Soil drying in Europe and its impact on atmospheric circulations

Bart van den Hurk[1], Rein Haarsma[1], Frank Selten[1]and Sonia Seneviratne[2]

[1] *KNMI, De Bilt, The Netherlands*
[2] *ETH Zurich, Switzerland*
corresponding author: hurkvd@knmi.nl

1. Introduction

The state of the land surface is sensitive to the atmosphere, this is evident. But at particular temporal and spatial scales and under particular conditions the atmospheric circulation will also be sensitive to the (wetness) state of the land surface. Many modeling studies have demonstrated the sensitivity of the mean climatological atmospheric state to the formulation of the land surface (e.g. Shukla and Mintz, 1982). At the synoptic time scale of several days to a week, however, the impact of soil wetness anomalies on the atmosphere is obscured by noise, and the impact is only conditionally present. For instance, dry European summer conditions are considered to be affected by soil moisture anomalies, particularly the associated temperature and precipitation anomaly, and probably also the duration of the dry spells (e.g. Ferranti and Viterbo, 2006).

The feedback from land to the atmosphere can take place via multiple mechanisms. A first order effect of soil wetness is to affect the surface Bowen ratio (sensible heat flux H divided by latent heat flux LE), thereby determining the surface heating and moisture supply to the atmosphere. Higher order effects can be the subsequent change of the stratification of the atmosphere, its ability to trigger or fuel convection and form precipitation, or the change of spatial surface pressure gradients affecting the atmospheric circulation that in turn affects the advection of moist air.

Koster et al (2004) used a nicely designed modeling experiment to identify areas where soil moisture variability on the intra-seasonal time scale had a discernible effect on the precipitation variability on the same time scale. A range of models showed quite a range of degrees to which this coupling is realized, but a number of areas (hotspots) emerged in transitional climate regimes where sufficient dependence of evaporation on soil moisture and sufficient sensitivity of precipitation formation to atmospheric moisture content were both present. In these hotspots most of the feedbacks between soil moisture and precipitation are likely of a local origin, that is, secondary effects on e.g. atmospheric circulation are presumably less important. Areas where precipitation is largely controlled by remote advection of moisture (like Europe) did not show up on Koster's map.

However, as stated above, certain conditions may well favor a strong impact of soil wetness on atmospheric circulation, its associated moisture advection, and the strength or duration of a hydrological anomaly in the region. The summer of 2003 has triggered many modeling and observational studies demonstrating such an impact of soil moisture. In addition, many future climate projections show strong changes in the land-atmosphere feedback patterns (Seneviratne et al, 2006) or responses of mean and variability of atmospheric circulation associated with enhanced warming and drying conditions. Many studies on the impact of greenhouse warming in Europe during summer have focused on the heat budget and the hydrological cycle. Most of these (e.g. Sterl et al, 2008) point towards a hotter and more arid climate with an increase of long lasting heat waves due to a positive feedback between the reduction of soil moisture and surface air temperatures. Changes in atmospheric circulation have received less attention. Therefore, a closer look is warranted.

2. Two Studies

This manuscript reports on two recent studies addressing the role of soil moisture anomalies on the atmospheric circulation in Europe. In the first study (Van den Hurk et al, submitted), the experimental set-up of Koster et al (2004) is repeated using a climate model integration covering 1950-2100, and it is analyzed whether cutting land-atmosphere feedback by prescribing soil moisture conditions has a discernible impact on the frequency and duration of blocked circulation patterns in Europe. The second study (Haarsma et al, submitted) relates Southern European drying in present and future summer conditions to enhanced easterlies in West and Central Europe, with an impact on the temperature and precipitation anomalies in this area. In both studies it is shown that anomalous soil conditions do have a systematic effect on the large scale summer circulation in Europe, but they also both show that a refinement of the experimental set-up and diagnostics is needed to obtain a thorough understanding of the relevant feedback processes.

