Clim. Past Discuss., 8, 1301–1318, 2012
www.clim-past-discuss.net/8/1301/2012/
doi:10.5194/cpd-8-1301-2012
© Author(s) 2012. CC Attribution 3.0 License.

Climate of the Past Discussions

This discussion paper is/has been under review for the journal Climate of the Past (CP). Please refer to the corresponding final paper in CP if available.

Mechanisms for European summer temperature response to solar forcing over the last millennium

D. Swingedouw[1], **L. Terray**[2], **J. Servonnat**[1], **and J. Guiot**[3]

[1]Laboratoire des Sciences du Climat et de l'Environnement, IPSL-CEA-CNRS-UVSQ – UMR8212, Centre d'Etudes de Saclay, Orme des Merisiers bat. 701, 91191 Gif Sur Yvette, France
[2]CERFACS, 42 Ave. G. Coriolis, Toulouse, France
[3]CEREGE, Aix-en-Provence, France

Received: 28 March 2012 – Accepted: 10 April 2012 – Published: 18 April 2012

Correspondence to: D. Swingedouw (didier.swingedouw@lsce.ipsl.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A simulation of the last millennium is compared to a recent spatio-temporal reconstruction of summer temperature over Europe. The focus is on the response to solar forcing over the pre-industrial era. Although the correlation between solar forcing and the reconstruction remains small, the spatial regression over solar forcing shows statistically significant regions. The meridional pattern of this regression is found to be similar in the model and in the reconstruction. This pattern exhibits a large warming over Northern and Mediterranean Europe and a lesser amplitude response over Central Europe. The mechanisms explaining this pattern in the simulation are mainly related to evapotranspiration fluxes. It is shown that the evapotranspiration is larger in summer over Central Europe when solar forcing increases, while it decreases over the Mediterranean area. The explanation for the evapotranspiration increase over Central Europe is found in the increase of winter precipitation there, leading to a soil moisture increase in spring. As a consequence, the evapotranspiration is larger in summer, which leads to an increase in cloud cover over this region, reducing the surface shortwave flux there and leading to less warming. Over the Mediterranean area, the surface shortwave flux increases with solar forcing, the soil becomes dryer and the evapotranspiration is reduced in summer leading to a larger increase in temperature. This effect appears to be overestimated in the model as compared to the reconstruction. Finally, the warming of Northern Europe is related to the albedo feedback due to sea-ice cover retreat with increasing solar forcing. These results show that the last millennium can be useful to evaluate the sensitivity of climate models to radiative forcing changes, using spatio-temporal reconstruction of climate.

1 Introduction

According to the IPCC-AR4 (Christensen et al., 2007), the response of summer temperature over Europe to a change in radiative forcing is anisotropic even for an isotropic

CPD
8, 1301–1318, 2012

forcing. In particular, the largest warming in summer is likely to occur in the Mediterranean area in climate projections of the coming century.

This large increase in temperature over this region has been related to a land-atmosphere positive feedback: in relatively dry regions, an increase in surface temperature decreases the soil moisture reservoir so that the evapotranspiration is partly replaced by sensible heat flux that warms the soil in place of the cooling associated with the latent heat flux from evapotranspiration (Seneviratne et al., 2006; D'Andrea et al., 2006). Under global warming, this mechanism leads to the existence of a transitional zone over Europe, located between 40 and 60° N, where the moisture availability allows to avoid the inception of the positive feedback (Boé and Terray, 2008). Nevertheless, there is a very large spread among the models concerning the location of this zone, illustrating the sensitivity of this mechanism to climate models parametrisation and the necessity to constrain them through observations. Evapotranspiration is a actually the key variable that control this transition zone. This is a complex flux that couples both the energy and water budget of the soil.

The uncertainty for the summer evapotranspiration response of models participating to IPCC-AR4 necessitates to evaluate their sensitivity to change in radiative forcing for past periods over sufficiently long time scale. Using reconstruction of the last few decades is a possibility, but analysing longer time scale will certainly help to filter out the signature of internal climate variability. The last millennium, with well documented variations in solar forcing (although uncertainties remains concerning its amplitude) appears to be an interesting candidate. Hunt (2006) actually shows that climate variability over this period could not be explained only by the internal variability of a climate model, but needs external forcing. Hegerl et al. (2011) confirm the importance of external forcing for the temperature variability over Europe for the last 500 yr. They also show that these forcings are mainly detectable in winter and less in summer. Moreover, they question the detectability of solar forcing in summer over this 500-yr time frame.

