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Supplementary material for this article is available [online](#)

Abstract

An increase of the 2 m temperature over Europe is expected within the current century. In order to consider health impacts, it is important to evaluate the combined effect of temperature and humidity on the human body. To achieve this, projections of a basic index—the humidex—representative of the perceived temperature, under different scenarios and periods, have been investigated. The simultaneous occurrence of observed extreme temperature events and perceived extreme temperature events is seldom found within the present climate, reinforcing the importance of investigating the combination of the two fields. A set of 10 km resolution regional climate simulations, provided within the EURO-CORDEX multi-model effort, demonstrates an ability in representing moderate to extreme events of perceived temperature over the present climate, and to be useful as a tool for quantifying future changes in geographical patterns of exposed areas over Europe. Following the RCP8.5 emission scenario, an expansion of the area subject to dangerous conditions is suggested from the middle of the current century, reaching 60°N. The most significant increase of perceived extreme temperature conditions is found comparing the 2066–2095 projections to the 1976–2005 period; bearing in mind that changes in relative humidity may either amplify or offset the health effects of temperature, a less pronounced projected reduction of relative humidity in the north-eastern part of Europe, associated with extreme humidex events, makes northern Europe the most prone region to an increase of moderate to extreme values of perceived temperature. This is in agreement with a pronounced projected specific humidity increase.

1. Introduction

Once the human body temperature reaches higher than 37 °C, internal heat needs to be released from the body into the environment, via the evaporation of sweat. In high humidity conditions, however, sweat evaporation is much less efficient than under dry conditions, and other physiological changes cannot prevent the core body temperature from reaching a dangerous level (Kjellstrom *et al* 2016).

It is well known that heat stress increases mortality (Basu and Samet 2002), but also a clear effect of a high perceived temperature on working/exercise capacity (Galloway and Maughan 1997, Kjellstrom *et al* 2016) and cognitive performance has been

demonstrated (Hocking *et al* 2001, Hancock and Vasmatzidis 2003). In addition, excessive heat exposure affects not only individuals but also the local economy through impacts on worker productivity (Levy and Patz 2015).

Previous studies suggest a future increase of high-impact heatwaves in the current century especially over the southern part of the European continent (Sterl *et al* 2008, Jacob *et al* 2014), a region already prone to increasing heat stress within the present climate (Zampieri *et al* 2016). A less pronounced increase of heatwaves and related negative physiological effects is projected for northern Europe (Fischer and Schär 2010). Furthermore the rise in heat-related mortality is projected to completely compensate the concomitant

Table 1. Regional climate models involved in this study.

Model name	Driving GCM	Institute
SMHI-RCA4	CNRM-CM5	Swedish Meteorological and Hydrological Institute, Rossby Centre
KNMI-RACMO22E	ICHEC-EC-EARTH	Royal Netherlands Meteorological Institute
INERIS-WRF331F	IPSL-CM5A-MR	IPSL (Institut Pierre Simon Laplace) and INERIS (Institut national de l'environnement industriel et des risques)
CNRM-ALADIN53	CNRM-CM5	Centre National de Recherches Meteorologiques

reduction of cold-related deaths within the last third of the current century (Ballester *et al* 2011).

Despite previous works suggesting an important role of humidity, which is particularly pronounced in the southern and eastern Mediterranean regions (Dif-fenbaugh *et al* 2007), until now not much attention has been devoted to the contribution that air humidity has in the modulation of perceived temperature under extremely warm conditions over Europe. Leveraging the on very high resolution (about 10 km) of the regional climate simulations (see section 2.1) and investigating future projections of air temperature and relative humidity, we aim to:

- Identify potential European sub-regions that might become prone to different degrees of heat stress, inducing not only potential health conditions for vulnerable groups such as elderly people, but also a reduction of performance during work, fitness and cognitive activities.
- Disentangle the relative role of temperature and humidity in determining future changes in heat stress conditions over Europe.

Considering the whole distribution of climate events, those determining its tails—the extreme events—are the ones that should have the strongest effect on health (Costello *et al* 2009, Watts *et al* 2017). For this reason we focus not only on moderate (90 percentile) events, but also intense (99 percentile) and extreme (99.9 percentile) perceived temperature events as defined on a daily time frequency basis over a 30 year period, under the next (2006–2035), near (2036–2065) and far (2066–2095) future.

