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Land–sea contrast, soil-atmosphere and cloud-temperature interactions: interplays and roles in future summer European climate change

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Abstract Europe and in particular its southern part are expected to undergo serious climate changes during summer in response to anthropogenic forcing, with large surface warming and decrease in precipitation. Yet, serious uncertainties remain, especially over central and western Europe. Several mechanisms have been suggested to be important in that context but their relative importance and possible interplays are still not well understood. In this paper, the role of soil-atmosphere interactions, cloud-temperature interactions and land–sea warming contrast in summer European climate change and how they interact are analyzed. Models for which evapotranspiration is strongly limited by soil moisture in the present climate are found to tend to simulate larger future decrease in evapotranspiration. Models characterized by stronger present-day anti-correlation between cloud cover and temperature over land tend to simulate larger future decrease in cloud cover. Large model-to-model differences regarding land–sea warming contrast and its impacts are also found. Warming over land is expected to be larger than warming over sea, leading to a decrease in continental relative humidity and precipitation because of the discrepancy between the change in atmospheric moisture capacity over land and the change in specific humidity. Yet, it is not true for all the models over our domain of interest. Models in which evapotranspiration is not limited by soil moisture and with a weak present-day anti-correlation between cloud cover and temperature tend to simulate smaller land surface warming. In these models, change in specific humidity over land is therefore able to match the continental increase in moisture capacity, which leads to virtually no change in continental relative humidity and smaller precipitation change. Because of the physical links that exist between the response to anthropogenic forcing of important impact-related climate variables and the way some mechanisms are simulated in the context of present-day variability, this study suggests some potentially useful metrics to reduce summer European climate change uncertainties.

Keywords Climate change · Soil-atmosphere interactions · Clouds · Land–sea contrast · Europe

1 Introduction

Summer ensemble climate change projections over the southern half of Europe are characterized by a large amplification in surface warming and severe precipitation decreases. Because of those features, this region is viewed as a “hot spot” of climate change (Giorgi 2006). Southern Europe is also one of the areas of the world where large decreases in relative humidity and cloud cover are simulated (Meehl et al. 2007). Those features are simulated by ensembles of global climate models (GCMs), for example from the Coupled Model Intercomparison Project 3 (CMIP3, Meehl et al. 2007) and of regional climate models (RCMs), for example from the ENSEMBLES project (van der Linden and Mitchell 2009). Notwithstanding those robust features, summer European climate change is also characterized by a large spread (e.g. Déqué et al. 2012; Terray and Boé 2013), especially over an intermediary band of latitude.

Both structural model uncertainties and internal variability contribute to the large spread seen in simulated European climate change. The role of internal variability

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during the next few decades is substantial, especially at the regional scales (Hawkins and Sutton 2009; Deser et al. 2012), but nevertheless structural model uncertainties explain an important part of the spread in summer European climate change, even in the middle of the twenty first century (Terray and Boé 2013). Dealing with model uncertainties is therefore both necessary and useful to improve ensemble climate projections.

Two parallel approaches can be followed to obtain more reliable multimodel climate projections: improving the realism of climate models to obtain more realistic projections thanks to the next generation of models or better using the information provided by current climate projections, by selecting only or giving more weight to the models considered as more realistic (e.g. Giorgi and Mearns 2002; Weigel et al. 2010). A critical issue with the second approach lies in the evaluation of the relative realism of the different climate models. It is always possible to measure how the models reproduce some observable present-day characteristics of the climate system (the term "metric" will be used in this paper to talk about such a measure in this context), but if there is no link between the representation of those characteristics in the models and their future response to anthropogenic forcing, it is hard to see how such a metric could be really useful. Therefore, a useful metric would be an observable characteristic of present-day climate simulations that is strongly linked to the response of the models to future anthropogenic forcing and even more to the spread of the responses.

At a fundamental level, uncertainties in climate projections somewhat reflect our incomplete understanding of the physical mechanisms involved. Better understanding the physical mechanisms responsible for the inter-model spread could therefore be an important step to define useful metrics (Hall and Qu 2006; Boé and Terray 2008). Moreover, it could also be useful with the objective of defining priorities for model improvement.

Several mechanisms could potentially be important for summer European climate change. The role of large scale circulation change in summer drying has been studied recently by Boé et al. (2009). This analysis of CMIP3 models shows that if large scale circulation does play a role in summer drying, that is important over north-western Europe (United Kingdom, north of France), its impact over southern Europe, where a very large drying takes place, is much less evident. This result is consistent with the findings of Rowell and Jones (2006) and Kendon et al. (2008) who have used a specific modelling set-up to evaluate the importance of different mechanisms in their regional climate model. They found that land-atmosphere interactions and the land–sea warming contrast are especially important for precipitation change over continental Europe, with a limited impact of large-scale circulation except over north-western Europe. The importance of land-atmosphere interactions has been highlighted by several other studies, regarding mean climate change (e.g. Boé and Terray 2008) or change in interannual variability (e.g. Seneviratne 2006; Fischer et al. 2012). Clouds are generally a large source of uncertainties (Soden and Held 2006) and Tang et al. (2012) based on observations suggested that clouds could have been an important actor in shaping recent summer European climate evolution (even though this observational study cannot conclude whether cloud changes are just a response or a cause of recent summer European warming). The results of Lenderink et al. (2007) support the importance of both soil-atmosphere interactions and cloud processes on western Europe climate change.

The role of the land–sea warming contrast on hydrological cycle changes over continents, noted for example by Rowell and Jones (2006) for Europe, has been recognized since early coupled climate simulations (e.g. Manabe et al. 1992). The specific humidity at saturation over land increases with continental surface temperature following the Clausius-Clapeyron relationship. Under the hypothesis that atmospheric moisture over land comes to a large extent from oceanic evaporation through atmospheric transport, continental specific humidity is expected to increase more in line with temperature change over oceans. As simulated warming is generally larger over land, following this line of reasoning, specific humidity over land would increase less than specific humidity at saturation, leading to a decrease in relative humidity (Rowell and Jones 2006). With decreasing relative humidity, saturation becomes harder to reach, the lifted condensation level increases, which could then lead to a decrease in continental precipitation (Rowell and Jones 2006) and cloud cover (Fasullo 2010). Manabe et al. (1992) attributed the land–sea warming contrast primarily to the thermal inertia of oceans. Yet, the thermal inertia explanation could only be valid for the transient period. As a land–sea warming ratio greater than one is generally seen even at equilibrium in current climate projections, other processes are likely to be involved (Sutton et al. 2007). Those authors argue that the different partitioning of surface turbulent fluxes over land and sea favors a larger increase in temperature over land. Additionally to the role of moisture availability at surface, Joshi et al. (2008) proposed another mechanism, based on a simple conceptual model. If one assumes that a level exists where temperature changes over land and ocean are identical because of efficient horizontal homogenization at this altitude and above, as the lapse rate over ocean (more often saturated) will necessary decrease more than the lapse over land (less often saturated) given its dependence to moisture and temperature, surface warming will be greater over land. In any case, if the role of ocean thermal inertia in land–sea warming contrast is not the dominant one, land–sea warming contrast cannot be seen as a simple independent forcing of continental hydrological changes. Land–sea warming contrast could indeed both influence and be influenced by continental hydrological changes and more generally continental processes, for example cloud change over land or soil-atmosphere interactions. It may therefore not be straightforward to disentangle the impacts on European summer climate change of land–sea warming contrast, cloud processes and soil-atmosphere interactions. Finally, there is some evidence that the representation of some of the processes mentioned above may be biased in current models, with impacts on the model response to anthropogenic forcing. For example, Boberg and Christensen (2012) suggest that the difficulties of RCMs to represent correctly dry and warm climate could bias their response in the future climate.

In this paper, our objective is to study in details the impact of local processes mentioned above in the large inter-model spread in summer climate changes over Europe: soil-atmosphere interactions, cloud-temperature interactions and land–sea warming contrast. We will also analyze how they interact, and try to define potentially useful metrics for those processes that could be subsequently used to obtain more reliable probabilistic estimates of future summer European climate change. Because of the local focus of this study, a recent set of regional climate projections over Europe at a high resolution of 25 km from the ENSEMBLES project (Sect. 2) is analyzed. One could hope that the good realism of orography and coasts in those high resolution simulations reduces some systematic biases in local climate that may exist in low resolution GCM simulations. For example, soil-atmosphere interactions are dependent on climatological soil-moisture which is itself strongly influenced by orography. The geography of the Mediterranean basin is poorly represented in low resolution GCM, which could impact land–sea warming contrast over Europe. In any case, the identical resolution of ENSEMBLES RCMs limits the structural spread that is commonly associated with the large differences in orography and coasts that exist in current GCM ensembles. First, land-atmosphere interactions (Sect. 3), cloud-temperature interactions (Sect. 4), and land–sea contrast (Sect. 5) are analyzed separately. As we will shall see, those mechanisms are actually often linked (Sect. 6). The impact of large scale forcing and the potential impact of biases in boundary forcing on the simulation of those local processes are then characterized in Sect. 7. Finally, a summary and a short discussion are provided in Sect. 8.

2 Data

In this paper, 17 regional climate projections over Europe at a 25 km resolution from the ENSEMBLES project (e.g. Hewitt 2004; Déqué et al. 2012) on the 1961–2050 period are analyzed. In these projections, the Special Report on Emissions Scenarios (SRES) a1b scenario is used after 2000, while historical forcing is used prior to that. The regional climate simulations studied in this paper are summarized in Table 1. Note that some RCMs are forced by several GCMs and some GCMs forced several RCMs. Therefore, the 17 projections are not perfectly independent by construction. Because of no satisfying alternative, the subsequent significance tests are still based on the hypothesis that the 17 projections are independent. In Sect. 7, control simulations in which the RCMs are forced by the ERA40 reanalysis (Uppala et al. 2005) are also analyzed. More details on the simulations set-up and references on the models are given for example by Déqué et al. (2012).