3. Land atmosphere interaction and European summertime blocking conditions

It is often suggested that land-atmosphere interactions indeed play a role in the persistence of drought conditions via a change in the atmospheric large scale circulation (e.g. Ferranti and Viterbo, 2006; Fischer et al, 2007). If this is true, an effect on the blocking frequency or duration should be visible when these land-atmosphere interactions are removed. Blocked conditions reduce the storm activity in the central part of Europe by deflecting low pressure westerlies to the north or south of the main track. For the land-atmosphere coupling experiment we use a GCM modeling framework that is largely inspired on Koster et al (2004). In some of the simulations land-atmosphere coupling was strongly reduced by prescribing daily soil moisture fields from a climatological dataset. The analysis compares the frequency and duration of blocked circulation events in a number of GCM simulations. Prior to addressing the blocking occurrences, we also investigate whether land-atmosphere interactions have a detectable impact on the storm activity in the European summer area.

The study uses model data from the ensemble experiment ESSENCE (Sterl et al, 2008) with the ECHAM5/OMI GCM (Roeckner et al, 2003; Marsland et al, 2003). 17 model integrations between 1950 and 2100 were carried out at a resolution of approximately 1.86° × 1.86° using slightly perturbed initial conditions. The SRES scenario A1b was used for greenhouse gas concentration forcings after 2000. For the present study only the results up to 2000 were analyzed. From these 17 members a mean global soil moisture and snow content field was calculated every day. This evolving pseudo-climatological time series was used to overwrite the daily values of soil moisture and snow in another realization of the model, labeled CLIMSOIL. From the 17 standard runs, 5 members were selected randomly for further analysis. This 5-member ensemble is labeled CTL. Daily soil moisture values from only one of these members were stored.

From each member of the analyzed runs a daily blocking index was calculated using the 500 hPa geopotential height (Z500) following Tibaldi and Molteni (1990). This index flags a meridional band as blocked when the south-north gradient of Z500 exceeds 0 m/deg south of a point at latitude y_c, and simultaneously is less than –10 m/deg north of y_c. For our study we have chosen y_c = 50°N (rather than 60°N used by Tibaldi and Molteni (1990)), to allow more focus on the continental part of Europe where land – atmosphere interactions are expected to play a stronger role. Figure 1 shows a zonal cross-section of the relative number of summer days (June-July-August, JJA) with a blocked circulation at any European longitude. Apart from the 5 CTL members and the CLIMSOIL run also results from the 40-yr reanalysis of ECMWF (ERA40, Uppala et al, 2005) are shown.

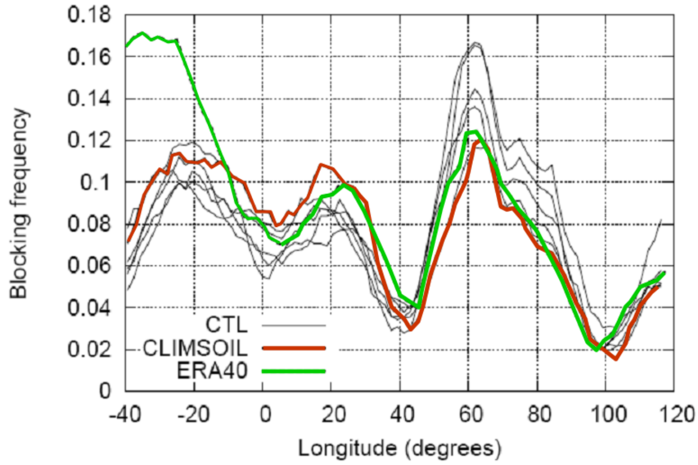

Figure 1: Mean fraction of blocked summer days per longitude band in the simulations covering the period 1976-2000. Shown are the 5 CTL members and the CLIMSOIL run, as well as the blocking index derived from ERA40 (see text).

