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Uncertainties in summer evapotranspiration changes over Europe and implications for regional climate change

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[1] Changes in summer evapotranspiration over central and eastern Europe are very uncertain in the World Climate Research Programme's (WRCP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set. We show that the response of evapotranspiration in the future climate over this area is strongly linked to the way the models represent the respective role of soil moisture and radiative energy at surface on evapotranspiration at the interannual time scale in the present climate. Actually, the models for which the limiting effect of soil moisture upon evapotranspiration is already large in the present climate generally responds by a decrease of evapotranspiration whereas the other models generally exhibit an increase of evapotranspiration. The uncertainties in evapotranspiration changes seem to have an important impact in precipitation and temperature changes. Finally, we assess the realism of the controls of evapotranspiration in the CMIP3 models over France using a hydro-meteorological simulation.
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1. Introduction

[2] The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) has confirmed that the climate of central and southern Europe may undergo very serious human-induced changes during summer [*Christensen et al.*, 2007], characterized by a large decrease of precipitation and increase of temperature. However, a large intermodel spread exists and major uncertainties remain regarding the amplitude of these changes. Given the serious potential socioeconomic and health impacts of these changes, it is critical to better assess the changes in European summer climate and to understand the associated uncertainties.

[3] As a first step, a better understanding of the physical origin of the uncertainties of regional climate changes during summer over Europe is needed. As a second step, an evaluation of model skill in representing key physical processes should be undertaken. This kind of approach has been successfully applied in different contexts for example by *Douville et al.* [2006], *Hall and Qu* [2006], and *Hall et al.* [2008].

[4] Land-atmosphere interactions may play an important role in climate changes over Europe during summer [*Seneviratne et al.*, 2006; *Rowell and Jones*, 2006], in particular in the central and eastern part of the continent. If the moisture available at the surface is sufficient, the energy used for evapotranspiration may avoid or limit an increase of the sensible heat flux and temperature in response to an increase of the radiative energy reaching the surface. Moreover, direct or indirect soil moisture-rainfall feedbacks [*Schär et al.*, 1999] may have an impact on precipitations changes. These different mechanisms involve changes in evapotranspiration, and the study of this variable might thus be critical to better understand the regional climate changes over Europe.

[5] The latitude band roughly between 40° N and 60° N (central and eastern Europe, France, south of United Kingdom) can be thought as a transitional climatic zone (henceforth TCZ) separating the dry soil conditions of the Mediterranean area and the wet soil conditions of northern Europe. In this paper, we show using the CMIP3 multi-model data set that during summer the large spread in evapotranspiration changes over the TCZ may be traced to a large extent to the way the models simulate the key mechanisms controlling evapotranspiration in the present climate. A part of the spread in temperature and precipitation changes may also result from it. To finish, we try to evaluate the skill of the models in simulating the key controls of evapotranspiration in the present climate.

2. Results

2.1. Changes in Evapotranspiration

[6] We analyse two sets of coupled climate model integration from the CMIP3 multi-model data set archive [*Meehl et al.*, 2007], realized in the context of the IPCC AR4. The first set ("20c3m") are 20th century climate simulations whereas the second set ("sreasa1b") uses the SRES-A1B emission scenario.

[7] Multi-model changes in evapotranspiration over Europe are depicted in Figure 1. Generally, the evapotranspiration increases in the north of the continent and decreases in southern Europe. The decrease of evapotranspiration is large in the Iberian peninsula, Greece, and the north of the Turkey. Interestingly, these areas are also those where the increase of temperature is the greatest in summer as shown in the IPCC AR4 [*Christensen et al.*, 2007].

[8] The intermodel standard deviation of evapotranspiration changes is very large over the TCZ, in particular over France, the Balkans and Ukraine (Figure 1 (bottom)). Over these areas, even the sign of the changes of evapotranspiration is not coherent among the different models.