2. Data and methods

2.1. Reference data

The *humidex* (Masterton and Richardson 1979) is a basic discomfort index computed through *2 m air temperature* and *relative humidity* parameters, and it is used to mimic the perceived temperature by the human body. The resulting values do not refer to any measurable temperature, but can help in the definition of heat-related conditions associated with high temperatures.

The index is defined as: $\text{humidex} = T + 5/9 \cdot (e - 10)$ where:

$$e = 6.112 \times 10^{7.5T/(237.7+T)} \cdot \text{RH}/100$$

$$T = 2 \text{ m air temperature } [^\circ\text{C}]$$

$$\text{RH} = 2 \text{ m relative humidity } [\%].$$

Five main categories are defined to represent different severities of heat-related conditions:

- humidex < 30 No discomfort
- $30 \leq \text{humidex} < 35$ Some discomfort
- $35 \leq \text{humidex} < 40$ Great discomfort
- $40 \leq \text{humidex} < 45$ Huge discomfort (Avoid exertion)
- humidex ≥ 45 Really dangerous (heatstroke possible)

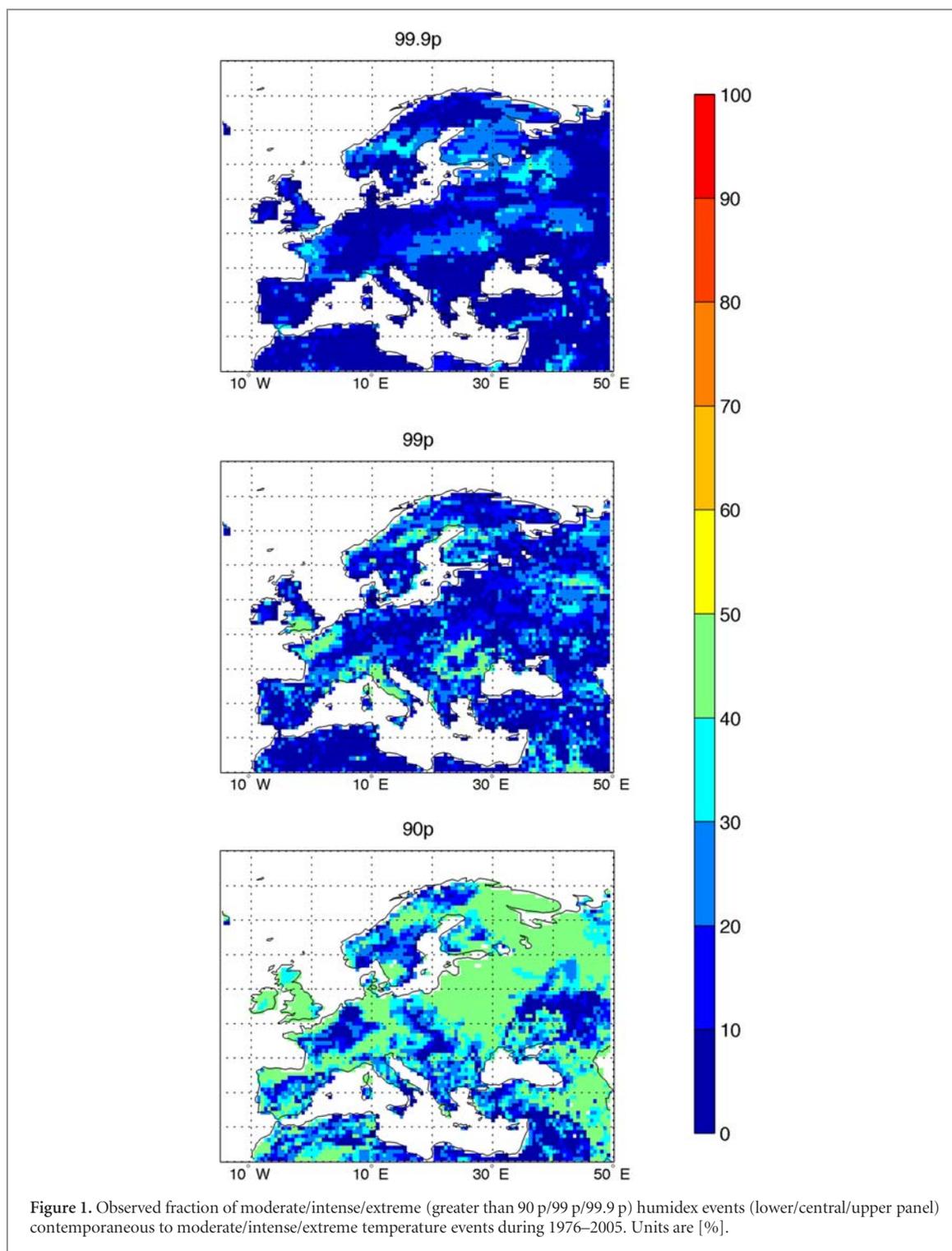
In this work we compute the humidex based on daily data from a set of simulations carried out by regional climate models (RCMs) participating in the last EURO-CORDEX initiative. The EURO-CORDEX experiment (Jacob *et al* 2014) aims to downscale CMIP5 simulations over Europe (www.euro-cordex.net) in a multi model framework: in the present analysis results from four RCMs are considered (see table 1) at the highest spatial resolution available, covering the EUR-11 domain (see figure 1) at about 10 km as horizontal resolution.