Figure 1 clearly shows the preferred locations of summertime blocking structures over the Eurasian Northern Hemisphere sector. This signature is present in both ERA40 and the model simulations, pointing at a reasonable model skill in reproducing this atmospheric circulation feature. The spread between the individual members demonstrates the large circulation variability on interannual to decadal time scales. This makes the interpretation of the CLIMSOIL run not straightforward. West of 40°E the CLIMSOIL run has a relatively high blocking frequency compared to the CTL ensemble, but East of this longitude the CLIMSOIL blocking frequency is at the low end of the CTL range. This signature is also present in the ERA40 blocking frequency for the longitudinal range between 40°W and 120°E. Further West all ESSENCE runs underestimate the blocking frequency in summer. The origin of this bias is not known.

To identify episodes with blocked conditions in the European domain a calendar day is labeled to be blocked if at least 3 subsequent grid points within the range 20°W – 60°E satisfy the above criterion. This procedure generates time series of daily data in the summer months with a flag for blocked or unblocked conditions for each of the model runs. From these time series the duration of the blocking episodes are tracked, and frequency distributions of the blocking duration are calculated. A similar procedure was applied using the ERA40 Z500 data. For this archive only the period 1976 – 2000 was used.

Using the time series of blocked days, composites are made of anomalies of soil moisture and geopotential heights of the 500 hPa and 975 hPa (nearly similar to mean sea level) pressure levels. All anomalies are calculated relative to the JJA mean fields in the 1950 – 2000 period for each of the model runs. In order to make a distinction between short and long (persistent) blocking episodes, the composites are assembled for all days within a blocking episode of a specified duration.

Another diagnostic indicative of blocked circulation is the (filtered) variance of the Z500 field. Blocked conditions are considered to reduce the number of transient low pressure systems entering the European continent, which is expressed as a reduction of the variance of Z500 and Z975 of the high-pass filtered time series below around 10 days (Blackmon, 1976). Here we calculated the variance of Z500 after removing a running mean signal with a 10-day averaging interval, which mimics a high-pass filter.

