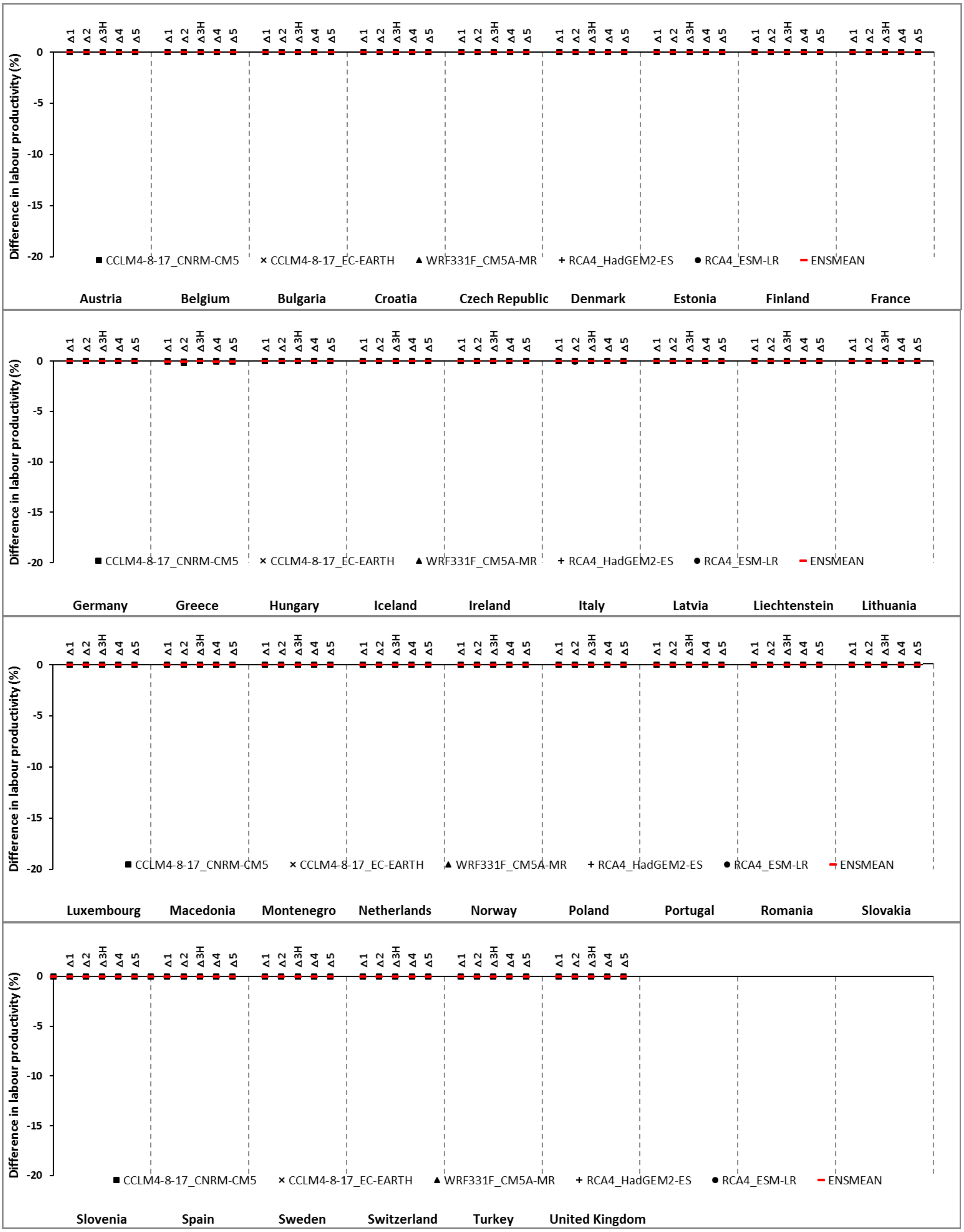


Figure 13: 2°C mean national differences (from present) in daily average indoor labour productivity due to climate change (*with adaptation*).