In this study we propose to evaluate the summer temperature response of a particular climate model to low frequency solar variations during the last millennium and compare it to a new reconstruction of summer temperature over Europe for this millennium time frame.

2 Experimental design

We analyse a simulation of the last millennium using the CNRM-CM3 coupled model (Salas-Mélia et al., 2005). This simulation is described in details in Swingedouw et al. (2011). It uses most of the known external forcing (solar, volcanoes, CO_2). The Total Solar Irradiance (TSI) variations are deduced from the Bard et al. (2000) reconstruction and we use the scaling from Crowley (2000). This simulation correctly simulates the large scale variations of the annual mean Northern Hemisphere temperature (Swingedouw et al., 2011). While Swingedouw et al. (2011) focused on winter delayed response to solar forcing, here we will concentrate on the response to solar forcing over Europe in summer and in phase with solar variations (lagged responses indeed exhibit lower statistical significance in summer over Europe in the simulation, not shown). For this purpose, we compare this simulation with the spatio-temporal reconstruction over Europe (10° W–60° E, 25° N–75° N) for summer (April to September) temperature from Guiot et al. (2010), based on different proxies (mainly tree rings and pollen reconstructions) covering a large part of Europe. To compare the fingerprint from solar forcing in the simulation with this reconstruction, we interpolate the summer data from the model onto the grid from Guiot et al. (2010) reconstruction. Then, we use regression analysis of the temperature for each point on the TSI variability (represented in Fig. 1a). To minimize the climatic signature of the volcanoes and of the interannual variability, we apply a low pass Lanczos time-filter (Duchon, 1979) to all the fields analysed hereafter, with a cutoff values of 13 yr. This technique does not allow to filter out the low frequency effect coming from the volcanoes (illustrated in Otterå et al., 2010). Nevertheless the correlation between volcanoes and solar forcing is lower than 0.1 for the last 1000 yr even with running mean going up to 50 yr. Thus, we make the assumption that the proposed regression mainly captures the response of the low frequency solar forcing

CPD
8, 1301–1318, 2012

forcing. This assumption remains a weakness of the present paper, but due to computation cost, we could not provide a simulation with only solar forcing using CNRM-CM3. The statistical significance of the correlations computed in this study are estimated by using a "random-phase" test that accounts for the serial correlation effect due to the low-pass filtering of the reconstruction (Ebisuzaki, 1997).

3 Results

The evolution of summer temperature averaged over the whole Europe is represented in Fig. 1. For the period 1001–1860, the standard deviation is 0.22 °C in the reconstruction and 0.18 °C in the model. The correlation between the two time series is 0.25 (statistically significant at the 95 % level). The simulation misses high amplitude variations especially for the period between 1500–1700, but the main trend, related to solar forcing (correlation of 0.24 between solar forcing and the temperature reconstruction and of 0.53 in the simulation), is respected. The correlation with solar forcing is higher when limited on the period 1100–1500 and reaches the same figure of 0.56 both in the model and the reconstruction.

Figure 2 shows the spatial temperature regression over the solar forcing in the reconstruction and the model for zero time lag. We notice that for most of the grid points the regression is positive and statistically significant at the 90 % level. This means that the surface temperature increases with an increase in solar forcing, in agreement with the associated changes in radiative forcing at the top of the atmosphere (Fig. 3a). The solar forcing is related with short wave variation at the top of the atmosphere. This forcing is almost isotropic over Europe as shown in Fig. 3a only with slight decrease of the forcing in latitude related with the rotundity of the Earth (26 % lower at 75° N than at 25° N, cf. Fig. 3a). Nevertheless the response to this radiative forcing changes exhibit a complex spatial response, with a large warming in the north and south of Europe and a lesser warming in the centre, both in the reconstruction and in the model. The latitudinal agreement is actually quantitatively correct as shown in Fig. 4: there

CC BY

is a similar minimum of warming around 55° N with an increased warming north of it, sharing a similar increase, although largely overestimated after 65° N in the model as compared to the reconstruction. South of the 55° N minimum, the regressed temperature also increases but south of 40° N, the increase in the model becomes more than twice larger than in the reconstruction. The signature of solar forcing over Central Europe is not significant in a lot of grid-points from the model and the reconstruction (Fig. 2). Given that the solar forcing is almost isotropic over Europe, the latitudinal temperature response found in Fig. 4 remains surprising and needs to be explained. For that purpose we analyse the response of the model to solar forcing variations.