Table 1 Summary of the climate simulations from the ENSEMBLES project analyzed in the paper

	HadCM3Q0	HadCM3Q3	HadCM3Q16	ARPEGE	BCM	ECHAM5	CGCM3	ERA40
C4IRCA3			X					X (except humidity)
CNRM-RM5.1				X				
DMI-HIRHAM5				X	X	X		X
KNMI-RACMO2						X		X
METNOHIRHAM	X				X			X
METO-HC_HadRM3Q0	X							X
METO-HC_HadRM3Q3		X						X
METO-HC_HadRM3Q16			X					X
MPI-M-REMO						X		X
ETHZ-CLM	X							X
OURANOSMRCC4.2.1							X	X
SMHIRCA		X			X	X		X

The name of the RCMs is given in the lines, the name of the GCMs (or reanalysis) providing the boundary conditions to the RCMs is given in the columns

In this paper, present-day variability is always characterized using the 1961–2000 period while future changes correspond to difference between the means of 2031–2050 and 1961–1990 periods.

The ENSEMBLES RCMs depict the now classical features of European climate change projections (Fig. 1). Even before the middle of the twenty first century, a large warming and a large decrease in precipitation, cloud cover and relative humidity occur over southern and central Europe. The inter-model spread is also very large for those variables. If strongest changes are simulated over southern Europe, strongest uncertainties are generally seen in central Europe, southern France, Ukraine.

Thanks to the work by Déqué et al. (2012), it is known that the spread in summer temperature change in ENSEMBLES RCM is dominated by the choice of boundary forcing. Regarding summer precipitation change, the spread is generally dominated by the choice of RCM.

Figure 2 shows the masks for two areas that will often be considered in the rest of the paper: land, i.e. France, and sea, the seas surrounding France. The choice of France as a test-bed to study land–sea warming contrast and its impact on regional climate change is motivated by its very favorable characteristics in that context. Indeed, France is mostly surrounded by large bodies of water, it is not too small and can therefore be well resolved by RCMs, and its medium-size limits spatial variations in mean-climate, which would obfuscate the analysis of land–sea warming contrast.

3 Soil moisture-atmosphere interactions

Evapotranspiration is an important variable of the climate system as it couples the surface energy budget and the surface water budget. As such, evapotranspiration depends on both water and energy availability at surface. The respective importance of those two constraints depends on local climatological characteristics. Over dry and warm areas, one expects evapotranspiration to be limited by the water available in the soil. Over cold and moist areas, evapotranspiration tends to be limited by available surface energy rather than soil-moisture. Boé and Terray (2008) showed that the present-day interannual correlation

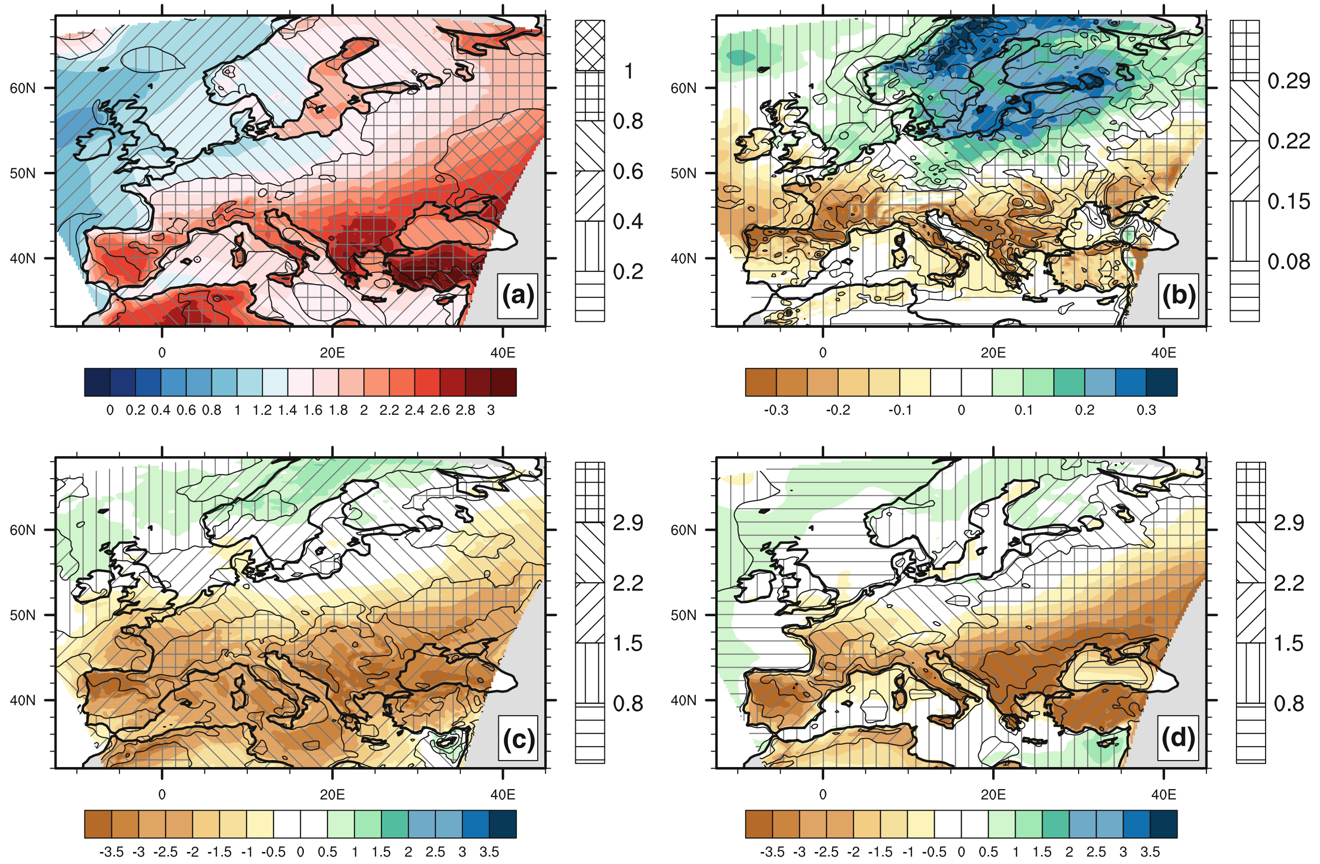

Fig. 1 Ensemble mean changes and associated spread in **a** air surface temperature (K), **b** precipitation (mm/day), **c** cloud cover (%) and **d** relative humidity (%). 2031–2050 versus 1961–1990. The *colors* show the ensemble mean, and the patterns show the inter-model standard deviation

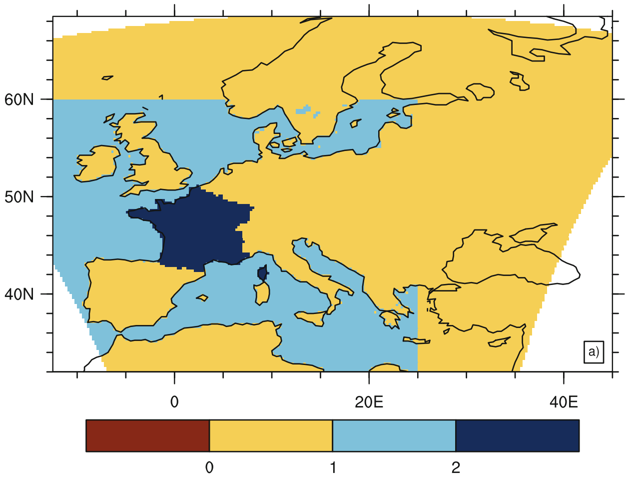

Fig. 2 Masks corresponding to the two areas studied subsequently in the paper: Land (or France) in *dark blue*, Sea in *light blue*

between latent heat flux and total downwelling radiation at surface in the present climate, that characterizes the control of evapotranspiration by energy at surface in the interannual variability context, is an interesting metric for future temperature change and, to a lesser extent, precipitation change over France and central Europe. Indeed, CMIP3 models for which evapotranspiration is tightly controlled by soil moisture in the present climate (i.e. weakly associated with available radiation at surface) tend to simulate larger decrease in evapotranspiration, larger increase in temperature and larger decrease in precipitation in response to anthropogenic forcing. It is interesting to assess whether this result holds for the ENSEMBLES high-resolution regional climate projections over Europe. In order to maximize the number of models used in the analysis, the interannual correlation of latent heat flux with soil moisture (this metric is named m_{soil} subsequently, see Table 2) rather than with available radiative energy at surface, is computed. But the idea is the same as in Boé and Terray (2008): to assess whether latent heat flux tends to be limited by soil moisture availability or energy availability at surface.

From an ensemble mean perspective, not surprisingly, a large positive correlation is found between soil moisture and latent heat flux in southern Europe, indicating that evapotranspiration there is strongly limited by soil moisture (Fig. 3a). The correlation remains positive up to roughly 54°N, with the notable exception of the Alps, where evapotranspiration is not limited by water. Summer soil moisture in the Alps is generally quite larger than in plains at the same latitude, thanks to water stored as snow during winter that melts during spring. In Northern Europe as in the Alps, the correlation is negative, as evapotranspiration becomes limited by available energy at surface rather than by soil moisture.

Table 2 Summary of the metrics used in the paper

Name	Definition
m_{soil}	Interannual correlation between latent heat flux and soil moisture
m_{cloud}	Interannual correlation between surface temperature and cloud cover
k_{hum}	Interannual regression coefficient between surface specific humidity and temperature (g/kg K^{-1})

The ensemble mean of m_{soil} actually hides large model-to-model variations. In particular, a very large intermodel spread in m_{soil} is seen over France and northern Russia, indicating that models diverge about the dominant mechanism controlling evapotranspiration in the context of present-day interannual variability over those areas (Fig. 3b). Note that the much higher resolution of ENSEMBLES models does not lead to a reduction of the uncertainties in the controls of evapotranspiration compared to CMIP3 models (see Boé and Terray 2008).

The consistency between future changes in latent heat flux and the mechanisms controlling the latent heat flux in the context of present-day variability is now tested. Figure 3c shows the correlation between future change in latent heat flux simulated by the 17 RCMs and the 17 corresponding values of m_{soil} at each point. Over some areas, the response of the models in the future climate is found to be consistent with their behavior in the present climate. Models for which evapotranspiration is not limited by soil moisture in the present climate (small m_{soil}) simulate smaller decrease in latent heat flux in the future climate (or even, in some case, an increase) over most of France, Ukraine and Russia. Those results are generally consistent with those described in Boé and Terray (2008), obtained for the CMIP3 global climate projections later in the twenty first century, even though the areas over which the controls of evapotranspiration are uncertain and impact future climate change are not always exactly the same.