4 Cross-sectoral relation

The projected impacts on labour productivity have implications for other sectors assessed in PESETA III. Working at night would require additional energy for lighting of work environments, which would create an increase in energy demand in the energy sector. There are also potential implications for human health. Working at night could be associated with adverse health effects, which could offset the initial potential benefits of working at night. There is evidence that night work can cause disturbances of the normal circadian rhythms of psychophysiological functions; interference with work performance as well as efficiency that can result in accidents; difficulties in maintaining relationships; disturbances of sleeping and eating habits; chronic fatigue, anxiety and depression; and longer-term effects such as coronary heart disease (Åkerstedt, 1998; Costa, 1996; Stevens, 2016; Vetter et al., 2016).

5 Caveats

5.1 Selection of impact models

A large range in impacts is projected with the different impact models, for any given climate model. This highlights the likely underestimation of impacts in earlier studies that have used only one impact model (e.g. Burke et al., 2015; Hsiang, 2010). Whilst the approach used in this study is not exhaustive, because not every ERF ever developed was applied, the study does show for the first time, the choice of impact model can have a significant effect on the projected impacts of climate change on labour productivity. Other researchers are therefore encouraged to account for this significant source of uncertainty in future work. Nevertheless, it is acknowledged that more impact models could have been used, such as those reported by Graff Zivin and Neidell (2014) and used by Houser et al. (2015). However, a balance needs to be struck between several competing factors: the number of impact models included, computational resources, and the form of the impact models. This is why only five impact models were used here. More specifically, all the impact models applied here, describe the relationship between WBGT and percentage changes in labour productivity. The model described by Graff Zivin and Neidell (2014), for instance, differs from these five in two fundamental ways: 1) it is based upon identifying the incremental influence of daily maximum temperature, not WBGT; and 2) it estimates the effects of maximum temperature on the number of minutes individuals work, not specifically a change in productivity in percentage terms. This is no more an advantage or a disadvantage over the approach used in the present assessment; it is just a different methodology. However, to maintain a degree of consistency between the impact models used in the report, only models that report changes in labour productivity in percentage terms and with WBGT were included.

5.2 Calculation of WBGT

Daily maximum WBGT was calculated from daily maximum temperature and daily relative humidity. However, this inherently assumes that the daily peaks in temperature and humidity occur at the same time of the day. They could, however, occur several hours apart. The highest temporal-resolution data available from the GCM-RCM combinations employed in this study was daily. It was not possible, therefore, to estimate WBGT more precisely. An alternative approach to estimating WBGT more precisely could involve calculating it from daily mean vapour pressure, which could be calculated from dewpoint temperature and daily maximum temperature, following Buck (1981). There is very little diurnal cycle in vapour pressure and so it is suitable for calculating WBGT at maximum temperature (Eurocontrol, 2011). However, bias corrected daily dewpoint temperature was not available from the GCM-RCM combinations used.

Thus there is likely to be a small error in the magnitude of daily maximum WBGT estimated from the climate models relative to what would actually be observed. To understand the magnitude of this error requires an evaluation using higher temporal resolution empirical data, ideally at hourly or 15-minute resolution. The magnitude of error could vary spatially across Europe, so the errors would need to be evaluated across the European domain, for multiple locations, to facilitate a robust analysis. This would require significant resource, because weather observations from multiple meteorological stations across Europe would need to be downloaded, quality controlled, and analysed. The magnitude of error between bias corrected simulated WBGT and observed WBGT would also need to be compared. The variety of methods that can be used to estimate WBGT (Lemke and Kjellstrom, 2012) would compound the evaluation further. Such an evaluation is beyond the remit of this study. The author is not aware of a study that has conducted such an evaluation, so this is a worthwhile avenue for further research.

This limitation means that the declines in labour productivity estimated for each impact model should be interpreted as an upper estimate, since the daily WBGT could be lower than what was calculated for each day.