We notice in the model (Fig. 3) an increase in cloud cover, precipitation and evapotranspiration over Central Europe related to the increase in solar forcing. For these variables, Central Europe is the region that exhibits the mains changes, which is surprising given the small temperature response. We argue that this response of evapotranspiration and clouds may indeed explain the minimum warming found around 55° N in the model because of a damping of the forcing effect on surface temperature. Over the Mediterranean area the opposite signal is found.

We propose that the changes in evapotranspiration is the explanation for the temperature response found. Following the mechanism proposed by Schär et al. (1999, see their Fig. 1) an increase in evapotranspiration in summer leads to convective clouds that may interact with the large-scale circulation. In the simulation we actually find that the increase in precipitation in the region 10° E–50° W, 45–65° N is $0.20\,\mathrm{mm\,W^{-1}\,m^{-2}}$, and we diagnose that 65 % of this increase is related to convective precipitations. This is similar to the Schär et al. (1999) mechanism: in response to an increase in evapotranspiration, there is an interaction between the convective cell with the main circulation, which increases the precipitation in this region, in addition to the recycling from the evaporative water from the soil. This change in cloud cover impacts the radiative budget over this region (Fig. 5) with less shortwave radiation at the surface and more longwave radiation and sensible heat fluxes, while the absolute latent heat flux increase accordingly with the evapotranspiration fluxes. The minimum warming over Central Europe

CPD
8, 1301–1318, 2012

CC BY

results from this surface heat fluxes changes, dominated by a decrease in shortwave fluxes. Over the Mediterranean area, the decrease in evapotranspiration (Fig. 5c) is associated with the drying of the soil (and the lack of soil moisture availability to increase this flux). Such a different behavior between Central Europe and Mediterranean area can be compared to the two stable states found in D'Andrea et al. (2006): depending on the soil moisture initial condition at the beginning of the summer, two very different states can take place.

The increase in evapotranspiration in Central Europe is actually related to a larger availability of soil moisture at the beginning of summer. This is what is shown in Fig. 6: in summer both in the model and in a reanalysis (Alkama et al., 2010), the evapotranspiration is controlled through moisture (rather than radiative flux, e.g. Severinatne and Stockli, 2008, their Fig. 3). The increase in evapotranspiration in summer is therefore related to an increase in soil moisture at the beginning of the summer, followed by the soil-precipitation feedback from Schär et al. (1999). To explain this increase in soil moisture we find an increase in precipitation in winter when regressed over the solar index over Central Europe (not shown). This increase may allow to increase the loading of soil moisture in winter and spring and leads to the mechanism proposed. This increase in precipitation in winter is not related to a change in large scale circulation (no significant correlation found with weather regimes frequency or empirical orthogonal function of the sea-level pressure over the North Atlantic region, not shown) but could be explained by the Clausius-Clapeyron relationship, since the temperature is enhanced in winter in response to the increase in solar forcing (Swingedouw et al., 2010, their Fig. 2a). The whole mechanism for Central Europe is summarized in Fig. 7.

For the Mediterranean area, this effect is not sufficient, so that the soil becomes dry leading to the large warming observed in the model, which seems overestimated as compared to the reconstruction. In the North, the evapotranspiration is not controlled by soil moisture but rather by radiative flux availability so that the former mechanism does not apply (Seneviratne et al., 2006). The large warming can be explained by the

CPD
8, 1301–1318, 2012

sea ice retreat (not shown) that leads through albedo feedback to a larger net short wave at the surface (Fig. 4) amplifying the warming there.

4 Conclusions

In this study, we have shown that over the preindustrial period of the last millennium, a regression of surface temperature in summer over solar forcing in the CNRM-CM3 model and the Guiot et al. (2010) reconstruction shares similar latitudinal pattern in Europe with a minimum response around 55° N. To explain the qualitatively correct representation of the temperature latitudinal response to solar forcing at low frequency in the model as compared to the reconstruction, we argue that the evapotranspiration changes as well as their interactions with atmosphere (convection, radiative adjustment with cloud) are the leading processes.