The causes of the large intermodel spread in m_{soil} remain to be fully understood. However, some hypotheses can be put forward. Climatological soil moisture could be important in this context but it is difficult to compare meaningfully climatological soil moisture between models with very different land surface schemes and reservoir sizes. Climatological available radiative energy at surface could also matter. Over some areas as France and Ukraine, a significant relationship between present-day climatological cloud cover and m_{soil} is found (Fig. 3d). Models with small cloud cover and therefore large climatological incoming solar radiation at surface tend to be characterized by a soil moisture control of evapotranspiration.

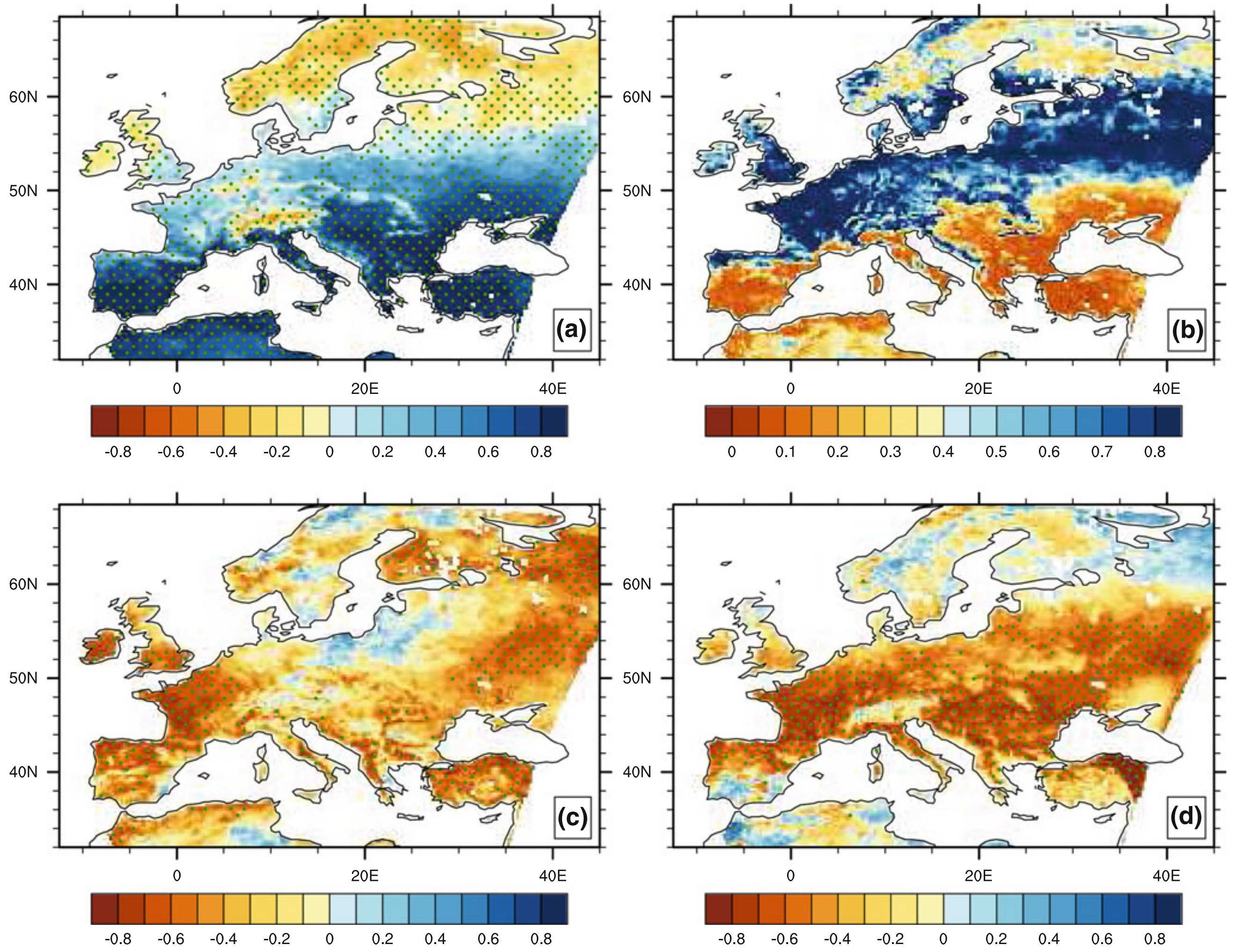

Fig. 3 Interannual correlation between soil moisture and latent heat flux (m_{soil}) over the 1961–2000 period (details are given in the text): **a** Ensemble mean, **b** Ensemble spread measured by the interquartile range. Areas where the interannual correlation (negative or positive) is significant with $p < 0.05$ in more than 2/3 of the models are shown with *green points* in (**a**). **c** Inter-model correlation between m_{soil} and future change in latent heat flux. *Green points* indicate significance with $p < 0.05$. **d** Inter-model correlation between m_{soil} and present-day climatological cloud cover. *Green points* indicate significance with $p < 0.05$

4 Cloud-temperature interactions

As shown in Fig. 1, ENSEMBLES RCMs as an ensemble simulate a large decrease in summer cloud cover over Europe. Yet, a large inter-model spread also exists. The objective of this section is to better understand the potential origin of those large model-to-model differences.

As a very simple potential indicator of cloud-temperature interactions, the interannual correlation between cloud cover and surface temperature is computed in the present climate (m_{cloud}) in each ENSEMBLES model. The ensemble mean and spread of m_{cloud} are shown in Fig. 4. Almost everywhere over Europe, smaller cloud cover in summer is associated with higher surface temperature, with larger negative value over France and Central Europe. The sign of the correlations is robust among models, but a substantial spread exists regarding their magnitudes, with an interquartile range greater than 0.2 for example over France.

In Fig. 5, it is tested to what extent the strength of m_{cloud} in the present climate is consistent with future cloud changes simulated by the models. A large negative and significant inter-model correlation between m_{cloud} and changes in downwelling shortwave radiation at surface is found over France and Spain. Models with a strong decrease in cloud cover and therefore a large increase in shortwave radiation at surface are generally the ones in which cloud cover and temperature are the most anti-correlated in the present climate. Even if the physical mechanisms behind the co-variability of temperature and cloud cover cover are complex, this result suggests an important role of cloud-temperature interactions in summer European climate change uncertainties over large parts of Europe.

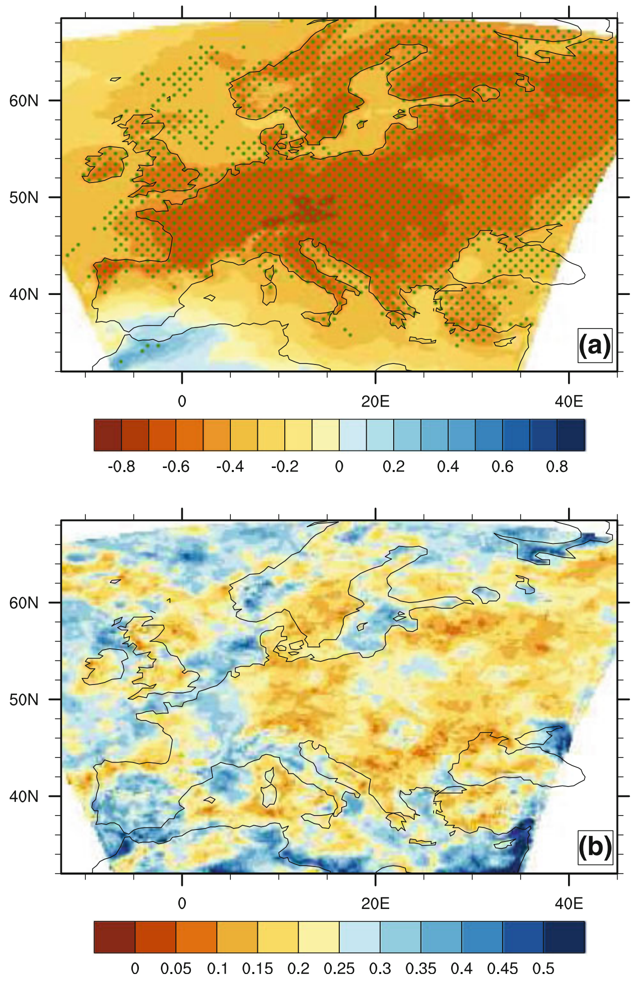

Fig. 4 Interannual correlation over the 1961–2000 period between cloud cover and surface temperature (m_{cloud}): **a** Ensemble mean, **b** Ensemble spread measured by the interquartile range. Areas where the interannual correlation (negative or positive) is significant with $p < 0.05$ in more than 2/3 of the models are shown with *green points* in (**a**)

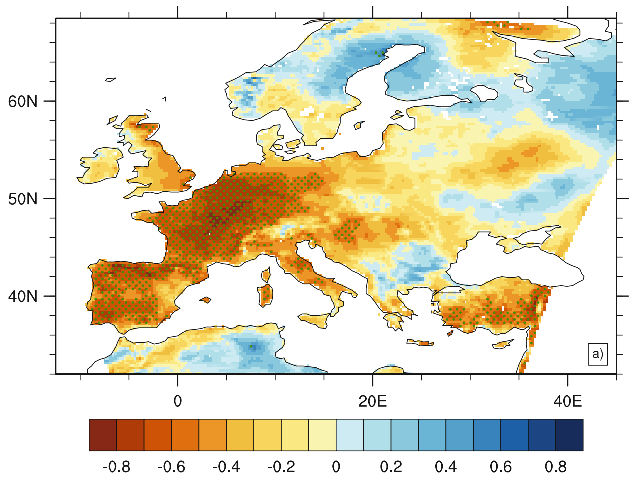

Fig. 5 Intermodel correlation between change in downwelling shortwave radiation at surface and m_{cloud}. *Green points* indicate significance with $p < 0.05$

5 Land–sea warming contrast

If one follows the line of reasoning put forward by Manabe et al. (1992) and summarized in the introduction, the relationships between specific humidity and temperature changes over land and over ocean should differ. Indeed, over ocean, because of unlimited water availability, the relation between specific humidity and temperature change is expected to be close to the Clausius-Clapeyron relation (here and subsequently for the sake of simplicity "close to the Clausius-Clapeyron relation", means that specific humidity changes with temperature in roughly the same way as specific humidity at saturation changes with temperature, i.e. following the Clausius-Clapeyron equation. It is equivalent to no change in relative humidity). A priori, such a relation is not expected to exist over land as explained previously. Figure 6 shows the scatter plot between changes in 2 m specific humidity and 2 m temperature averaged over land (France) points and sea points (see masks in Fig. 2). Not surprisingly, a strong linear inter-model relationship exists between temperature and humidity changes over the ocean, consistently with the Clausius-Clapeyron relation (for a climatological specific humidity corresponding to the ensemble mean, this slope corresponds to a relative increase of 7.36 % by Kelvin).