5.3 Representing adaptation

Daily minimum temperature was used with daily mean relative humidity, to estimate daily minimum WBGT, which was assumed to occur at night. Similar to the limitation of estimating maximum WBGT, it is possible that the minimum daily temperature and minimum daily relative humidity do not occur at the same time of day. It is plausible that on some days, relative humidity at night could be higher than mean daily humidity, or it could be lower. To account for this, in the absence of climate model data at a resolution finer than daily, mean relative humidity was used, since it is between minimum and maximum relative humidity. Night WBGT would, ideally, be estimated from a timeseries of WBGT calculated at 15-minute or 1-hourly timesteps but finer resolution data was not available from the GCM-RCM combinations. This means that the projections of labour productivity under adaptation are somewhat optimistic. They are not as optimistic as if night WBGT had been calculated with daily minimum relative humidity, but they are less optimistic than if daily maximum humidity had been used. Nevertheless, the projections are indicative of the potential benefits of adaptation through working at night, although they could be more precise if higher temporal resolution data was available.

There are a number of other reasons why the projections under adaptation could be considered optimistic. It is assumed that the entire work force shifts to working at night. In practical terms, if such a planned adaptation mechanism were to be implemented, it is more likely that certain types of jobs, or a certain proportion of the workforce would shift to working at night. In addition, it might be more practical to move to earlier start times for work, than to shift to night working. Whilst the adaptation assumption is in line with recommendations by OSHA (2016), the temporal resolution of the climate data (daily) meant that it was not possible to investigate changes in working hours that might be more straightforward to implement (e.g. earlier starts).

It is possible that working at night could be more expensive than working during the day because of the energy costs required to provide lighting and higher wages for working unsocial hours – this would need to be assessed in an economic cost-benefit analysis. Moreover, a population-size shift to working at night would require a significant change in culture and attitude. This does not mean that the adaptation assumption employed in this study is implausible though. The adjustment considered is in line with recommendations by OSHA (2016) to consider during hot periods the adjustment of work shifts to allow for earlier start times, or evening and night shifts. In addition, around 20% of workers in Europe are already employed on shift work involving night work (Harrington, 2001). Thus the estimates under adaptation are generally optimistic, but not implausible.

The only aspect of the modelling approach that lowers the overall optimism of the effects of adaptation, is an imposed limit where adaptation alone cannot result in labour productivity in the future that is higher than present-day labour productivity (although this is possible due to climate change alone, if WBGT decreases in the future). This limit is the result of calculating impacts with adaptation, relative to labour productivity as if all labour is conducted at night-time in the present-day. This was done to avoid inflating the potential benefits of adaptation, which would have occurred if instantaneous future adaptation had been assumed and impacts estimated relative to present-day day-time labour productivity. The estimates of the impacts of climate change with adaptation assumed, are, therefore, an upper estimate of the impacts under such a scenario. If the impacts with adaptation were estimated relative to present-day day-time working, the potential benefits of adaptation would likely be larger and in some cases might result in a net increase in labour productivity relative to present-day. Whilst the approach used in this study avoids an unrealistic assumption of instantaneous future adaptation, which is made in many climate change impact assessments, it is acknowledged that a more advanced approach to modelling adaptation could include a phasing-in of night-time working over several decades.

Moreover, a follow-on study, that explores the sensitivity of impacts to adaptation modelling assumptions, such as that presented by Gosling et al. (2017) for heat-related mortality, would be beneficial to academics working in the field of labour productivity and climate change. Such a study would explicitly explore the sensitivity of impacts to 1) changing the proportion of the total workforce that works at night-time; and 2) changing the time when the adaptation mechanism is deployed.

6 Conclusions

Without climate change mitigation, daily average outdoor labour productivity could decline by around 10-15% from present-day levels in several southern European countries by the end of the century (Bulgaria, Greece, Italy, Macedonia, Portugal, Spain and Turkey). Countries in northern Europe could also see declines in daily average outdoor labour productivity with climate change, but they are considerably smaller than for the southern countries, at around 2-4% (Denmark, Estonia, Finland, Norway and Sweden).

However, with European-wide planned adaptation that shifts the hours of working for people engaged in moderate to intense working activity, from day-time to night-time, daily average outdoor labour productivity could remain at, or very close to, present-day levels in many European countries at the end of the century. For some countries, specifically those where impacts are largest across Europe without adaptation, the impacts can be up to around 10 percentage points lower with adaptation than without (e.g. Bulgaria, Croatia, Greece, Italy, Spain and Turkey) - nevertheless, even in these cases, labour productivity still declines by around 5% relative to present (and up to 10% for Greece, with one climate model) due to significant increases in night-time WBGT.