This study therefore shows that spatio-temporal temperature reconstruction can be useful to evaluate simulated low frequency variability. Such a long time scale as the last millennium allows to increase the signal to noise ratio of the radiative forcing of the climate. The latitudinal agreement between model and observed reconstruction is correct except at 75° N and around the Mediterranean area, where warming is overestimated in the model. This difference can be due to an incorrect representation of the soil processes in the model. There are also large uncertainties for the scaling used for solar forcing, which can explain the difference. Indeed a lower solar forcing may induce lower response in the model, more in agreement with the reconstruction. Moreover, there are fewer data over the Mediterranean area in the Guiot et al. (2010) reconstruction, which may increase the uncertainty over this area. Reconstruction and model show a similar minimum around 55° N, but the model misses another local minimum in the reconstruction located around 45° N. This disagreement could indicate that the transition zone defined by Boé and Terray (2008) is too far in the north in the model as compared to the one we found in the reconstruction. This result may suggest a deficiency in the

CPD
8, 1301–1318, 2012

CC BY

response that implies that caution has to be exercised when considering projections over this region with this model.

We would like to make some caveats concerning this study. First of all, the correlation between the reconstruction and solar forcing remains small when globally averaged over Europe, in agreement with Hegerl et al. (2011). Nevertheless we argue here, that this is notably because the signal over Central Europe is considerably damped, implying very small correlation with solar forcing. The extension of our time frame to period before 1500 (as compared to Hegerl et al., 2011) also improve the correlation we find with solar forcing. Moreover, it will be very useful to extend the present analysis to other climate models in order to evaluate if they found a similar large evapotranspiration response to solar forcing in summer as in the CNRM-CM3 and a similar latitudinal response and minimum.

Finally, we conclude that it is useful to continue the improvement of spatio-temporal reconstruction of the last millennium, and to simulate this long period with climate models in order to evaluate the processes explaining the response to change in radiative forcing such as the solar one.

Acknowledgements. We thank Ramdane Alkama for providing the data of the soil moisture and evapotransiration over Europe. This paper is a contribution to the project ESCARSEL funded by the French Agency for National Research (ANR VMC 2006). The use of the software packages statpack, safo and ferret is acknowledged.

INSU
Institut national des sciences de l'Univers

The publication of this article is financed by CNRS-INSU.

CPD
8, 1301–1318, 2012

cc BY

References

Alkama, R., Decharme, B., Douville, H., Becker, M., Cazenave, A., Sheffield, J., Voldoire, A., Tyteca, S., and Le Moigne, P.: Global evaluation of the ISBA-TRIP continental hydrological system, Part I: Comparison to GRACE terrestrial water storage estimates and in situ river discharges, J. Hydrometeorol., 11, 583–600, 2010.

Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J.: Solar irradiance during the last 1200 years based on cosmogenic nuclides, Tellus B, 50, 985–992, 2000.

Boé, J. and Terray, L.: Uncertainties in summer evapotranspiration changes over Europe and implications for regional climate change, Geophys. Res. Lett., 35, L05702, doi:10.1029/2007GL032417, 2008.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W.-T., Laprise, R., Magana Rueda, V., Mearns, L., Mennndez, C. G., Raisanen, J., Rinke, A., Sarr, A., and Whetton, P.: 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: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, New York, 2007.

D'Andrea, F., Provenzale, A., Vautard, R., and DeNoblet-Ducoudré, N.: Hot and cool summers: multiple equilibria of the continental water cycle, Geophys. Res. Lett., 33, L24807, doi:10.1029/2006GL027972, 2006.

Duchon, C. E.: Lanczos filtering in one and two dimensions, J. Appl. Meteorol., 18, 1016–1022, 1979.

Ebisuzaki, W.: A method to estimate the statistical significance of a correlation when the data are serially correlated, J. Climate, 10, 2147–2153, 1997.

Guiot, J., Corona, C., and ESCARSEL members: Growing season temperatures in Europe and climate forcings over the past 1400 years, PLoS ONE, 5, e9972, doi:10.1371/journal.pone.0009972, 2010.

Hegerl, G., Luterbacher, J., González-Rouco, F., Tett, S. F. B., Crowley, T., and Xoplaki, E.: Influence of human and natural forcing on European seasonal temperatures, Nat. Geosci., 3, 688–694, 2011.

Hunt, B. G.: The Medieval Warm Period, the Little Ice Age and simulated climatic variability, Clim. Dynam., 27, 677–694, 2006.