Over land, when considering the full ensemble, no clear relation between temperature and specific humidity changes is discernible. However, the picture is different if one looks at subgroups of models. Indeed, the points for land of a subgroup of 7 models are within (or very close to) the uncertainty range of the regression line established for ocean points. In these seven models, changes in humidity are roughly proportional to temperature changes, and therefore those models do not exhibit change in relative humidity over France, as shown in Fig. 7b. This subgroup of models is named "CRH" models as "constant relative humidity". For other models, consistently with the reasoning of Manabe et al. (1992), specific humidity over land increases less with temperature than over ocean, and therefore not following the Clausius-Clapeyron relation. A second subgroup of models is defined, the "DRH" models as "decrease in relative humidity" (Fig. 7b), by selecting the six models the furthest away from the ocean points regression line.

For the two groups of models, changes in different variables averaged over France or sea are shown in Fig. 7. First, it is verified that CRH models simulate virtually no change in relative humidity while DRH models simulate a large decrease, as expected given the criterion of selection. Given the changes in relative humidity, saturation becomes harder to reach in DRH models and the lifted condensation

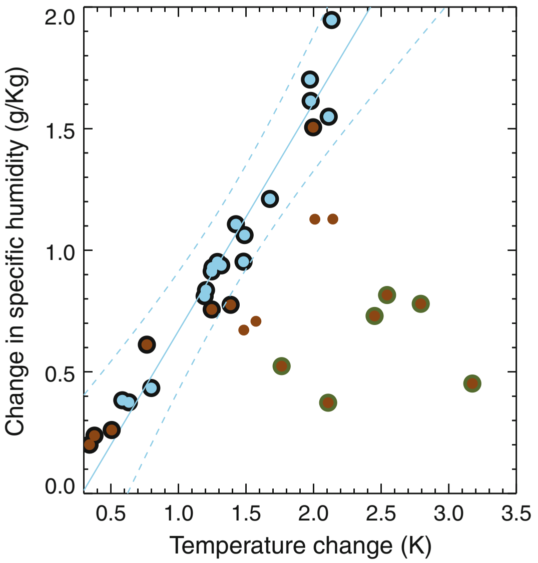

Fig. 6 Change in 2 m specific humidity (*g/kg*) versus change in 2 m surface temperature (*K*), averaged over land (France, *brown points*) and surrounding ocean (*blue points*). See masks in Fig. 2. The *solid blue line* is the regression line computed for ocean points and the *dashed blue lines* are the 95 % confidence bands. *Brown points circled* of *green* are DRH models and *brown points circled* of *black* are CRH models (see text for details)

level is expected to increase. Consistently with that, larger decreases in cloud cover and precipitation are seen in DRH models while the CRH ensemble mean simulates virtually no change in precipitation. Consistently with a decrease in cloud cover (and probably with the decrease in evapotranspiration that is expected to be associated with the decrease in precipitation noted previously), continental surface warming is greater in DRH models, which results in a land–sea warming ratio much larger than one. Interestingly, the land–sea ratio in surface warming of CRH models is even most of the time smaller than one.

The changes in specific humidity over land are very similar in CRH and DRH models, indicating that the differences in the humidity to temperature change ratios are mainly driven by the differences in land surface warming. Also, DRH models are characterized by much larger changes in specific humidity over sea compared to CRH models. In the end, change in specific humidity is only slightly larger over sea than over land in CRH models, while change in specific humidity over land in DRH models is much smaller than the corresponding change over sea.

While DRH models perfectly fall into the classical picture put forward by Manabe et al. (1992) (with a land–sea warming ratio greater than one and a decrease in continental precipitation), it is not the case for CRH models over France. Figure 7 clearly shows that the two groups of models, simply selected from the relation between continental specific humidity and temperature changes depict a strikingly different picture of the future French climate. In average, DRH models simulate severe climate changes (2.5 K warming, −20 % in precipitation) even before the middle of the twenty first century while CRH models simulate very moderate changes as an ensemble (less than 1 K warming and virtually no change in precipitation). Obviously, such different climate changes would lead to very different impacts. Consequently, it would be very useful to know which group of models is the more reliable. As a first step, a better understanding of the processes responsible for the differential behavior of CRH and DRH models is required.

We first study the relation between temperature and specific humidity in the context of present-day variability in the ENSEMBLES models to assess whether CRH and DRH models already differ in the present climate. Because of the Clausius-Clapeyron relation, very strong correlations between specific humidity and temperature are seen over oceans (Fig. 8). High correlations are also seen over continental northern Europe, while correlations decrease southward, with slightly negative values seen in Greece, Italy, Turkey. As in Fig. 3, the Alps stand apart from the low-altitude points at the same latitude, with larger positive correlations. A large intermodel spread exists over land, especially over France and central Europe, so that models sometimes do not agree on the simple sign of the correlation between humidity and temperature there. A large spread in the regression coefficient is also found over central and western Europe. Interestingly, a larger scatter is also found for the regression coefficient over the Mediterranean sea. Regarding the ensemble mean, the spatial pattern of the regression coefficient is quite similar to the pattern of the correlation coefficient. However, higher regression coefficients are seen over the Mediterranean sea compared to the Atlantic ocean, despite smaller correlations. This is accounted for, at least partially, by the nonlinearity of the Clausius-Clapeyron relation. Indeed, this relation actually (approximately) links the relative change in specific humidity at saturation to temperature change. Therefore, higher absolute specific humidity changes for a given temperature change are expected over areas with larger climatological specific humidity and temperature, respectively. The climatological specific humidity over the Mediterranean sea is much larger than over the Atlantic ocean over our area of study (not shown).

We now investigate to what extent the differential behavior of DRH and CRH models in the future climate is already discernible in the context of present-day interannual variability by looking at the three potential metrics previously defined m_{soil}, m_{cloud}, k_{hum}. The composite differences between CRH and DRH models are computed for the three metrics (Fig. 9). Significant differences in k_{hum} are found over continents (northern and western France, Benelux, some parts of Russia). CRH models tend to have larger interannual regression coefficients between specific

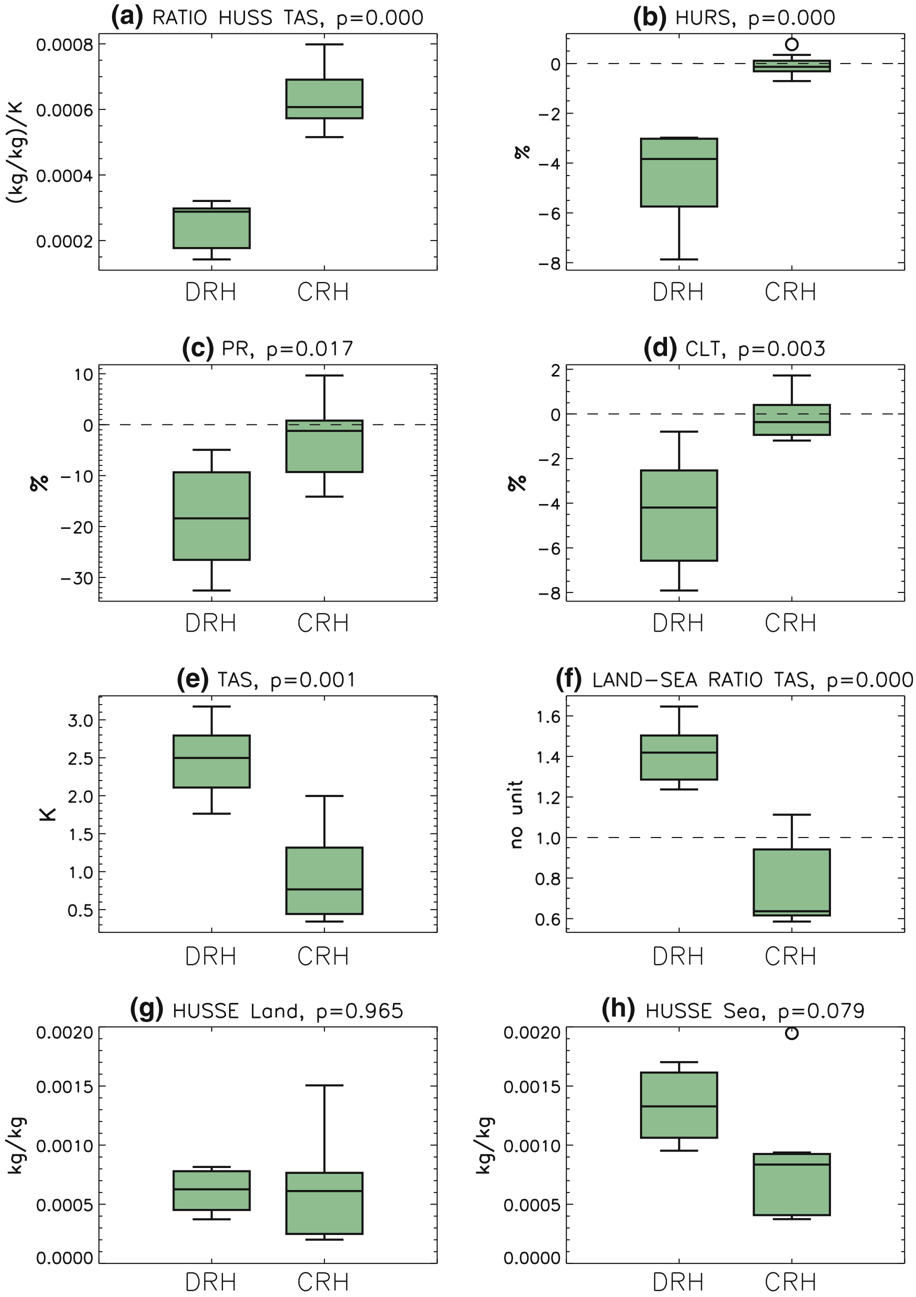

Fig. 7 *Box* and *whiskers* plot of changes in different variables averaged over France for CRH and DRH models. **a** Ratio between specific humidity and temperature changes. **b** Relative humidity. **c** Precipitation. **d** Cloud cover. **e** Temperature. **f** Land–sea warming ratio. **g** Specific humidity over land. **h** Specific humidity over sea (See masks in Fig. 2). The *lines* show the 25th and 75th quartile, and the median of the data. The *whiskers* are defined by the minimum and maximum values in the sample, or by 1.5 times either the 25th and 75th quartile. In that case, values greater than 1.5 times the 25th or 75th quartile are shown with a circle. The *p* value of the *t* test on the difference of the means between DRH and CRH models is given in the title of each graph

humidity and temperature, which is consistent with their behavior in the context of climate change (larger specific humidity to temperature change ratio, Fig. 6). Interesting and less anticipated is the signal of the opposite sign seen over seas, which is significant over a large part of the Mediterranean sea. This signal will be discussed in the next section.