In order to provide an evaluation of the mentioned multi-model framework in simulating the humidex over the present climate, we compare RCM results to the JRA-55 reanalysis (Kobayashi *et al* 2015) covering the entire globe. The Japanese 55 year re-analysis data set has a spatial resolution of 0.5° longitude by 0.5° latitude and 60 vertical levels with a top layer at 0.1 hPa. The data assimilation system in JRA-55 has been improved since the time of the production of the prior JRA-25 (Onogi *et al* 2007), including the introduction of a new radiation scheme, and a 4D-Var assimilation scheme, a state of the art algorithm which uses observations to update the past in addition to the current model state.

The use of a reanalysis data set is necessary to obtain relative humidity gridded data at the daily time frequency. Noteworthy 2 m temperatures from JRA-55 reanalysis compare favorably well with the observed values (Simmons *et al* 2017) over Europe (not shown). For the sake of simplicity we will refer to JRA-55 climate fields as ‘observations’ in the rest of the paper.

2.2. Methodology

Different degrees of discomfort are investigated under moderate, intense and extreme conditions, defined as percentile values (respectively 90th–99th and 99.9th) of the humidex index, resulting from a daily time series of gridded data covering the European domain. With such parameters we aim to characterize the right tail

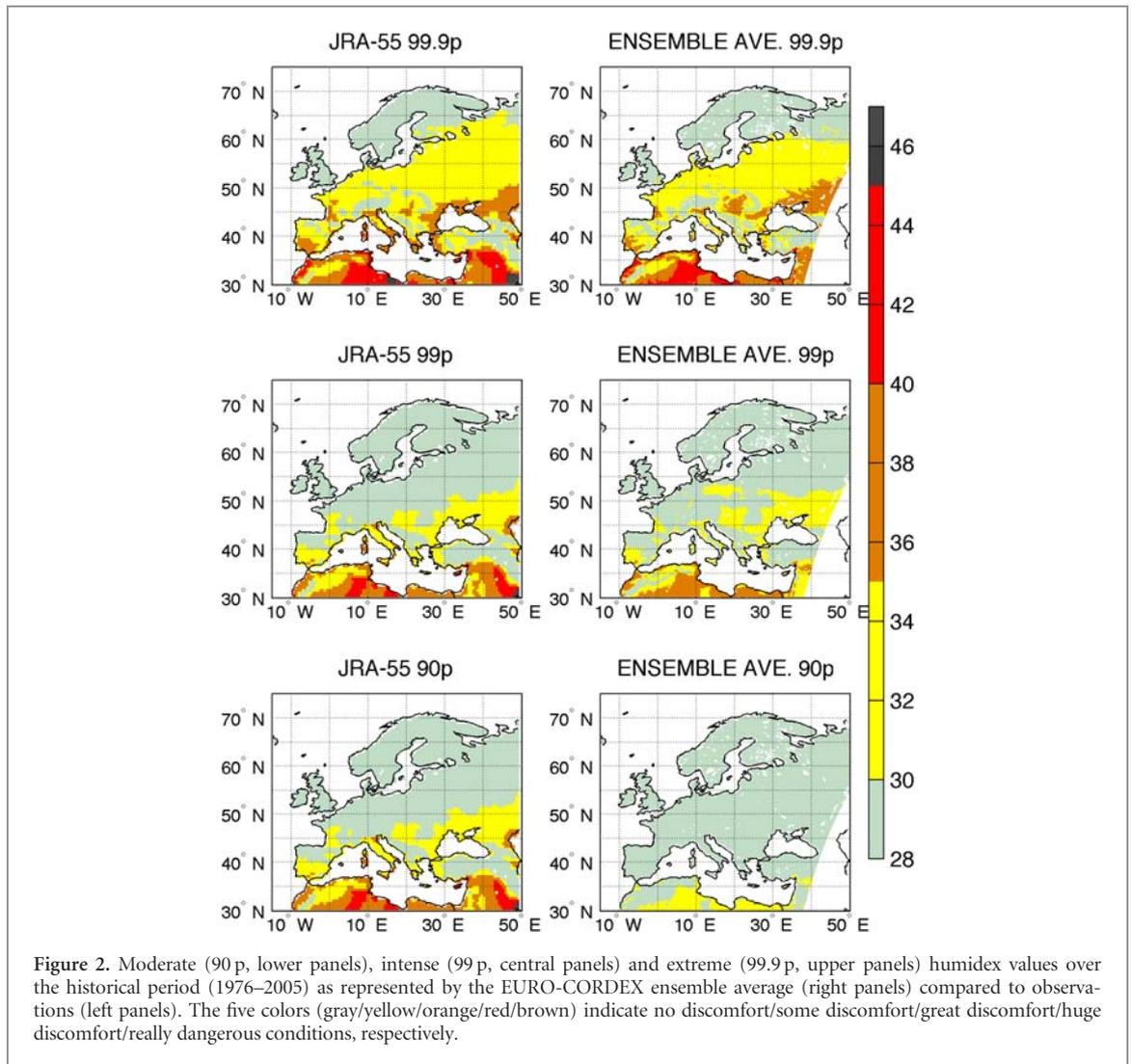


of the event's distribution and its changes under different future emission scenarios. Percentiles are computed based on 10 950 elements (365 days \times 30 years) for each period over each grid point within the investigated domain (figure 1).