CPD
8, 1301–1318, 2012

Mechanisms for European summer temperature

D. Swingedouw et al.

Otterå, O. H., Bentsen, M., Drange, H., and Lingling, S.: External forcing as a metronome for Atlantic multidecadal variability, Nat. Geosci., 4, 99–103, 2010.

Salas-Mélia, D., Chauvin, F., Déqué, M., Douville, H., Gueremy, J. F., Marquet, P., Planton, S., Royer, J. F., and Tyteca, S.: Description and validation of the CNRM-CM3 global coupled model, CNRM technical report 103, http://www.cnrm.meteo.fr/scenario2004/paper_cm3.pdf, available from CNRM/GMGEC, Toulouse, France, 2005.

Schär, C., Luthi, D., Beyerle, U., and Heise, E.: The soil-precipitation feedback: a process study with a regional climate model, J. Climate, 12, 722–741, 1999.

Seneviratne, S. I. and Stockli, R.: The role of land-atmosphere interactions for climate variability in Europe, in: Climate Variability and Extremes during the Past 100 years, edited by: Brönnimann, S., Luterbacher, J., Ewen, T., Diaz, H. F., Stolarski, R. S., and Neu, U., Adv. Global Change Res., vol. 33, Springer Verlag, 2008.

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

Swingedouw, D., Terray, L., Cassou, C., Voldoire, A., Salas-Mélia, D., and Servonnat, J.: Natural forcing of climate during the last millennium: fingerprint of solar variability, Clim. Dynam., 36, 1349–1364, 2011.

CPD

8, 1301–1318, 2012

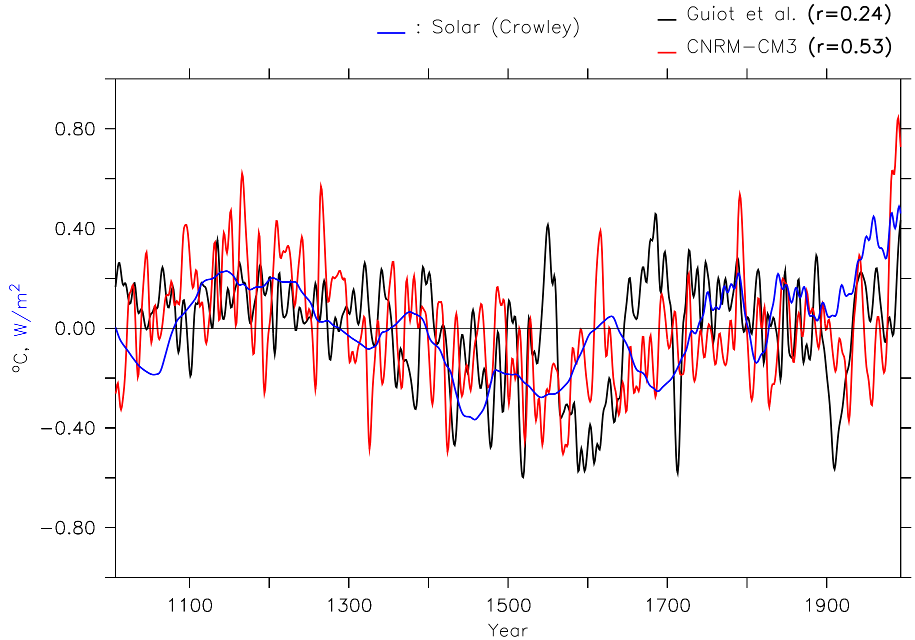

Fig. 1. Time series of the summer (April to September) European mean temperature (in °C) filtered with a 13 yr cutoff value. In black is the reconstruction from Guiot et al. (2010) and in red is the simulation from the model CNRM-CM3. In blue is represented the mean radiative forcing from solar variations (in $W m^{-2}$) from Crowley (2000) with its own axis on the right.