2.2. Controls of Evapotranspiration Variability in Present Climate

[9] The evapotranspiration is linked both to the surface energy and water budgets. Consequently, both the availabil-

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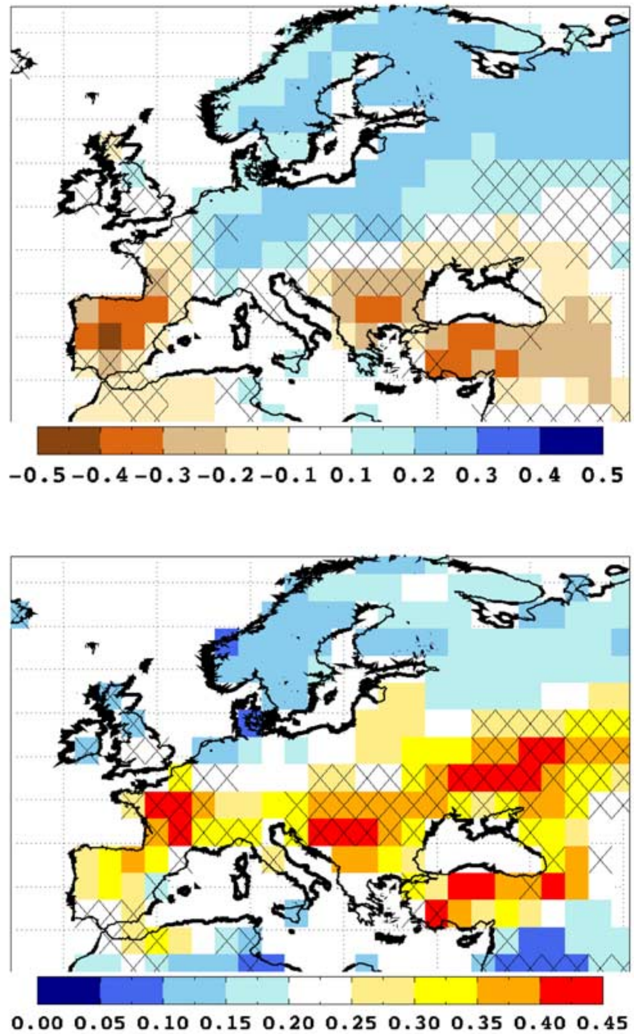

Figure 1. (top) Multi-model change in mean summer evapotranspiration (mm/day) over Europe between 2079–2099 and 1961–1990 for the SRES-A1B scenario. (bottom) Intermodel standard deviation (mm/day). The crosses indicate the grid points where less than 70% of the models give a change of the same sign. Given the availability of the necessary variables, the models considered in this study are BCCR-BCM2.0, CGCM3.1(T47), CGCM3.1(T63), CNRM-CM3, CSIRO-Mk3.0, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, FGOALS-g1.0, INM-CM3.0, IPSL-CM4, MIROC3.2(hires), MIROC3.2(medres), ECHO-G, ECHAM5/MPI-OM, MRI-CGCM2.3.2, CCSM3, and PCM.