Strong and significant differences in m_{soil} between CRH and DRH models are also noted (Fig. 9b). DRH models exhibit much larger positive present-day correlations between soil moisture and evapotranspiration over a large part of western and central Europe. Therefore, in the present climate, continental evapotranspiration in DRH models tends to be limited by soil moisture. It has been shown that models in which evapotranspiration is limited by soil moisture simulate larger decreases in evapotranspiration in the future climate (Fig. 3c) which should lead to larger temperature change (and potentially smaller specific humidity change over land), what is consistent with the results shown in Fig. 6.

Finally, strong differences in m_{cloud} are also noted (Fig. 9c), with DRH models exhibiting a much larger present-day negative correlation between cloud cover and surface temperature over central and western Europe. Those models tend to simulate a larger decrease in cloud cover in the future climate (Fig. 5), leading to larger increase in

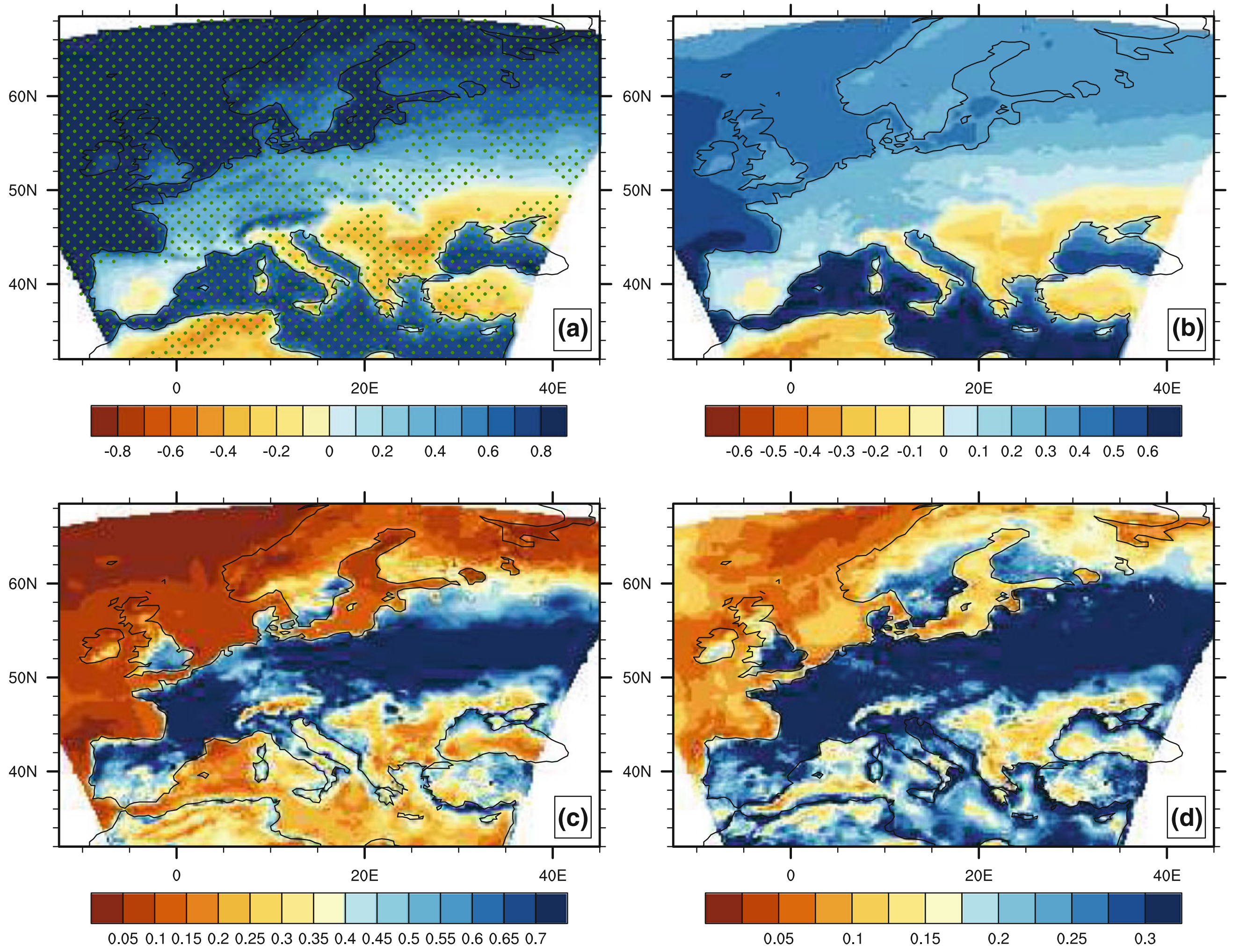

Fig. 8 Present-day interannual correlation between 2 m specific humidity and 2 m temperature: **a** ensemble mean, **c** ensemble spread measured by the interquartile range. Present-day inter-annual regression coefficient between 2 m specific humidity and 2 m temperature, named k_{hum} subsequently (in g/kg K^{-1}): **b** ensemble mean, **d** ensemble spread measured by the interquartile range. Areas where the interannual correlation (negative or positive) is significant with $p < 0.05$ in more than 2/3 of the models are shown with *green points* in (**a**)

temperature and consequently, all else being equal, to the smaller specific humidity to temperature changes ratio over land that are characteristic of DRH models (Fig. 6).

In conclusion, the differential behavior of CRH and DRH models in the future climate could be to a large extent anticipated from their behavior in the context of present-day interannual variability. DRH models tend to simulate stronger soil moisture-atmosphere and cloud-temperature interactions compared to CRH models. The stronger cloud-temperature interaction leads to larger continental surface warming while the stronger limitation of evapotranspiration by soil moisture leads to a larger decrease in evapotranspiration and therefore a larger warming. In the end, a smaller specific humidity to temperature change ratio is simulated by the DRH models over land as well as a larger land–sea warming ratio.

6 Inter-relationships between the different metrics

In the previous sections, three metrics useful to understand and potentially reduce the uncertainties of summer European climate projections have been introduced: m_{soil}, m_{cloud} and k_{hum}. The different metrics are not necessarily independent and can be affected to some extent by the same basic physical mechanisms. Exploring and understanding their inter-relationships is therefore useful to better understand the mechanisms underlying summer European climate change.

The same reasoning explaining the link between m_{soil} and the specific humidity to temperature changes ratio in the future climate proposed in the previous section suggests that m_{soil} and k_{hum} could be related. Figure 10 shows the intermodel correlation between those two quantities. Over

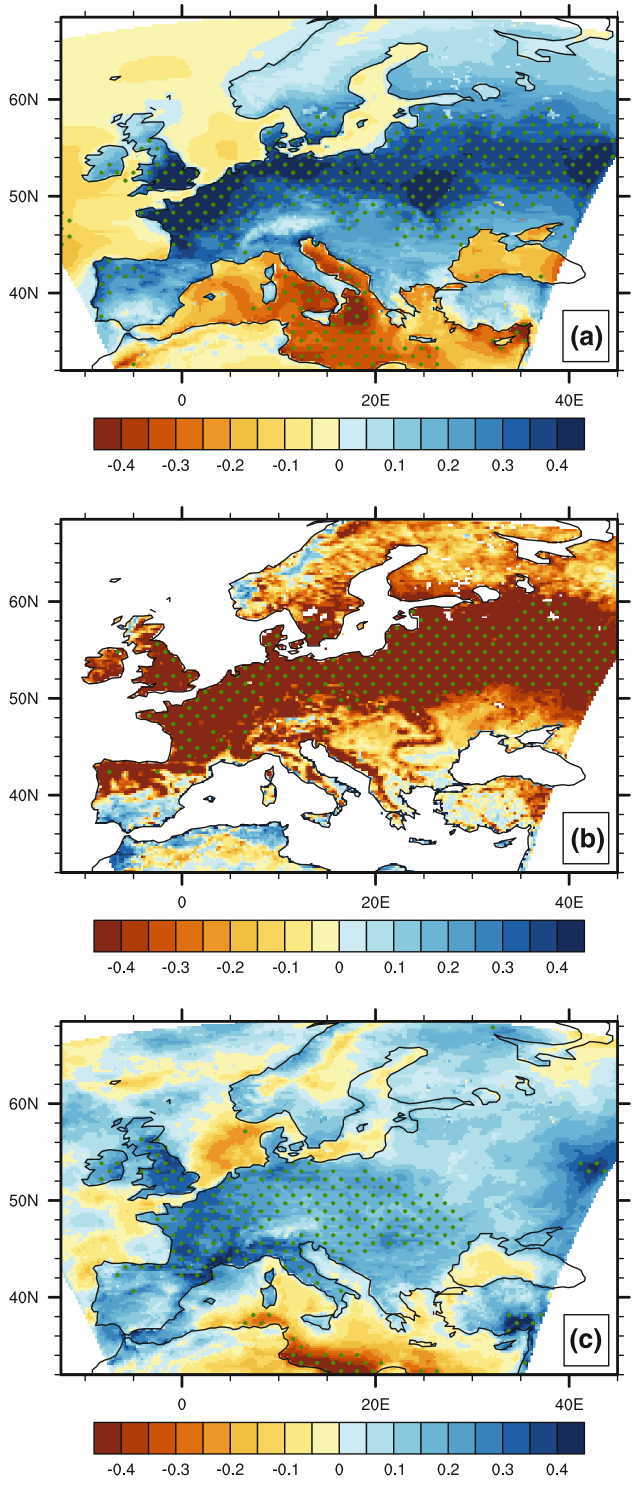

Fig. 9 Composite difference in **a** k_{hum} (in g/kg K^{-1}), **b** m_{soil} (no unit), **c** m_{cloud} (no unit) between CRH and DRH models. *Green points* indicate significance with $p < 0.05$

most central western Europe, a very large negative correlation is found. In the context of present-day interannual variability, models for which evapotranspiration is strongly limited by soil moisture (large m_{soil}) tend to respond to an increase in radiative energy at surface by a smaller increase in evapotranspiration which leads to a larger temperature anomaly, hence a smaller k_{hum}. The co-variability between temperature and specific humidity over land is therefore mostly controlled by soil-atmosphere interactions.