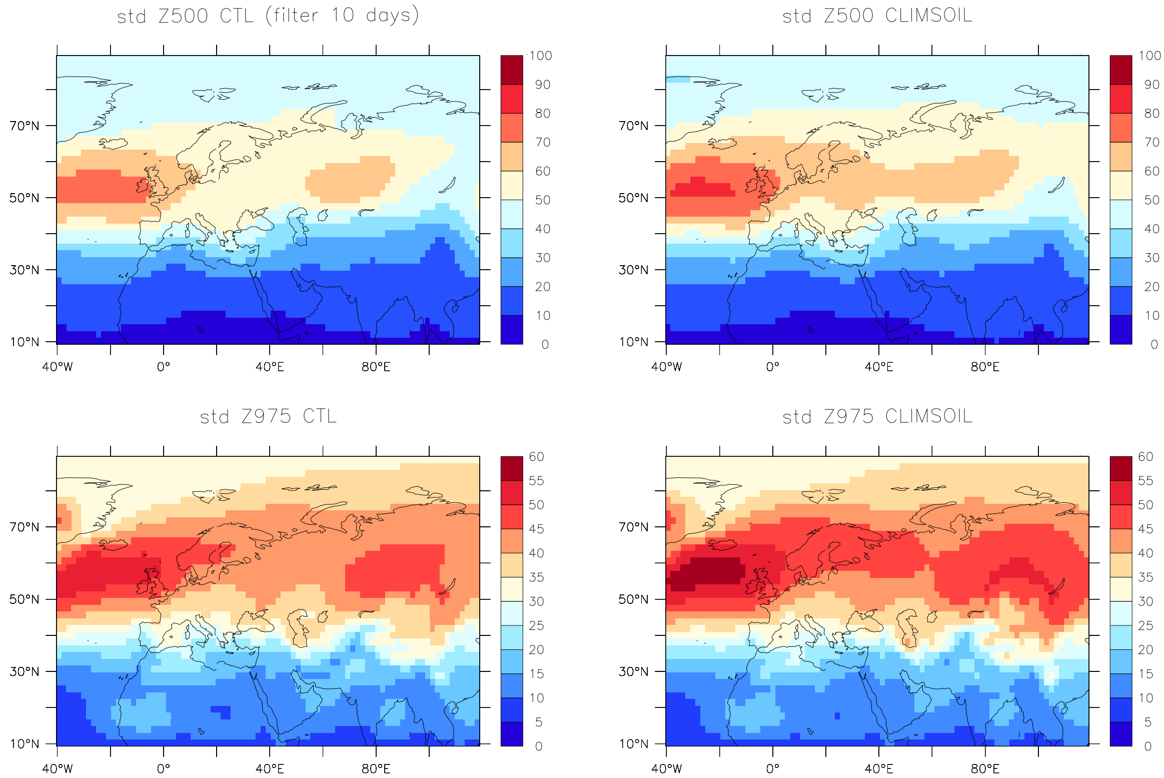

Figure 2: Standard deviation [m] of filtered Z500 (top) and Z975 (bottom) during JJA for the CTL ensemble (left) and the single CLIMSOIL run (right). The time filtering is achieved by subtracting a 10-day running mean from the raw time series. Note the difference in color scale between the top and bottom panels.

Figure 2 shows the effect of reducing land-atmosphere interactions on the high-pass filtered variance of Z500 and Z975. It can be seen that the overall variance shows a zonal and land-sea pattern, where a maximum is present around 50°N, which is more pronounced over the ocean than over land. In the CTL runs this variance is lower than in the CLIMSOIL runs for both height levels, particularly in the zone around 50°N. In the CLIMSOIL run the maximum in the variance around this latitude is more pronounced, and penetrates further to the East. Also above the Atlantic Ocean (West and North of the UK) increased Z500 variability is seen in the CLIMSOIL run. The removal of some of the variability in the climate system in the CLIMSOIL experiment (the prescribed soil moisture has a lower variability than in the CTL runs) apparently does not compensate for other factors in that experiment leading to an increase of the Z500 variability.

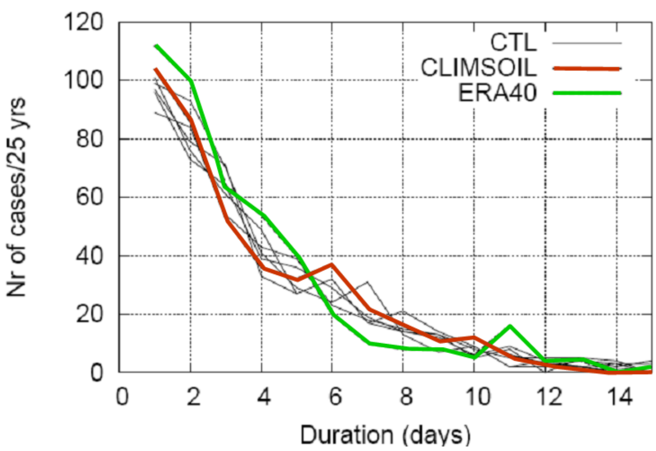

Figure 3: Frequency distribution of number of JJA blocking episodes of a specific duration [days]. The blocking occasions are diagnosed in the 20°W - 60°E sector in all simulations and ERA40. The model simulations cover the period 1950 – 2000, the ERA40 data the 1976 – 2000 period.

Figure 3 shows a frequency distribution of the duration of the blocking conditions in the 20°W – 60°E sector in ERA40 and our GCM experiments. In all simulations and the ERA40 observations the frequency of episodes reduces if the episode length increases. Note that the average blocking frequency in this sector is approximately 10%. More than half of these days are part of short blocking events (≤ 3 days).

From Figure 3 a slight underestimation of the number of short duration events is shown when comparing the model data to ERA40. The model shows a good overall correspondence of the frequency distribution. Also, from this figure one can see that the CLIMSOIL experiment does not show a clear distinct behavior compared to the CTL runs. The number of very long blocking events (> 12 days) in CLIMSOIL lies in the low end of the range of the CTL simulations, but the statistical confidence in this finding is low given the rare occasion of these events.