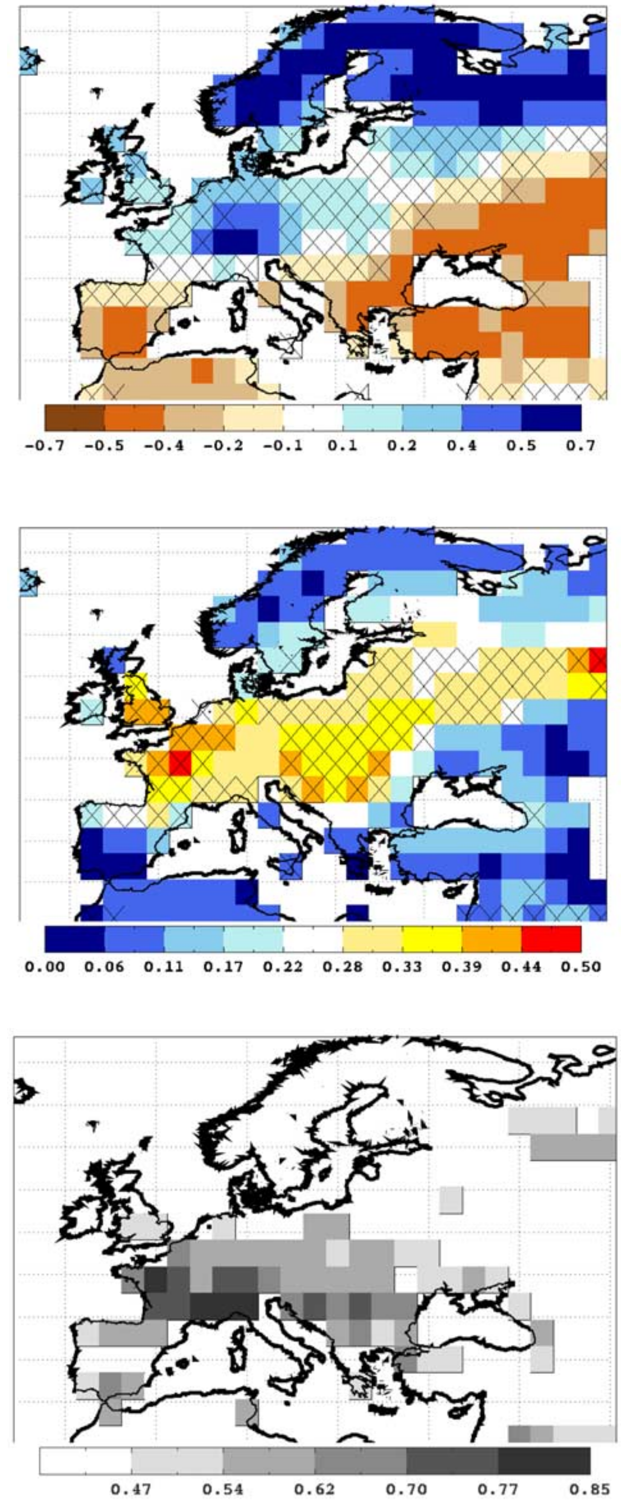

Figure 2 Interannual correlation (ρ_{ef}) between the total (solar and thermal) downwelling radiation flux at surface and evapotranspiration during summer for the 1970–2000 period: (top) multi-model ensemble mean and (middle) intermodel standard deviation. The crosses indicate the grid points where less than 70% of the models give a correlation coefficient of the same sign. (bottom) Correlation between ρ_{ef} and the changes of evapotranspiration in the 18 CMIP3 models. Only the grid points where the correlation is significant at the 0.05 level are shown.

ity of energy at the surface (provided by downwelling longwave and shortwave fluxes) and the availability of moisture in the soil may thus limit and/or control the actual evapotranspiration. Here, we test how the CMIP3 models compare regarding these two potential controls of the interannual variability of evapotranspiration in summer. As the soil moisture is not available for all the CMIP3 models, we focus on downwelling radiation fluxes. The interannual correlation (henceforth ρ_{ef}) between the total (solar and thermal) downwelling radiation flux at the surface (henceforth DRF) and the evapotranspiration during