CC BY

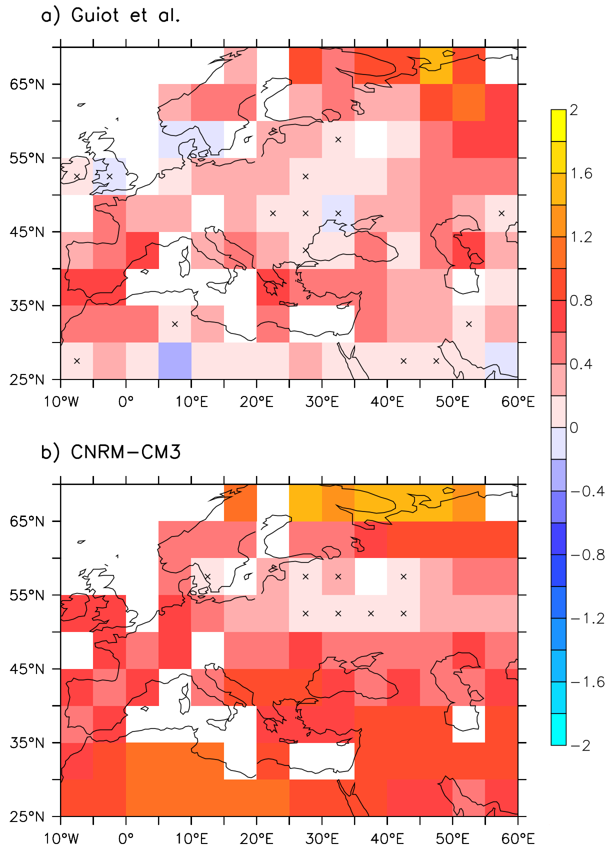

Fig. 2. (a) Spatial regression of the summer temperature from Guiot et al. (2010) on the solar variations (in $^{\circ}C\,W^{-1}\,m^{2}$) for the period 1001–1860. The black crosses indicate the point not significant at the 90 %. **(b)** Same as **(a)** but for the simulation (note that the ocean point have been excluded since the data used by Guiot et al., 2010, are from land).

CPD
8, 1301–1318, 2012

cc BY

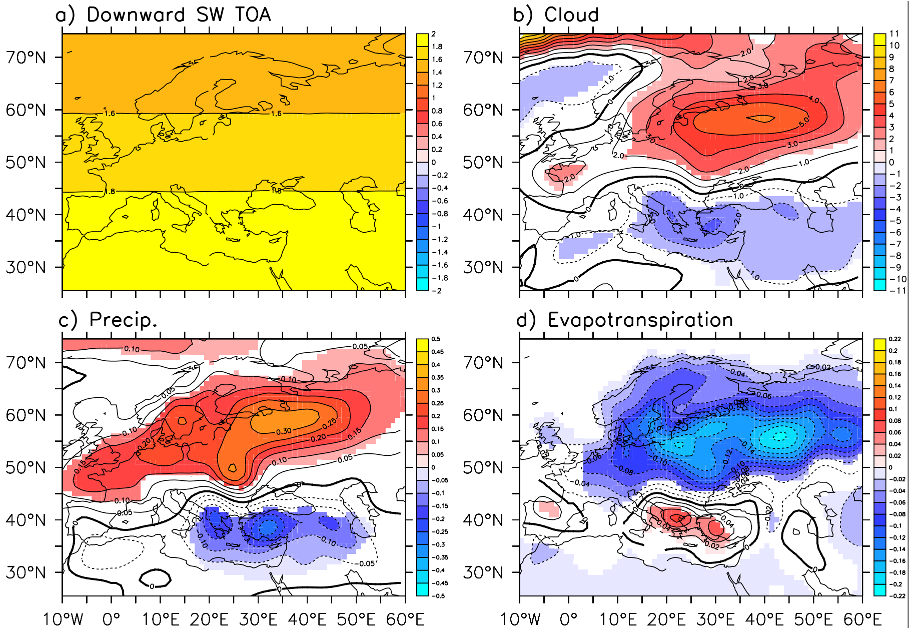

Fig. 3. Regression of different variables from the model simulation on the solar variations for the period 1001–1860. **(a)** Downward shortwave (SW) radiation at the top of the atmosphere (TOA) in $\mathrm{W\,m^{-2}/W\,m^{-2}}$. **(b)** Cloud concentration in $\%/\mathrm{W\,m^{-2}}$. **(c)** Precipitation in $\mathrm{mm\,day^{-1}/W\,m^{-2}}$. **(d)** Evapotranspiration in $\mathrm{mm\,day^{-1}/W\,m^{-2}}$. The sign is positive for cloud, precipitation and downward SW and when the variables increases with solar forcing increases and negatibe for evapotranspiration (seen as a lost of moisture for land).