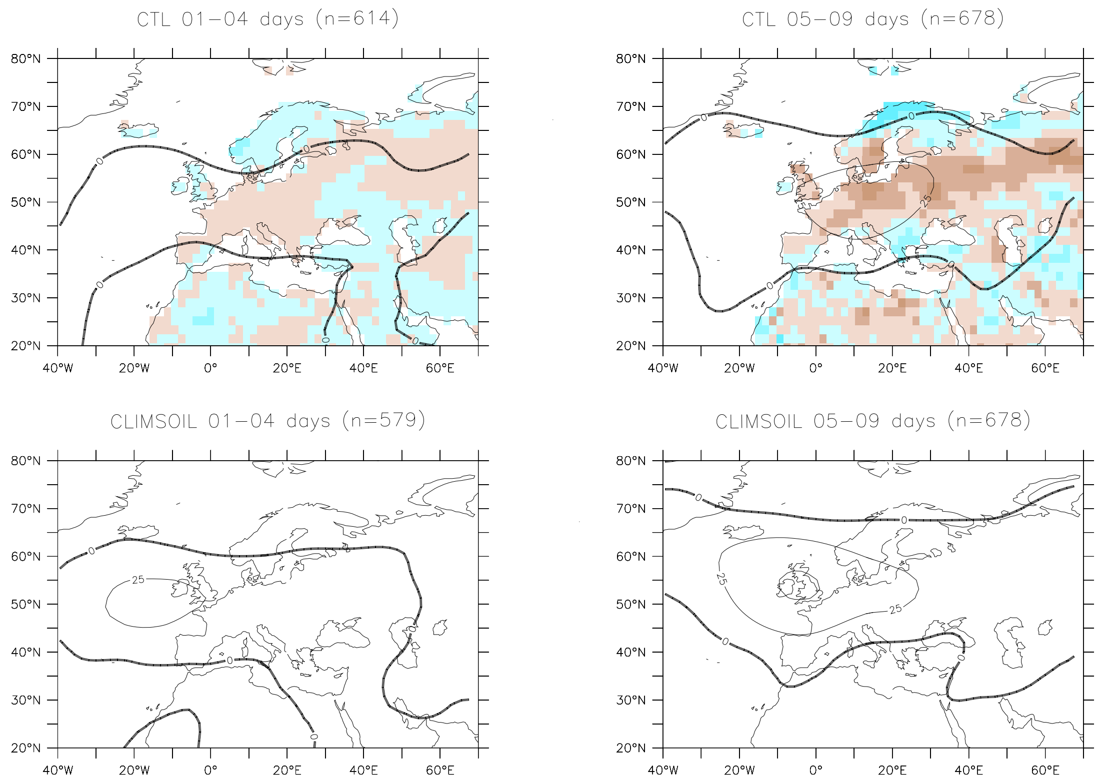

Figure 4: Composite of Z500 anomalies (contour at 25 m intervals) and soil moisture anomalies (color shading, indicated the number of standard deviations of seasonal mean values) for two classes of blocking episode duration: 1 – 4 days (left), and 5 – 9 days (right). The top row represents the CTL runs (Z500 anomalies derived averaged for all runs, soil moisture anomalies from only one member), the bottom row the CLIMSOIL experiment.

For two classes of blocking episode duration (1 – 4 days and 5 – 9 days) composites were constructed of the anomalies of Z500, Z975 and soil moisture. Figure 4 shows contour plots of (ensemble mean) Z500 anomalies overlying soil moisture anomalies from one of the CTL members.

In all simulations a common feature is the increase of Z500 in a zonal band between roughly 40°N and 60°N (and a tendency for reduced Z500 levels in the Eastern part of the Mediterranean Sea), and an enhancement of this pattern as the blocking episode is longer. A developing high pressure system around 50°N is straightforward, given the definition of a blocked situation as a relative maximum around this latitude. Also, the intensification of the signal as the blocking episode lasts longer is a plausible result, as strong pressure anomalies are more likely to survive longer. Results for longer blocking durations confirm the trend of higher Z500 anomalies for longer episodes, but the number of independent events is too low to separate this signal from the inherent noise in the system.