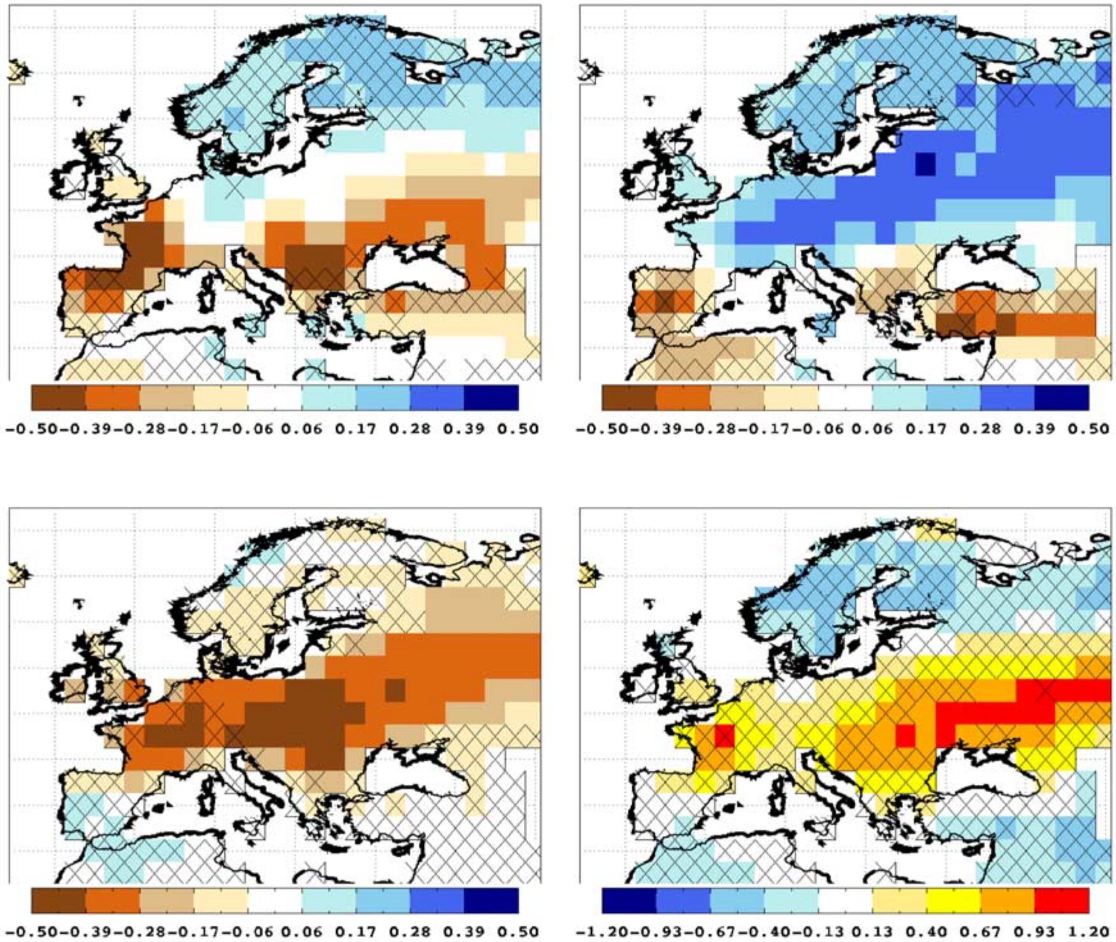

Figure 3. (top) Composite of the changes in evapotranspiration (mm/day) in summer between 2079–2099 and 1961–1990 for (left) Group A (8 models) and (right) Group B (10 models). (bottom) Differences of the composite of the changes in (left) precipitation (mm/day) and (right) temperature over the same period between Group A and Group B. The crosses indicate the grid points where the difference of mean between Group A and Group B is not significant at the 0.1 level (t-test).

summer in the 1970–2000 period is computed for the 18 CMIP3 models (Figure 2).

[10] The multimodel average of ρ_{ef} is strongly positive over northern Europe and negative over southern Europe. The intermodel standard deviation is weak over these areas. In northern Europe, as the availability of moisture in the soil is large, the evapotranspiration is strongly linked to the availability of energy. The negative values seen in southern Europe, that correspond to summers with high values of radiative energy available at the surface but low evapotranspiration, indicate a strong limiting role of soil moisture.