References

Åkerstedt T (1998) Shift work and disturbed sleep/wakefulness. Sleep Medicine Reviews 2:117-128.

Baccini M, Biggeri A, Accetta G, Kosatsky T, Katsouyanni K, Analitis A, Anderson HR, Bisanti L, D'Ippoliti D, Danova J, Forsberg B, Medina S, Paldy A, Rabczenko D, Schindler C, Michelozzi P (2008) Heat Effects on Mortality in 15 European Cities. Epidemiology 19:711-719.

Batista e Silva F, Gallego J, Lavalle C (2013) A high-resolution population grid map for Europe. Journal of Maps 9:16-28.

Buck AL (1981) New Equations for Computing Vapor Pressure and Enhancement Factor. Journal of Applied Meteorology 20:1527-1532.

Budd GM (2008) Wet-bulb globe temperature (WBGT)—its history and its limitations. Journal of Science and Medicine in Sport 11:20-32.

Burke M, Hsiang SM, Miguel E (2015) Global non-linear effect of temperature on economic production. Nature 527:235–239.

Costa G (1996) The impact of shift and night work on health. Applied Ergonomics 27:9-16.

Dunne JP, Stouffer RJ, John JG (2013) Reductions in labour capacity from heat stress under climate warming. Nature Clim. Change 3:563-566.

Eurocontrol (2011) "Challenges of growth" environmental update study.

Federspiel CC, Liu G, Lahiff M, Faulkner D, DiBartolomeo DL, Fisk WJ, Price PN, Sullivan DP (2002) Worker performance and ventilation: Analyses of individual data for call-center workers. Proceedings of the Indoor Air 2002 Conference, Monterey, CA. Indoor Air 2002, Santa Cruz, CA.

Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, Tobias A, Tong S, Rocklöv J, Forsberg B, Leone M, De Sario M, Bell ML, Guo Y-LL, Wu C-f, Kan H, Yi S-M, de Sousa Zanotti Stagliorio Coelho M, Saldiva PHN, Honda Y, Kim H, Armstrong B (2015) Mortality risk attributable to high and low ambient temperature: a multicountry observational study. The Lancet 386:369-375.

Gosling SN, Hondula DM, Bunker A, Ibarreta D, Liu J, Zhang X, Sauerborn R (2017) Adaptation to climate change: a comparative analysis of modelling methods for heat-related mortality. Environmental Health Perspectives.

Graff Zivin J, Neidell M (2014) Temperature and the Allocation of Time: Implications for Climate Change. Journal of Labor Economics 32:1-26.

Hancock PA, Ross JM, Szalma JL (2007) A Meta-Analysis of Performance Response Under Thermal Stressors. Human Factors: The Journal of the Human Factors and Ergonomics Society 49:851-877.

Hancock PA, Vasmatzidis I (2003) Effects of heat stress on cognitive performance: the current state of knowledge. International Journal of Hyperthermia 19:355-372.

Harrington JM (2001) Health effects of shift work and extended hours of work. Occupational and Environmental Medicine 58:68-72.

Houser T, Hsiang S, Kopp R, Larsen K (2015) Economic risks of climate change: an American prospectus. Columbia University Press.

Hsiang SM (2010) Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. Proceedings of the National Academy of Sciences 107:15367-15372.

Jeremiah C, Vidhya V, Kumaravel P, Paramesh R (2016) Influence of occupational heat stress on labour productivity – a case study from Chennai, India. International Journal of Productivity and Performance Management 65:245-255.

Kjellstrom T, Briggs D, Freyberg C, Lemke B, Otto M, Hyatt O (2016) Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. Annual Review of Public Health 37:97-112.

Kjellstrom T, Kovats RS, Lloyd SJ, Holt T, Tol RSJ (2009) The Direct Impact of Climate Change on Regional Labor Productivity. Archives of Environmental & Occupational Health 64:217-227.

Kjellstrom T, Lemke B, Otto M (2013) Mapping Occupational Heat Exposure and Effects in South-East Asia: Ongoing Time Trends 1980-2011 and Future Estimates to 2050. Industrial Health 51:56-67.