The Z500 increase around 50°N is present in both the CTL runs and the CLIMSOIL simulation. However, in the CLIMSOIL run the maximum in Z500-anomalies is shifted westward by approximately 20°, particularly in the longer lasting events. This signature is consistent with the higher number of blockings in CLIMSOIL compared to the CTL ensemble in the sector west of 20°E, and a relatively low number of blockings east of this longitude (Figure 1). Thus, although the number of blocking days as defined by counting high anomalies anywhere in the sector 20°W – 60°E may not be sensitive to land-atmosphere interactions, the positions of the blockings seem to be different.

4. Drying in Southern Europe and the European atmospheric circulation

Land-atmosphere interaction is not only relevant on the synoptic or intraseasonal timescale. Future GCM projections reported by IPCC show a consistent summertime heating and drying over North Africa and the Mediterranean, which may be partly emphasized by the role of land surface processes. In addition, the models fairly well agree in projecting a systematic decrease of mean sea level pressure (MSLP) in the area, suggesting a common cause at the monthly to seasonal time scale. This MSLP reduction has an effect on the atmospheric circulation outside the domain. For instance, an increase of easterly winds over Central Europe (Van Ulden and Van Oldenborgh, 2006) is consistent with the Southern-European MSLP decrease. These easterly winds enhance the warming and drying over Central Europe. Here we show that the decrease of the Mediterranean MSLP is related to the drying and enhanced heating of that area, a robust result of greenhouse warming.

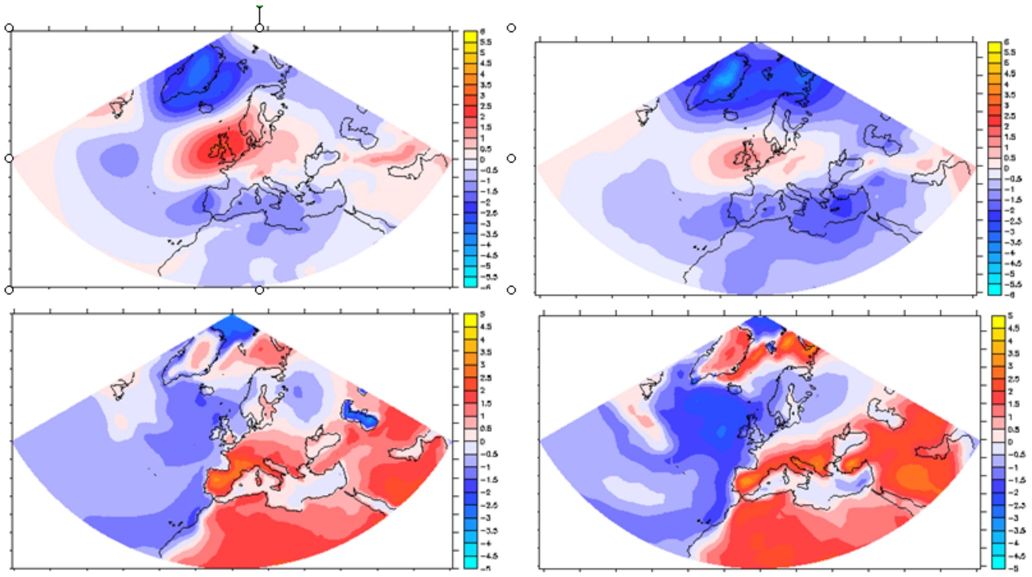

Figure 5: Difference in MSLP [hPa] (upper) and SAT [°C] for JJA between 1971-2000 and 2071-2100 for ECMWF (left) and ESSENCE (right). For SAT the global mean has been subtracted.