[11] Between northern Europe with a DRF-controlled evapotranspiration and southern Europe with a soil-moisture-controlled evapotranspiration, there is actually a transitional zone (previously named TCZ), where the intermodel standard deviation of ρ_{ef} is strong and where even the sign of ρ_{ef} is not well defined in the CMIP3 multimodel (except for the Alps, which is not surprising). Indeed, the latitude where ρ_{ef} changes of sign varies among the different CMIP3 models. This may result from biases in soil moisture, linked to biases in atmospheric variables like precipitation and/or from intrinsic structural differences of the surface schemes.

2.3. Links With Regional Climate Change

[12] The area where the intermodel spread of ρ_{ef} is strong is similar to the area where a large intermodel standard deviation of evapotranspiration changes is seen. To further study the link between these two quantities, the correlation between the value of ρ_{ef} in the present climate and the change in evapotranspiration simulated by the 18 models is computed at each grid point (Figure 2 (bottom)).

[13] Over France and central Europe a strong link generally exists between the changes in evapotranspiration and the value of ρ_{ef} in the present climate. In particular, over a large part of France, the correlation is about 0.8. The area with significant correlations roughly corresponds to the TCZ, except for the eastern part of Europe. In all the models, DRF increases over continental Europe in the climate scenario, due to a strong increase of the downwelling solar radiation (not shown). The models for which the limiting effect of soil moisture upon evapotranspiration is already large in the present climate (negative ρ_{ef}) generally responds by a decrease of evapotranspiration whereas the other models generally simulate an increase of evapotranspiration. However, it must not be forgotten that the value of ρ_{ef} may also evolve between future and present climate.

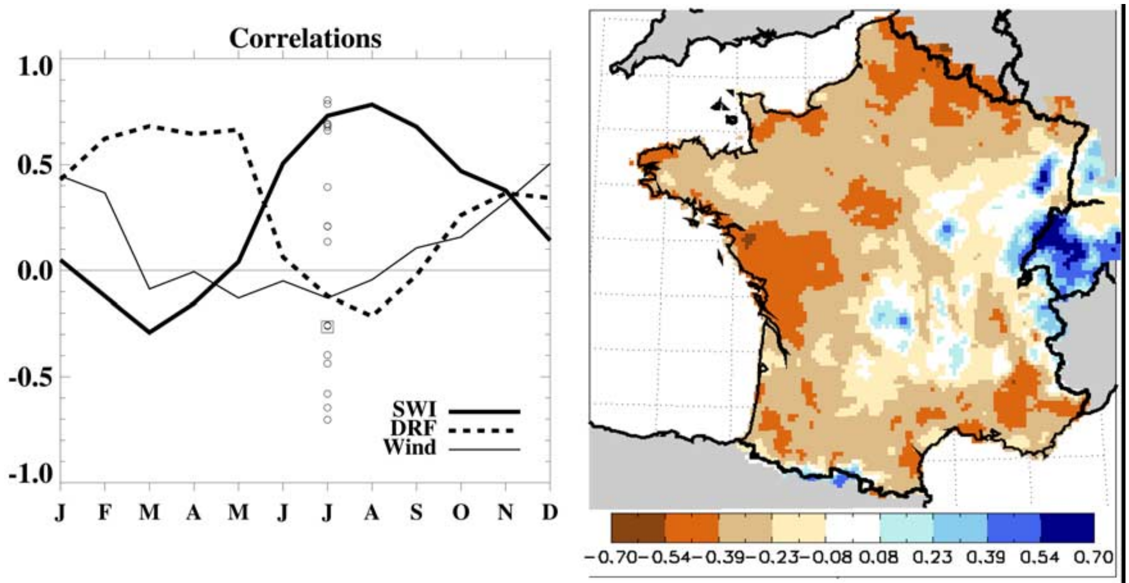

Figure 4. (left) Area-averaged interannual monthly correlations between evapotranspiration and wind speed, DRF, and SWI (see text for details) for the 1970–2000 period from SIM. The points give the correlation between DRF and evapotranspiration for summer (JJA) in the CMIP3 models (circle) and in SIM (square). (right) Interannual correlation (ρ_{ef}) between DRF and evapotranspiration from SIM during summer for the 1970–2000 period.