The mentioned percentiles are computed for each of the considered RCMs, over each period, and then averaged (inter-model) to obtain an ensemble representation of the EURO-CORDEX output for the considered time-slice. Four periods are analyzed: 1976–2005, 2006–2035, 2036–2065 and 2066–2095,

hereafter *historical*, *next-future*, *near-future* and *far-future*, respectively.

Model results are compared to the observations over the historical period for validation purposes. In order to perform a pattern correlation comparison between each model and the observations, JRA-55 results have been interpolated on the common EURO-CORDEX higher resolution grid. Also, the fraction of contemporaneous humidex and temperature moderate to extreme observed events is evaluated searching the correspondence in time of



daily events greater than the percentile threshold of the humidex, being also temperature events greater than the same percentile threshold of the 2 m temperature.

Future projections over the three mentioned periods—*next-future*, *near-future* and *far-future*—are investigated under two different climate scenarios. EURO-CORDEX scenario simulations use the last representative concentration pathways (RCPs) defined for the IPCC Fifth Assessment Report (Moss *et al* 2010). The present analysis is performed following the RCP8.5 and RCP4.5 scenarios up to 2095. RCP8.5 is the one with the highest rate of increase in greenhouse gas (GHG) concentrations within the new set of RCPs and it assumes the fastest population growth, a massive increase in world poverty, plus high energy use.

On the other hand, RCP4.5 is a stabilization scenario with a moderate rate of increase in GHGs (Riahi *et al* 2011, Taylor *et al* 2012) invoking climate policies to achieve the goal of limiting emissions and radiative forcing.