For the analysis of the change in the summer circulation over Europe we have used the output of two climate models: The integrated forecast system (IFS) atmosphere model of the European Centre of Medium Range Weather Forecast (ECMWF) (cycle 31R1), and the above mentioned ensemble experiment ESSENCE. The ECMWF model is the atmospheric component of the earth system model EC-EARTH that is under development in a joint project of several European institutes. All model data was analyzed for the 30 year periods 1971-2000 and 2071-2100, which will be denoted henceforth as present and future. IFS was run using climatological SST for the present. Future SST and sea-ice coverage were computed from the multi-year mean of an ensemble of AR4 coupled climate models forced with the SRES A1b scenario.

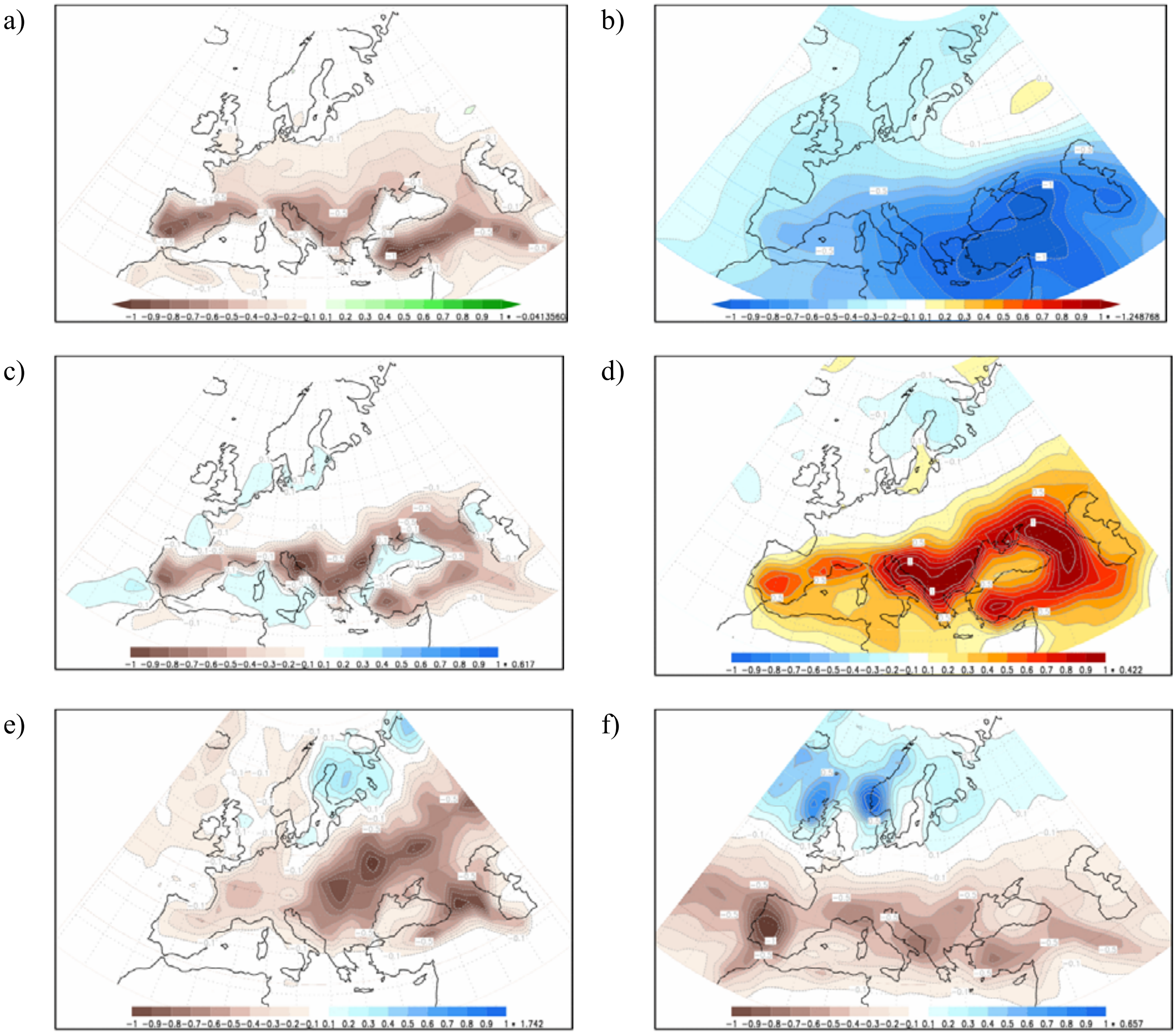

Figure 6: Upper Panels: First lagged SVD between soil moisture (a) [m] in June and MSLP (b) [hPa] in July-August averaged for all the ensemble members of ESSENCE for the period 1971-2000. The patterns are normalized to one standard deviation of the principle components (PCs). Middle and lower panels: Regressions between the soil wetness SVD pattern and evaporation [mm day^{-1}] (c), SAT [°C] (d), precipitation [mm day^{-1}] in July-August (e) and precipitation in January-May [mm day^{-1}] (f).

Figure 5 displays the ensemble mean change of MSLP during June-August (JJA) for ESSENCE and ECMWF. These figures show for both models a similar response of a high pressure over the British Isles and a low pressure over Southern Europe and the Mediterranean. This pressure distribution over Europe and North Africa is similar to the AR4 multi-model response displayed in its Fig. 10.9 and induces an increase of easterly flow over Central Europe. The Mediterranean low is confined to the lower troposphere, which indicates that it is the result of a change in the surface forcing.

Figure 5 also shows the change in Surface Air Temperature (SAT). For both models there is a relatively large increase in the land SAT over the Mediterranean. Compared to Northern Europe and the Atlantic the relative increase in SAT is about 3°C. Haarsma et al. (2005) showed that in a future warmer climate the relative increase of SAT over Northern Africa resulted in an increase of the Sahara low, with a corresponding increase of the West African monsoon. Figure 5 suggests that the deepening of the surface pressure