Indeed, the multi-model mean of ρ_{ef} actually decreases over France and central Europe (not shown).

[14] The 18 CMIP3 models are now partitioned in two groups, according to the sign of ρ_{ef} in the present climate. Group B (A) includes the models for which ρ_{ef} is positive (negative) in average over France. France is chosen here as it is the area where the link between ρ_{ef} and evapotranspiration changes is the greatest (Figure 2).

[15] First the composites of evapotranspiration changes for the two groups are computed (Figure 3 (top)). The models of Group A simulate a strong decrease of evapotranspiration over France and more generally over the south of central and eastern Europe whereas the models of Group B simulate an increase of evapotranspiration over these areas. The differences of evapotranspiration changes between the two groups are significant over the TCZ but not over southern and northern Europe.

[16] Precipitation decreases much more (0.40 mm/day) over France and central Europe in Group A and the increase of temperature is greater (around 1 K) (Figure 3 (bottom)). For precipitation, the differences between the two groups are significant over most of the TZC. It is not the case for temperature. The differences between the two groups are important: to give an order of magnitude, the intermodel standard deviation of precipitation (temperature) changes of the 18 models ensemble is around 0.40 mm/day (1.25 K) over France.

[17] Even if the causality between the difference of representation of the controls of evapotranspiration in the present climate and the response in precipitation and temperature in the future climate cannot be strictly affirmed, it is physically plausible given the dominant processes of land-atmosphere interactions.

2.4. Skill of the CMIP3 Models

[18] Given the link between ρ_{ef} in the present climate and the regional climate changes over the TCZ, the knowledge of the value of ρ_{ef} "in the real world" would be very useful to evaluate the results of the different models.

[19] Consequently, we estimate the value of ρ_{ef} over France using the SAFRAN-ISBA-MODCOU (SIM) hydro-meteorological system [*Habets et al.*, 2007] forced by the meteorological variables from a mesoscale atmospheric analysis in the period 1970–2000 (SAFRAN data set [*Quintana Seguí et al.*, 2008]). SIM thus provides an estimate of evapotranspiration over France, based on weather observations and constrained by known physical principles. Moreover, the comparison of simulated and observed river flows allows to partially validate the water budget of SIM [*Habets et al.*, 2007] and thus to have a relative confidence in the simulated evapotranspiration.

[20] The evapotranspiration and soil moisture simulated by SIM and the DRF and the wind from the SAFRAN forcing data set are used to analyse the different controls of evapotranspiration over France. The interannual monthly correlations between evapotranspiration and wind speed, DRF and the Soil Moisture Index (SWI, following the equation SWI = $(w_{tot}-w_{wilt})/(w_{fc}-w_{wilt})$ where w_{tot} is the volumetric water content of the soil column, w_{fc} the field capacity and w_{wilt} the wilting point) are computed (Figure 4).

[21] During winter and spring, in average over France, the evapotranspiration is mainly controlled by DRF, but at the end of spring, the correlation of DRF with evapotranspiration falls and becomes negative during summer. In parallel, the correlation of evapotranspiration with soil moisture becomes strongly positive (correlation around 0.8 in August). The wind plays a role on evapotranspiration mainly limited to the end of autumn and winter. The mean value of ρ_{ef} over France for the summer season is -0.26. The mean value for the CMIP3 models is 0.10, and the spread is very large as shown in Figure 4. For example, ρ_{ef} is greater than 0.6 in six models. It suggests that the CMIP3 multimodel might actually underestimate the decrease of

evapotranspiration and precipitation and the increase of temperature over the TCZ.

[22] Note that there is a spatial variability of ρ_{ef}. Over the main mountainous massifs of France (Alps, Pyrenees, Central Massif) the correlation between DRF and evapotranspiration from SIM generally remains positive during summer (Figure 4 (right)). Indeed, the soil moisture is rather high over the mountainous massifs during summer due to snowmelt in spring. The CMIP3 multi-model ensemble mean is in agreement with SIM over the Alps (Figure 2). Elsewhere, the correlation from SIM is negative, contrary to the CMIP3 multi-model ensemble mean.