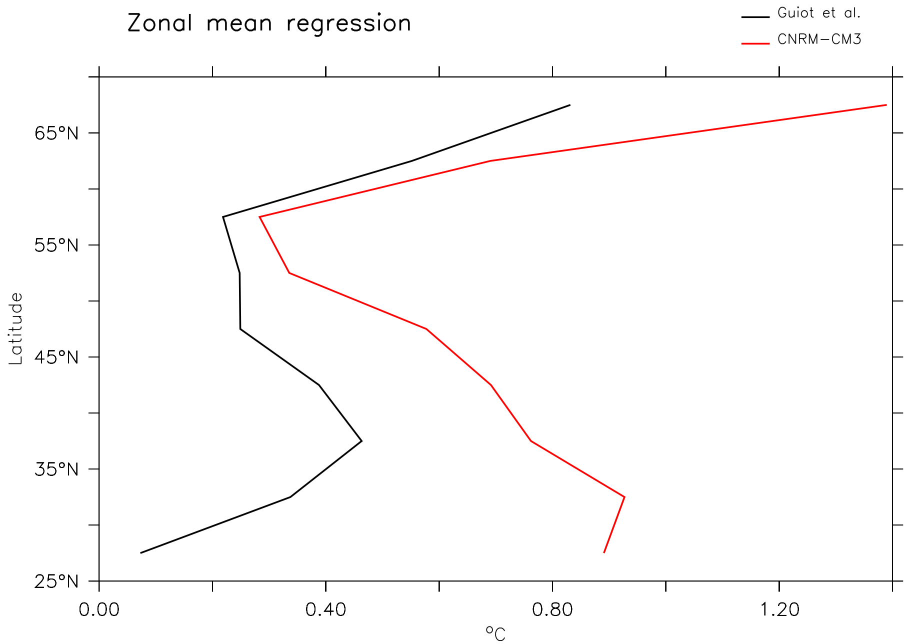

Fig. 4. Zonal mean of the summer temperature regression, in black for the reconstruction and in red for the simulation.

CPD
8, 1301–1318, 2012

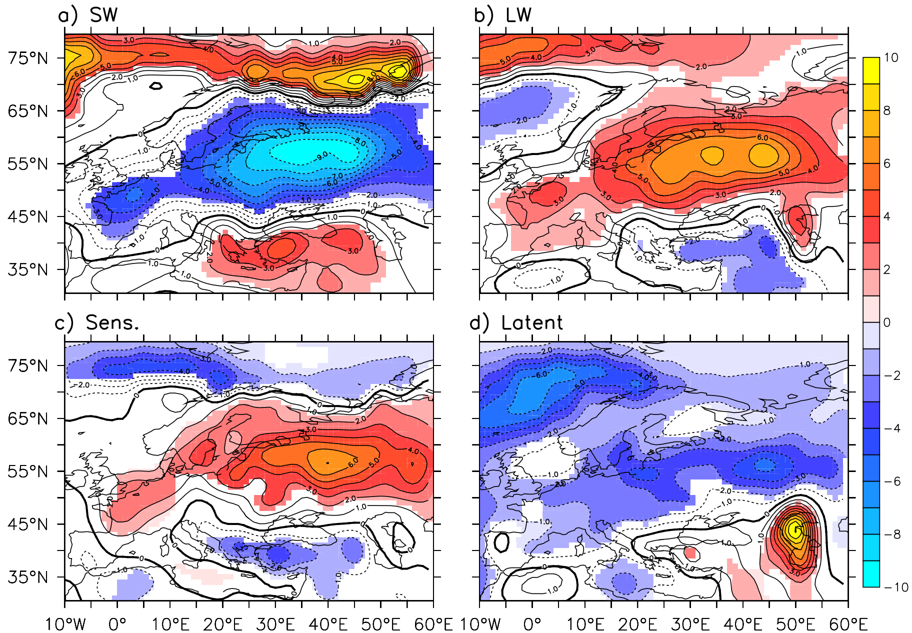

Fig. 5. Same as Fig. 2 but for **(a)** the net shortwave radiation at the surface, **(b)** the net longwave radiation at the surface, **(c)** the sensible heat flux, **(d)** the latent heat flux. All panels are expressed in $\mathrm{W\,m^{-2}/W\,m^{-2}}$.