As shown in Fig. 11, a positive intermodel correlation between m_{cloud} averaged over France and k_{hum} exists over most continental Europe, although it is significant mainly over the north of western and eastern Europe. If for a given positive temperature anomaly, specific humidity increases less in a model, a negative anomaly of relative humidity and therefore potentially of cloud cover will tend to result. Therefore, it is not surprising to find a positive correlation between m_{cloud} averaged over land and k_{hum}. However, the fact that even over France where m_{cloud} is averaged for this diagnostic the correlation is seldom significant suggests that other processes are important for the the spread of cloud-temperature interactions over land. It is interesting in that context to note that a high and significant negative correlation coefficient between m_{cloud} averaged over France and k_{hum} over the surrounding ocean is seen, especially over the Mediterranean sea. The larger the specific humidity anomaly over sea for a given temperature anomaly, the stronger the negative correlation between cloud and temperature over land. This is reminiscent of the result shown in Fig. 9a. Indeed, DRH models, that are characterized by stronger cloud-temperature interactions, also exhibit a larger k_{hum} over sea. Together, these results suggest that the relation between specific humidity and temperature over sea could be important for the continental climate, through a modulation of cloud cover.

Note that at first this is somewhat counterintuitive. If a large fraction of atmospheric humidity over land comes from surrounding ocean, a larger increase in specific humidity over sea for a given change in temperature would

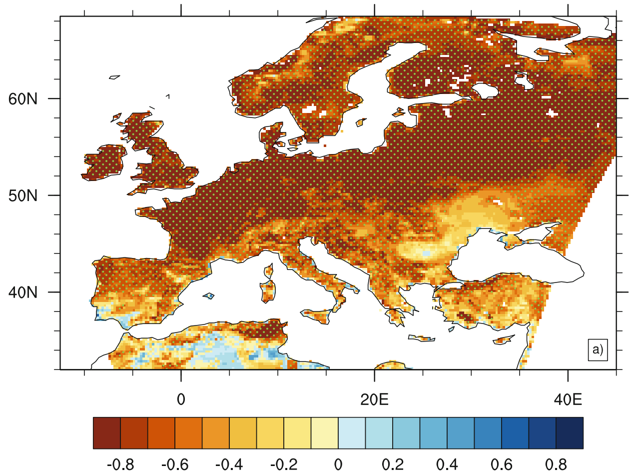

Fig. 10 Inter-model correlation between m_{soil} and k_{hum}. *Green points* indicate significance with $p < 0.05$

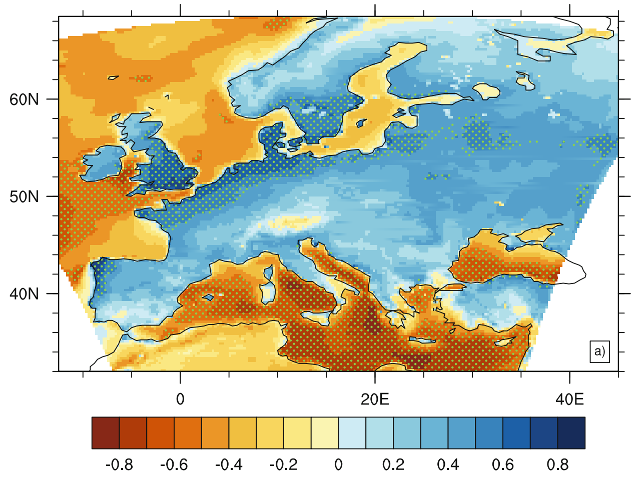

Fig. 11 Inter-model correlation between m_{cloud} averaged over France and k_{hum} at each point. *Green points* indicate significance with $p < 0.05$. Here m_{cloud} is averaged over France in order to highlight non-local relations with k_{hum}

tend to be associated with larger specific humidity change over land and a higher relative humidity, thus potentially enhancing cloud cover, all else being equal. However, the opposite is noted, which is consistent with the fact that k_{hum} over land and k_{hum} over sea are mostly independent (r = 0.04) and that k_{hum} over land is very dependent on soil-atmosphere interactions (Fig. 10).

The relation between k_{hum} over sea and m_{cloud} over land could be linked to the radiative properties of water vapor. Indeed, as water vapor is a greenhouse gas, specific humidity advected over land from ocean also impacts the radiative budget at surface and therefore surface temperature. Depending on the soil state, the impact of larger downwelling radiation at surface could be more or less amplified over land through a modulation of evapotranspiration by soil-moisture for example. Resulting changes in surface temperature could then lead to smaller relative humidity over land, higher LCL and smaller cloud cover. Change in the vertical profile of temperature associated with specific humidity advected from ocean could also impact cloud cover. A question arises here about the potential impact of the experimental set-up. As forced experiments are analyzed, if for the same change in SST the humidity increases more in a model (larger k_{hum} over sea), no feedback on ocean temperature through backward radiation could happen. Yet, after transport, atmospheric humidity coming from ocean could impact land temperature because of its greenhouse effect and enhance the land–sea warming contrast. In a coupled system, surface temperature over oceans could also adjust to larger atmospheric humidity and increased greenhouse effect. It remains to be seen if the forced framework could really lead to substantial differences compared to a coupled ocean-atmosphere framework.

The mechanisms described above are very hypothetical and more work, with dedicated experiments, would be required to better understand the mechanisms behind the link between k_{hum} over sea and m_{cloud} over land. In any case, it appears that the covariability between temperature and cloud over land could be affected by the covariability of specific humidity and temperature over surrounding seas, and that it is important for the model response to anthropogenic forcing over land.

Given the importance of k_{hum} over sea for continental climate change and variability a question that needs to be addressed is then why k_{hum} varies so much over sea between models and in particular over the Mediterranean sea, especially since consistently with the Clausius-Clapeyron relation all models exhibit a large and consistent correlation between temperature and specific humidity there (Fig. 8).

The same explanation from the previous section about the spatial variation of k_{hum} is pertinent here. The change in

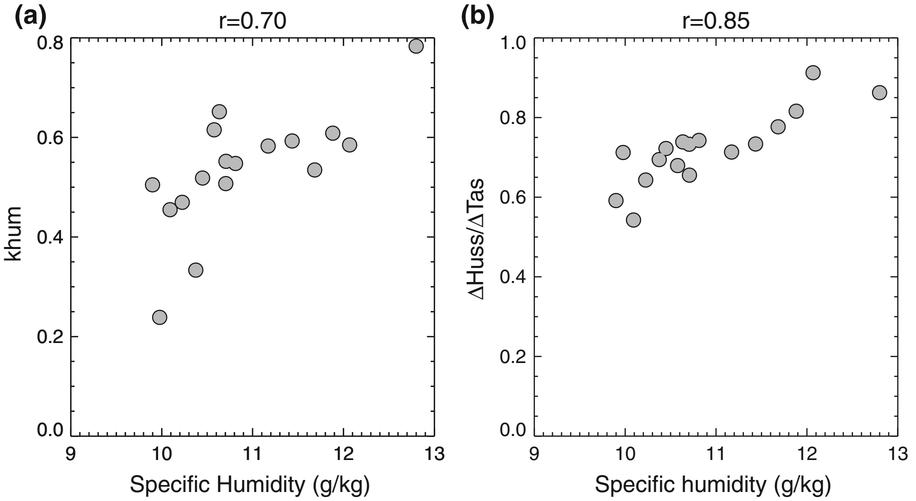

Fig. 12 **a** Scatter plot between the 1961–2000 climatological value of specific humidity over sea and k_{hum} over sea. **b** Scatter plot between the 1961–2000 climatological value of specific humidity (g kg^{-1}) over sea and the future specific humidity to temperature changes ratio over sea (g kg^{-1} K^{-1}). (See masks in Fig. 2). The correlation between k_{hum} and the climatological value of specific humidity is 0.70. The correlation between the specific humidity to temperature change ratio and the climatological value of specific humidity is 0.85