[23] Our estimation of the value of ρ_{ef} relies on the ability of the SIM system to correctly simulate the evapotranspiration. To go further, we use data from the Global Soil Wetness Project 2 (GSWP 2) [*Dirmeyer et al.*, 2006] that provides a multi-model estimation of evapotranspiration in the 1986–1995 period. The interannual correlation between the GSWP2 and SIM mean evapotranspiration over France in summer is around 0.80. This result reinforces our confidence in the evapotranspiration simulated by SIM.

2.5. Summary and Discussion

[24] Evidence has been presented supporting the idea that the changes in evapotranspiration over France and central Europe in the CMIP3 models during summer are linked to the way that these models represent the respective role of soil moisture and radiative energy at the surface on evapotranspiration. It may explain a substantial part of the spread in temperature and precipitation 21st century changes.

[25] Using an hydrometeorological model over France to estimate the observed evapotranspiration we suggest that the CMIP3 multimodel mean may underestimate the decrease of precipitation and increase temperature over the TCZ.

[26] The results of this study stress the necessity of a better monitoring of continental water and energy budgets and the usefulness of model intercomparison projects concerning land-atmosphere interaction like the Global Land-Atmosphere Coupling Experiment (GLACE) projects [*The GLACE Team*, 2004].

[27] However, other mechanisms may also be important in European summer climate change, in particular changes in the large scale circulation, which will be the object of a future study.

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References

Christensen, J. H., et al. (2007), Regional climate projections, in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 847–940, Cambridge Univ. Press, Cambridge, U. K.

Dirmeyer, P. A., X. Gao, M. Zhao, Z. Guo, T. Oki, and N. Hanasaki (2006), Multimodel analysis and implications for our perception of the land surface, *Bull. Am. Meteorol. Soc.*, *87*, 1381–1397, doi:10.1175/BAMS-87-10-1381.

Douville, H., D. Salas-Mélia, and S. Tyteca (2006), On the tropical origin of uncertainties in the global land precipitation response to global warming, *Clim. Dyn.*, *26*, 367–385, doi:10.1007/s00382-005-0088-2.

Habets, F., et al. (2007), The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France, *J. Geophys. Res.*, doi:10.1029/2007JD008548, in press.

Hall, A., and X. Qu (2006), Using the current seasonal cycle to constrain snow albedo feedback in future climate change, *Geophys. Res. Lett.*, *33*, L03502, doi:10.1029/2005GL025127.

Hall, A., X. Qu, and J. D. Neelin (2008), Improving predictions of summer climate change in the United States, *Geophys. Res. Lett.*, *35*, L01702, doi:10.1029/2007GL032012.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor (2007), The WCRP CMIP3 multimodel dataset: A new era in climate change research, *Bull. Am. Meteorol. Soc.*, *88*, 1383–1394, doi:10.1175/BAMS-88-9-1383.

Quintana Seguí, P., P. Le Moigne, Y. Durand, E. Martin, F. Habets, M. Baillon, C. Canellas, L. Franchisteguy, and S. Morel (2008), Analysis of near surface atmospheric variables: Validation of the SAFRAN analysis over France, *J. Appl. Meteorol. Climatol*, in press.

Rowell, D. P., and R. G. Jones (2006), Causes and uncertainty of future summer drying over Europe, *Clim. Dyn.*, *27*, 281–299, doi:10.1007/s00382-006-0125-9.

Schär, C., D. Lüthi, and U. Beyerle (1999), The soil-precipitation feedback: A process study with a regional climate model, *J. Clim.*, *12*, 722–741.

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

The GLACE Team (2004), Regions of strong coupling between soil moisture and precipitation, *Science*, *305*, 1138–1140, doi:10.1126/science.1100217.

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