CPD
8, 1301–1318, 2012

CC BY

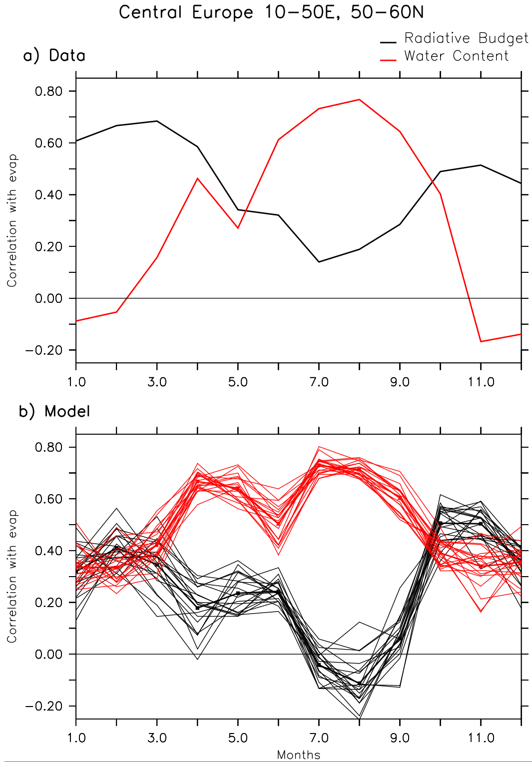

Fig. 6. Correlation between radiative forcing and evapotranspiration (in black) and soil water content and evapotranspiration (in red) for a region of Central Europe (10–50° E, 50–60° N) for different months (on the x-axis) **(a)** in a reanalysis from Alkama et al. (2010) and **(b)** in the model simulation the period 1001–1800 (each line correspond to a computation each century to evaluate the stationarity of the relationship in the model).

CPD
8, 1301–1318, 2012

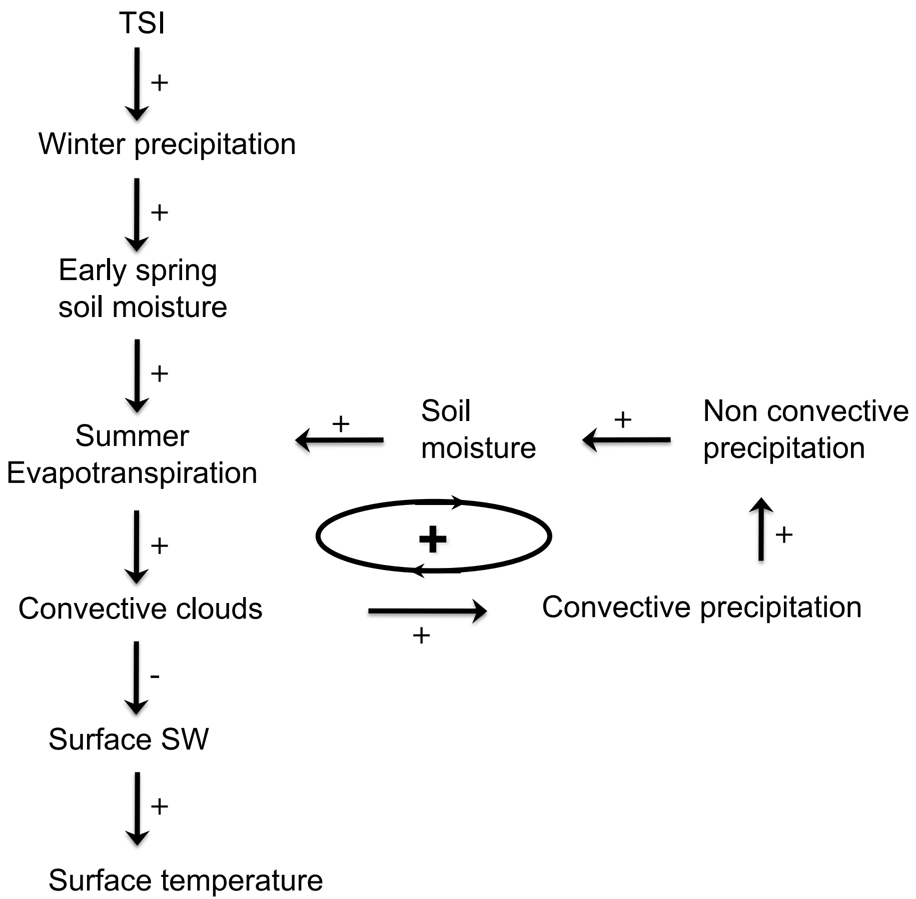

Fig. 7. Scheme of the proposed mechanism operating in Central Europe.

CPD
8, 1301–1318, 2012

CC BY