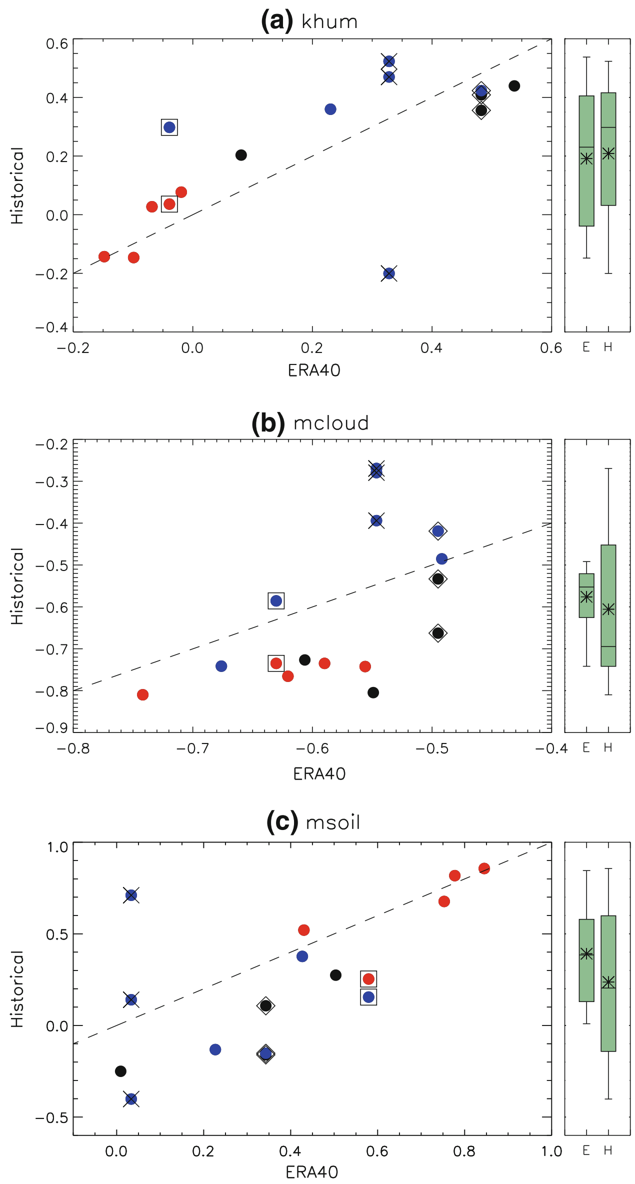

Fig. 13 Scatter plot between the metrics averaged over France in historical RCM simulations and the metrics from the corresponding RCM forced by ERA40 reanalysis. When an RCM has been been forced by n GCMs, the corresponding value from the ERA40-forced simulation is repeated n times. The 1961–1990 period is used. **a** k_{hum}, **b** m_{cloud}, **c** m_{soil}. The corresponding correlations are respectively: 0.67, 0.55, 0.65. DRH models are represented by *red points*, CRH models by *blue points* and other models by *black points*. The RCMs that have been forced by several GCMs are highlighted thanks to a second symbol: (*square*) METNOHIRHAM; (*diamond*) SMHIRCA, (*star*) DMI-HIRHAM5. On the right of each *scatter plot*, a *boxplot* shows the distributions of the metrics from ERA40 simulations (E) and historical simulations (H)

saturation specific humidity for a given change in temperature depends on the climatological value of saturation specific humidity and temperature. Models with higher climatological saturation specific humidity will tend to have a larger absolute increase in saturation specific humidity for a given temperature anomaly. If variations in specific humidity follow the ones of saturation specific humidity as it is generally the case over sea, the same should also be true for specific humidity. It is confirmed by Fig. 12a as a clear link between k_{hum} and climatological humidity over sea is noted. Moreover, Fig. 12b shows that the same mechanism plays in the future climate. The inter-model spread in the specific humidity to temperature change ratio over sea in the future climate closely follows the spread in climatological specific humidity in the present climate.

Finally, to conclude the analysis of the inter-relationships between the metrics we note that the link between cloud-temperature interactions and soil moisture interactions is rather weak. The correlation between m_{cloud} and m_{soil} is indeed not significant (−0.37 over France for example).

The analyses of this section indicate that the three metrics are partially dependent. m_{soil} and k_{hum} over land (France) are essentially two ways of characterizing the same basic physical mechanism, that is the influence of soil moisture on surface temperature (and humidity) through a modulation of evapotranspiration. Somewhat surprisingly maybe, cloud-temperature interactions over land appear to be weakly sensitive to land-atmosphere interactions. They are impacted by surrounding oceans, and in particular by the co-variability between temperature and specific humidity over sea. However, other mechanisms could be important in that context. Large scale forcing, for example by modulating climatological atmospheric humidity over our domain of interest, could impact cloud processes over land. The impact of boundary forcing on the metrics is investigated in the next section.

7 Impact of boundary forcing on the metrics

The different metrics previously studied have been estimated in historical simulations, in which RCMs are forced by historical simulations from different GCMs (see Table 1). These estimations of the metrics are therefore influenced by biases and uncertainties in boundary forcing. To gain a clearer view of the impacts of boundary forcing in the simulation of the different metrics by the RCMs, the metrics are now estimated in control simulations, in which the RCMs were forced by the ERA40 atmospheric reanalysis, and compared to the metrics from historical simulations.

A clear influence of boundary forcing on the metrics averaged over France is noted (Fig. 13). Indeed, if significant statistical relations between the values of the metrics in ERA40 and historical simulations exist, because of the impact of RCM on those metrics, it is far from perfect

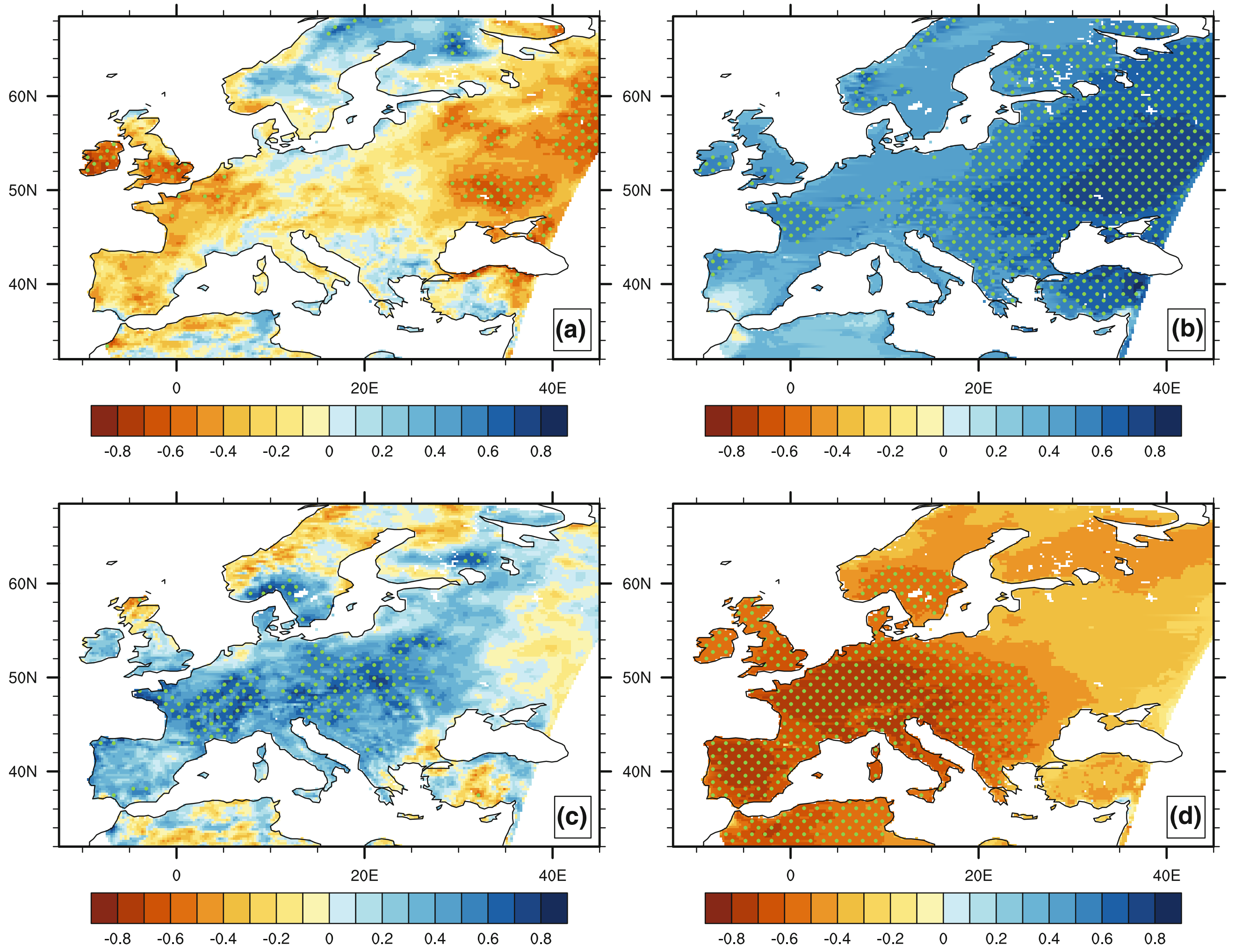

Fig. 14 **a** Inter-model correlation between m_{soil} averaged over France and relative precipitation change at each point. **b** Inter-model correlation between m_{soil} averaged over France and temperature change at each point. **c** Inter-model correlation between m_{cloud} averaged over France and relative precipitation change at each point. **d** Inter-model correlation between m_{cloud} averaged over France and temperature change at each point. *Green points* indicate significance with $p < 0.05$

(Fig. 13). Even if the metrics are associated with local processes, they are still influenced by boundary forcing. For example, an RCM that simulates a value of m_{soil} close to 0 when forced by ERA40, simulates very different values, from −0.4 to 0.7, when it is forced by different GCMs (Fig. 13c). Depending on boundary forcing, evapotranspiration in this RCM can therefore be strongly controlled by soil moisture in one case or controlled by radiative energy at surface in another case. Regarding k_{hum}, the difference in spread between historical and ERA40 simulations is small, suggesting a somewhat moderate role of boundary forcing for this metric (moreover, except for one point, the correlation between the values in historical and ERA40 simulations would be quite good). Conversely, important reductions of the spread in m_{soil} and m_{cloud} in ERA40-forced simulations are noted, as it is especially clear on the boxplots (Fig. 13). Important shifts in the distribution of m_{soil} and m_{cloud} are noted when the RCMs are forced by ERA40 compared to historical simulations. m_{soil} tends to be larger in ERA40 simulations and, interestingly, all the negative values seen in GCM-forced simulations disappear with ERA40 boundary forcing. Forced with more realistic boundary conditions, RCMs tend to better agree on the control of evapotranspiration by soil moisture over France. Interestingly, the climatological cloud cover over France is in average smaller in ERA40-forced simulations compared to GCM-forced simulations (by roughly 6 %, not shown) which could explain to some extent why m_{soil} is in average greater in ERA40-forced simulations. Indeed, Fig. 3d suggested that a control of evapotranspiration by soil moisture over France tends to be favored by smaller climatological cloud cover.