3. Results

Focusing on the observations it emerges that moderate humidex events tend to coincide with moderate temperature events in many cases (up to 50%, figure 1 lower panel). On the other hand, moving to intense and extreme humidex events (figure 1, central and upper panels), this synchronous behavior between humidex and air temperature becomes more sporadic. This is the main reason which suggests the need for a direct evaluation of the extreme events of the humidex parameter in the future, as a complement to the already available information on heat wave projections over Europe (Jacob *et al* 2014), in order to have an explicit measure of potential heat-related illnesses under particularly rare conditions. Noteworthy moderate, intense and extreme events of the humidex are never associated with the corresponding relative humidity percentiles (less than 5% of cases, not shown), also due to the tendency for a reduction of the relative humidity once the temperature increases over land. Even if the amount of water that can be stored in a volume of air increases

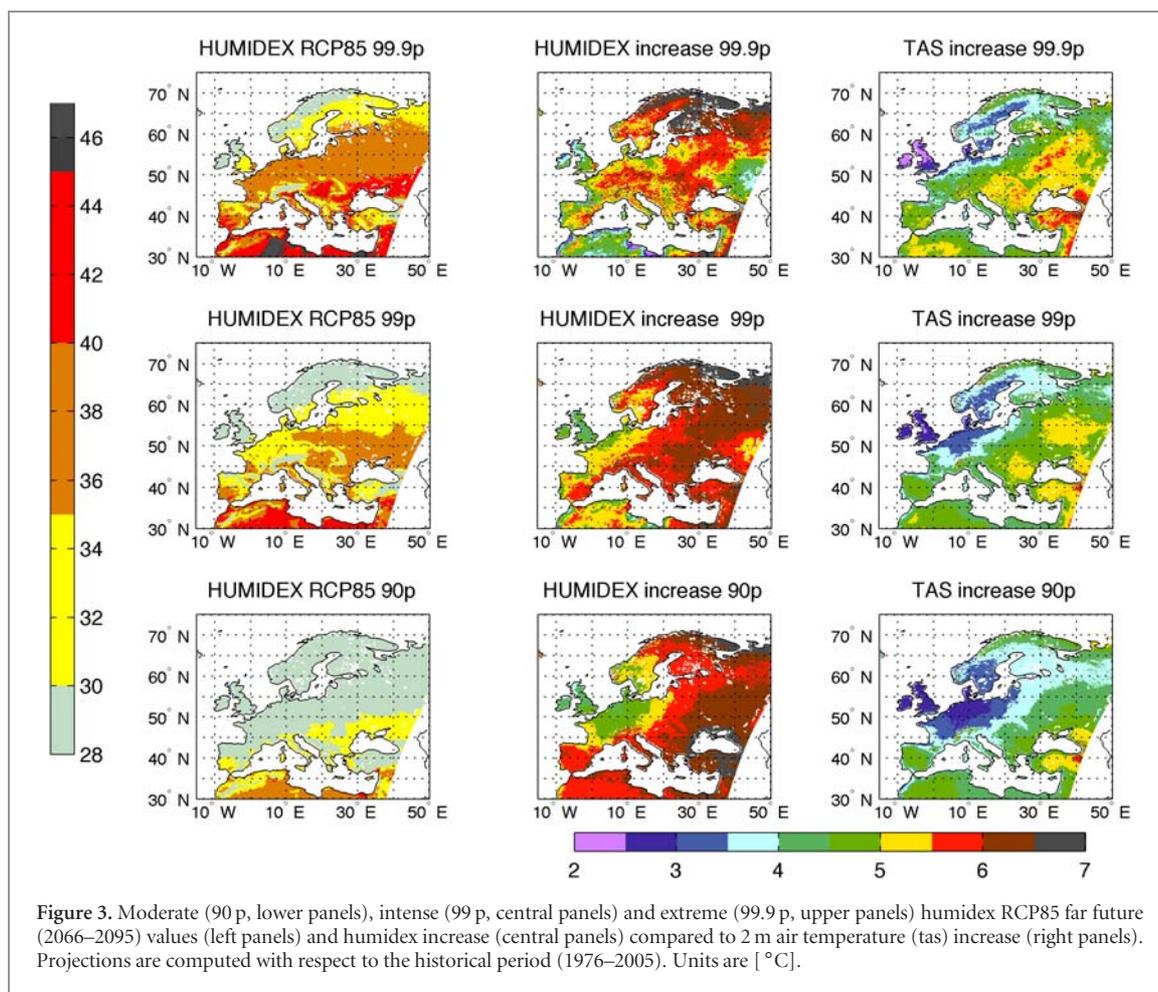


Figure 3. Moderate (90 p, lower panels), intense (99 p, central panels) and extreme (99.9 p, upper panels) humidex RCP85 far future (2066–2095) values (left panels) and humidex increase (central panels) compared to 2 m air temperature (tas) increase (right panels). Projections are computed with respect to the historical period (1976–2005). Units are [$^{\circ}\text{C}$].

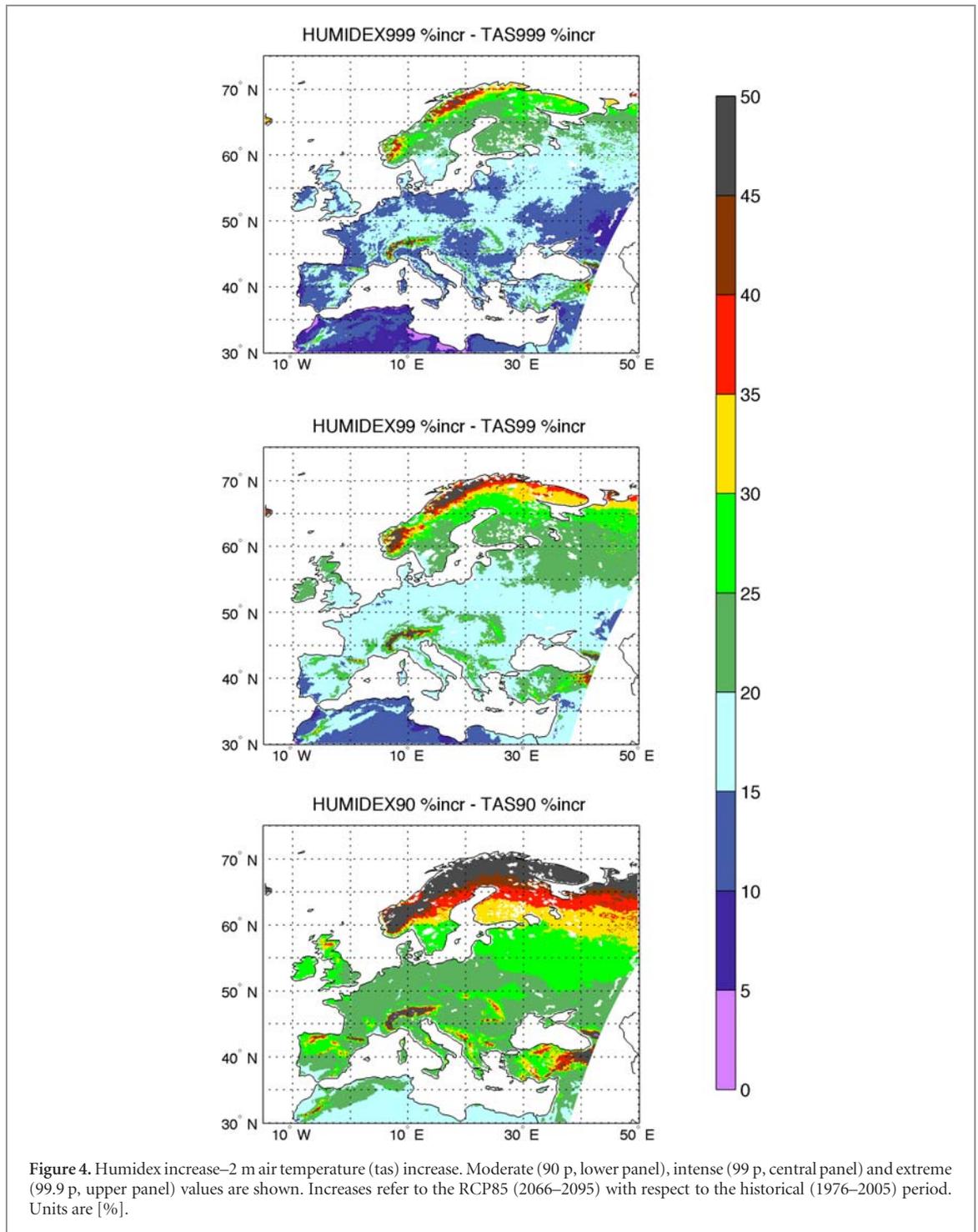
at higher temperature, the real amount of water in the volume can be limited by the absence of a water source.