Kjellstrom T, Lemke B, Otto M, Hyatt O, Dear K (2014) Occupational Heat Stress Contribution to WHO project on "Global assessment of the health impacts of climate change", which started in 2009. Technical Report 2014: 4. Available from: http://climatechip.org/sites/default/files/publications/TP2014_4_Occupational_Heat_Stress_WHO.pdf, ClimateCHIP = Climate Change Health Impact & Prevention.

Lemke B, Kjellstrom T (2012) Calculating Workplace WBGT from Meteorological Data: A Tool for Climate Change Assessment. Industrial Health 50:267-278.

Li X, Chow KH, Zhu Y, Lin Y (2016) Evaluating the impacts of high-temperature outdoor working environments on construction labor productivity in China: A case study of rebar workers. Building and Environment 95:42-52.

Lin R-T, Chan C-C (2009) Effects of heat on workers' health and productivity in Taiwan. Global Health Action 2:10.3402/gha.v3402i3400.2024.

Link J, Pepler R (1970) Associated fluctuations in daily temperature, productivity and absenteeism. ASHRAE Transactions 76:Part II: 326-337.

Nag A, Nag PK (1992) Heat stress of women doing manipulative work. American Industrial Hygiene Association Journal 53:751-756.

Nag PK, Nag A (2009) Vulnerability to heat stress: Scenario in Eestern India. National Institute of Ocuppational Health, Ahmedabad, India, 380016.

Niemelä R, Hannula M, Rautio S, Reijula K, Railio J (2002) The effect of air temperature on labour productivity in call centres—a case study. Energy and Buildings 34:759-764.

Niemelä R, Railio J, Hannula M, Rautio S, Reijula K (2001) Assessing the effects of indoor environment on productivity. Proceedings of the Seventh World Congress, CLIMA 2000, Naples, Itraly.

NIOSH (1986) Criteria for a Recommended Standard: Occupational Exposure to Hot Environments (Revised Criteria 1986). Washington DC.

OSHA (2016) Occupational Safety & Health Administration - Protective Measures to Take at Each Risk Level. https://www.osha.gov/SLTC/heatillness/heat_index/protective_high.html.

Parsons K (2006) Heat Stress Standard ISO 7243 and its Global Application. Industrial Health 44:368-379.

Pilcher JJ, Nadler E, Busch C (2002) Effects of hot and cold temperature exposure on performance: a meta-analytic review. Ergonomics 45:682-698.

Ramsey JD, Morrissey SJ (1978) Isodecrement curves for task performance in hot environments. Applied Ergonomics 9:66-72.

Sahu S, Sett M, Kjellstrom T (2013) Heat Exposure, Cardiovascular Stress and Work Productivity in Rice Harvesters in India: Implications for a Climate Change Future. Industrial Health 51:424-431.

Stevens RG (2016) Circadian disruption and health: Shift work as a harbinger of the toll taken by electric lighting. Chronobiology International 33:589-594.

Stull R (2011) Wet-Bulb Temperature from Relative Humidity and Air Temperature. Journal of Applied Meteorology and Climatology 50:2267-2269.

Vetter C, Devore EE, Wegrzyn LR, et al. (2016) Association between rotating night shift work and risk of coronary heart disease among women. JAMA 315:1726-1734.

Witterseh T, Wyon DP, Clausen G (2004) The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work. Indoor Air 14:30-40.

Wyndham CH (1969) Adaptation to heat and cold. Environmental Research:442-469.

List of abbreviations and definitions

GCM	Global Climate Model
NIOSH	National Institute for Occupational Safety and Health
OSHA	US Occupational Safety & Health Administration
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RHmax	Maximum relative humidity
Tmax	Maximum temperature
Tmin	Minimum temperature
Tw	Psychrometric wet bulb temperature
WBGT	Wet Bulb Globe Temperature
WBGTid	Indoor Wet Bulb Globe Temperature
WBGTod	Outdoor Wet Bulb Globe Temperature

List of figures

KJ-NA-29423-EN-N

The European Commission's science and knowledge service
Joint Research Centre

JRC Mission
As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2760/07911
ISBN 978-92-79-96912-6