The largest impact of boundary forcing is noted for m_{cloud}, indicating that cloud-temperature interactions over

France are largely influenced the large scale climate state. The distribution of m_{cloud} in historical simulations tends to be skewed towards very negative values, mainly because of DRH models but not only (Fig. 13). It is not the case in ERA40-forced simulations, as the very strong negative correlations between temperature and cloud cover generally disappear when the RCMs are forced by ERA40. The small negative values of m_{cloud} simulated by some RCMs when forced by GCMs also disappear with the ERA40 forcing. This result suggests that the extreme behaviors regarding cloud-temperature interaction seen in some historical RCM simulations could be the result of the biases in the boundary forcing.

Note that given the links between the metrics and future climate change previously described, biases in boundary conditions would tend to lead to an overestimation of cloud decrease (m_{cloud} too negative) but also to an underestimation of the decrease in latent heat flux (m_{soil} too small), with opposite effects on surface warming. Equivalently, ERA40 simulations suggest that the large negative m_{cloud} characteristic of DRH models might not be realistic. Conversely the small m_{soil} and even negative value of m_{soil} seen in several CRH (or neutral) GCM-forced simulations might not be realistic. One has however to be very cautious as it is still possible that compensating errors between RCMs and boundary forcing make the values simulated by GCM-forced RCM more realistic than the ones from ERA40-forced simulations.

8 Discussion and conclusion

In this paper, we defined two groups of models based on how they simulate future change in relative humidity over France. These groups are characterized by very different simulated summer climate changes. We showed that the simulation of some processes (e.g. soil-atmosphere interactions and cloud-temperature interactions, characterized in the paper by m_{soil} and m_{cloud}, respectively) in the context of present-day variability are also largely different in the two groups of models. This suggests that m_{soil} and m_{cloud} could lead to useful metrics for future summer European climate changes. Before concluding, we test whether links exist between the representation of those metrics in the present climate and future changes of important impact-related variables. Figure 14 shows the intermodel correlations between m_{soil} and m_{cloud} averaged over France and temperature and precipitation change over Europe.

The sign of the correlations between the metrics and temperature an precipitation change are consistent with the physical mechanisms described in the previous sections. Over western Europe, m_{cloud} averaged over France is highly and significantly negatively correlated with future temperature change (with r often smaller than -0.7). Significant positive correlations at the 0.05 level are also found for precipitation changes over most of France and large parts of central Europe. Despite being averaged over France, the highest correlations between averaged m_{soil} and temperature change are obtained over eastern Europe and especially Russia and Ukraine (r as high as 0.7). Over France, correlations are often not significant at the 0.05 level (but they are significant at the 0.10 level, not shown). Regarding precipitation changes, significant correlations with m_{soil} averaged over France are also seen over Eastern Europe, Ireland, and southern England.

In that context, one should note that it is expected that a part of the spread in European climate change analyzed here is due to internal variability. This question cannot be tackled with the ENSEMBLES RCM dataset, as only one member of each simulation is generally available. Some work done with CMIP5 models by Terray and Boé (2013) shows that, regarding the middle of twenty first century, for example over France, uncertainties due to internal variability are roughly half the uncertainties due to models for temperature change in summer and almost identical for summer precipitation change. It would therefore be impossible even for a perfect metric, if such a thing could exist, to explain all of the spread shown in Fig. 1.

In this paper, the high-resolution regional projections from the ENSEMBLES project over Europe have been studied with the objective to better understand the causes of the large inter-model spread in simulated climate change during summer. Important model-to-model differences in the simulation of several processes have been found in the context of present-day interannual variability (soil-atmosphere interactions, cloud-temperature interactions and the co-variability between specific humidity and temperature). The climate change signals simulated by the models are generally consistent with the way those processes are simulated in the present climate. Indeed, models characterized by a limitation of evapotranspiration by soil moisture in the context of interannual variability (large m_{soil}) tend to simulate larger evapotranspiration decreases and consequently larger surface warming. Models with a large present-day interannual anti-correlation between cloud cover and temperature (m_{cloud}) tend to simulate a larger decrease in cloud cover and therefore a larger surface warming. As a result, specific humidity changes over land cannot keep pace with changes in specific humidity at saturation (controlled by land temperature change) in models with large positive m_{soil} and large negative m_{cloud}. Those models are therefore characterized by a decrease in relative humidity, precipitation and larger land–sea warming ratio. The models characterized by a small m_{soil} and a small negative m_{cloud} tend to simulate no change in relative humidity over France and greater warming surrounding oceans than over France. Those results show that land–sea warming contrast, soil-atmosphere interactions and cloud-temperature interactions are not independent.

The large spread in evapotranspiration controls over Europe has been found to be associated to some extent with the climatological cloud cover and therefore incoming solar radiation at surface. The large spread in cloud-temperature interactions has been found to be somewhat associated with the co-variability between specific humidity and temperature (k_{hum}) over seas. Even if an hypothesis has been proposed, some progresses remain to been made on the understanding of the exact physical mechanisms responsible for this relationship. The climatological specific humidity has been shown to play an important role in the spread of k_{hum} over sea because of the non-linearity of the Clausius-Clapeyron relationship.

Several properties of the ENSEMBLES RCMs in the present climate are therefore strongly linked because of plausible physical mechanisms to the changes in important impact-related variables as precipitation and temperature.

We analyzed RCM simulations, that are forced at the boundaries by definition, and for which no coupling with the ocean exists. One could wonder whether the potential inconsistencies between the boundary forcing and the internal dynamic and thermodynamic of the RCM, and the absence of ocean feedback could impact the simulation of the key processes and make our conclusion on the metrics framework-dependent. Preliminary analyses of CMIP5 models, some of them shown in Terray and Boé (2013), suggest that it is not the case: a large spread also exists in m_{cloud} as simulated by CMIP5 GCMs, with also an important impact for future temperature change over France.

A second limitation of our study is that it only deals with a subset of the processes that could play on summer European climate change. For example, it does not deal with the role of changes in large scale circulation (which had been explored by previous studies: e.g. Rowell and Jones 2006; Boé et al. 2009; Cattiaux et al. 2013). Therefore, it should not be concluded from this study that no other important mechanism for summer European climate change exists.

The information provided by the metrics described in this paper, together with some observational estimates, have the potential to help reducing the uncertainties in regional climate projections over Europe during summer. However some crucial questions have first to be addressed to show that it can be done in practice: what are the uncertainties on the observational estimates of the metrics? What is the impact of internal variability on the simulated and observed metrics? What is the best statistical approach to combine the information from the different metrics in the presence of observational errors and internal variability, with a limited sample of models? Those questions will be the object of a future study.

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References

Boberg F, Christensen JH (2012) Overestimation of Mediterranean summer temperature projections due to model deficiencies. Nat Clim Change 2:433–436

Boé J, Terray L (2008) Uncertainties in summer evapotranspiration changes over Europe and implications for regional climate change. Geophys Res Lett 35:L05702

Boé J, Terray L, Cassou C, Najac J (2009) Uncertainties in European summer precipitation changes: role of large scale circulation. Clim Dyn 33(2–3):265–276

Cattiaux J, Douville H, Peings Y (2013) European temperatures in CMIP5: origins of present-day biases and future uncertainties. Clim Dyn (published online). doi:10.1007/s00382-013-1731-y

Déqué M, Somot S, Sanchez-Gomez E, Goodess CM, Jacob D, Lenderink G, Christensen OB (2012) The spread amongst ENSEMBLES regional scenarios: regional climate models, driving general circulation models and interannual variability. Clim Dyn 38:951–964

Deser C, Phillips A, Bourdette V, and Teng H (2012) Uncertainty in climate change projections: the role of internal variability. Clim Dyn 38(3–4):527–546

Giorgi F (2006) Climate change hot-spots, Geophys Res Lett 33:L08707

Giorgi F, Mearns LO (2002) Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the reliability ensemble averaging (REA) method. J Climate 15:1141–1158

Fasullo JT (2010) Robust land–ocean contrasts in energy and water cycle feedbacks. J Climate 23:4677–4693

Fischer EM, Rajczak J, Schär C (2012) Changes in European summer temperature variability revisited. Geophys Res Lett 39:L19702

Hall A, Qu X (2006) Using the current seasonal cycle to constrain snow albedo feedback in future climate change. Geophys Res Let 33:L03502

Hawkins E, Sutton RT (2009) The potential to narrow uncertainty in regional climate predictions. Bull Am Meteorol Soc 90(8): 1095–1107

Hewitt CD (2004) Ensembles-based predictions of climate changes and their impacts. Eos Trans AGU 85(52):566

Joshi MM, Gregory JM, Webb MJ, Sexton DMH, Johns TC (2008) Mechanisms for the land–sea warming contrast exhibited by simulations of climate change. Clim Dyn 30:455–465

Kendon EJ, Rowell DP, Jones RG, Buonomo E (2008) Robustness of future changes in local precipitation extremes. J Climate 21:4280–4297

Lenderink G, van Ulden A, van den Hurk B, van Meijgaard E (2007) Summertime inter-annual temperature variability in an ensemble of regional model simulations: analysis of the surface energy budget. Clim Change 81:233–247 van der Linden P, Mitchell JFB (eds.) (2009) ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK, 160 pp

Manabe S, Spelman MJ, Stouffer RJ (1992) Transient response of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part II. Seasonal response. J Climate 5:105–126

Meehl GA et al (2007) Global climate projections. In: Climate change 2007: the physical science basis, in climate change 2007: the physical science basis. In: Solomon S et al (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Rowell DP, Jones RG (2006) Causes and uncertainty of future summer drying over Europe. Clim Dyn 27(2–3):281–299

Seneviratne SI, Lüthi D, Litschi M, Schär C (2006) Land-atmosphere coupling and climate change in Europe. Nature 443:205–209

Soden BJ, Held IM (2006) An assessment of climate feedbacks in coupled ocean-atmosphere models. J Climate 19:3354–3360

Sutton RT, Dong B, Gregory JM (2007) Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations. Geophys Res Lett 34:L02701

Tang Q, Leng G, Groisman PY (2012) European hot summers associated with a reduction of cloudiness. J Climate 25:3637–3644

Terray L, Boé J (2013) Quantifying 21st-century France climate change and related uncertainties. C R Geosci 345:136–149

Uppala SM et al. (2005) The ERA-40 re-analysis. Q J R Meteorol Soc 131:2961–3012

Weigel AP, Knutti R, Liniger MA, Appenzeller C (2010) Risks of model weighting in multimodel climate projections. J Climate 23:4175–4191