As a first step to evaluate the skill of the EURO-CORDEX RCMs in representing moderate to extreme humidex values, we compare the RCMs' results to the observations (figure 2). Bearing in mind that differences might be also related to the different horizontal resolution, models tend to underestimate the moderate events (figure 2 lower panels) in the southern part of Europe, missing the representation of 'some discomfort' (yellow pattern) observed regions. On the other hand, intense (figure 2 central panels) and extreme (figure 2 top panels) events are well represented by the RCMs, with 'some' (yellow) and 'great' (orange) discomfort patterns appearing over many regions of Europe. The correlation pattern between the observations and the ensemble average for the 90th/99th/99.9th percentile value, is 0.96/0.94/0.94. In addition, the lower correlation found within the four single model comparisons is 0.91/0.82/0.78 respectively.

Focusing on the far future humidex projections, modelled following the RCP8.5 scenario, large areas subject to great discomfort appear in case of intense and extreme events in central and northern Europe (figure 3 left panels). Also 'huge' discomfort under extreme events is projected over plains in southern and central Europe, such as the southern Portuguese

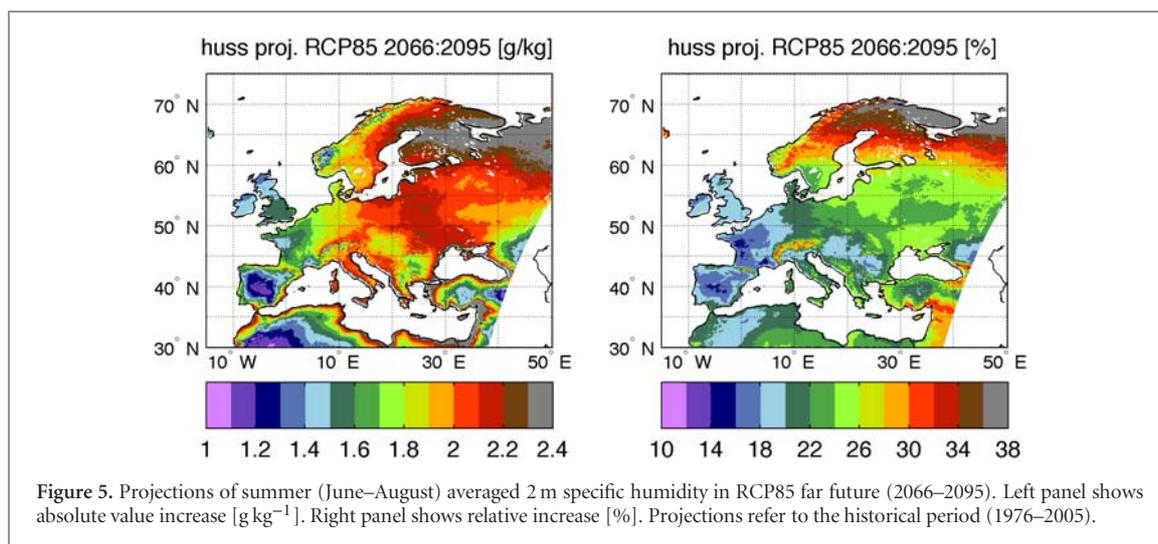
and south-western Spanish plains, the Italian Pianura Padana, the Hungarian Pannonian Plain and the Black Sea Lowland (figure 3, upper left panel). A less pronounced increase is projected for the near and next future, but extreme events under 'great' discomfort conditions are found also for the near future (supplementary figures S1 and S2 available at stacks.iop.org/ERL/12/114029/mmedia). The projections under the RCP4.5 scenario are very similar to the RCP8.5 for the near and next future (figures S4 and S5 compared to S1 and S2 respectively). The two scenarios, on the other hand, appear to be quite different in the far future when, under the moderate scenario, no more than 'great' discomfort is reached under extreme conditions, without regions being affected by the 'huge' discomfort projected under the RCP8.5 scenario (figure S3 compared to figure 3).

In general, for a given value of relative humidity, the humidex increase with temperature follows an exponential law, thus a more pronounced increase of the index in warmer projections is expected, compared to temperature. We found that this is not the main source of difference between the projection of humidex compared to temperature projections. The projections of moderate, intense and extreme humidex events are more pronounced in the eastern and northern parts of Europe (figure 3, central panels). Evaluating air



temperature projections only, different patterns appear (figure 3 right panels), with no particular increases over north-eastern Europe justifying the increase found in the humidex projections. The more pronounced increase in the humidex projections compared to the air temperature projections is shown in figure 4, where also the higher rate for low temperatures (over mountains and northern regions or lower percentiles) is evident. This suggests a major role played by the changes in relative humidity in determining the projections of perceived temperature extremes.

While the potential amount of water vapor that can be contained by an air parcel before saturation increases with air temperature, the actual amount may be limited by water vapor availability. In the latter case, an increase in air temperature might cause a decrease of the relative humidity. This explains why computing composites (see figure S6 caption) of the relative humidity values associated with humidex events from moderate to intense, makes apparent the tendency toward a reduction of the composited parameter in future projections, mainly due to the increase of the associated higher temperature (figure S6). On the other hand, focusing



on the water content of the atmospheric surface layer, we found an increase in specific humidity projections during northern summer (June to August) (figure 5), that is when the considered events are supposed to occur. This positive projection, also evident when looking at the specific humidity composites over moderate to extreme events only (figure S7), confirms the role of the water content of the atmospheric surface layer in modulating the spatial variability of the perceived temperature projected increase. The pronounced increase of specific humidity over the northeastern part of the domain is consistent with the projected moderate reduction of the relative humidity over these regions, thus with a higher increase of perceived temperature despite a moderate increase of the air temperature.

4. Discussion and conclusions

It is well established (IPCC 2014) that according to climate change projections, the European population is expected to face a warmer climate in the future. The magnitude of this warming depends on the future scenario and the European sub-region considered. An averaged warming ranging from $3\text{ }^{\circ}\text{C}$ – $6\text{ }^{\circ}\text{C}$ is expected by the end of the worst-case scenario (RCP8.5). Temperature extremes are also expected to increase, up to 50% even though the associated spatial structure does not resemble the one shown by mean temperature projections (Dosio 2016).

In this work we wanted to include the effect of humidity on the temperature perceived by the human body under moderate to extreme conditions, also considering the different spatial distribution of the two projected involved parameters (temperature and humidity) under future scenarios. Reliable information on the projections of such a human health related index is important to define changes in the location and size of European regions subject to dangerous conditions and to help experts systematically exploring the impact that green and blue infrastructures

(Gunawardena *et al* 2017) can have on human health and wellbeing (Gascon *et al* 2017, Grellier *et al* 2017). To this end, high resolution regional climate simulations from the EURO-CORDEX EUR11 effort have been investigated in a multi-model and multi-scenario framework. Models suggest that no particular changes are expected in terms of moderate to extreme perceived temperature in the next future (until 2035), while in the near future (2035–2065) ‘great’ discomfort areas appear over the central European plains in both considered scenarios. In addition, such ‘great’ discomfort rare conditions are expected to reach northern Europe by the end of the century (2065–2095) when also ‘huge’ discomfort, under extreme conditions is expected over central Europe.

The perceived temperature projections are more intense than temperature projections in terms of moderate to extreme events, especially in northern Europe. This is only partially due to the exponential relationship between temperature and humidex climate parameters, and mainly caused by the projected increase in air specific humidity. The projections of a major increase of water content in the air—thus a more pronounced perceived temperature projections in the northern Europe—is consistent with previous studies investigating the same climate scenarios based on lower resolution CMIP5 general circulation models (Scoccimarro *et al* 2016).

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