is not confined to the Sahara but extends to the southern part of Europe and affects also the circulation over Central Europe at the northern flank of this heat low. The increase in SAT over the Mediterranean is confined to the land areas; the Mediterranean sea is relatively cool compared to the surroundings. At 925 hPa (not shown) a rather uniform warming over the entire Mediterranean area is present. This warming is confined to the lower troposphere. We therefore expect that the heat low mechanism operates for the entire Mediterranean area notwithstanding the relatively cool Mediterranean Sea.

We first tested the Mediterranean heat low hypothesis and its relation to the drying of the soil on intraseasonal time scales using monthly mean ESSENCE data. A lagged Singular Value Decomposition (SVD) analysis is used, which is designed to find spatial patterns of (lagged) fields with a strong correlation. The SVD analysis revealed a weak but statistically significant relationship in the Mediterranean between the soil moisture content in June and the MSLP in July-August (Fig. 6ab). This implies that anomalous low soil moisture in June in the Mediterranean forces the development of a low in MSLP during July-August. Due to the large data set of ESSENCE (510 summer seasons) this relationship is statistically significant. For individual members, with 30 summer seasons, this relationship is less clear. A regression analysis of the amplitude of the SVD June soil moisture pattern with evaporation (Fig. 6c) and SAT (Fig. 6d) in July-August reveals anomalous high temperatures in the dry areas with reduced latent heat flux, confirming that the anomalous low pressure pattern in August is indeed a heat-low. Although statistically significant the correlations are small with maxima of about 0.4. The reduced latent heat flux in July-August is due to the reduced soil moisture (not shown). The reduced soil moisture in July-August is partly due to persistence and partly due to reduced rainfall (Fig. 6e), indicating a positive feedback. The largest signal in rainfall is, however, not seen over the areas with the largest reduction in soil moisture, but over Central and Eastern Europe were the largest gradient in the MSLP is found. This suggests that there the reduced rainfall is mainly due to the increased easterly winds that block the inflow of moist maritime air from the Atlantic. This mechanism is probably also partly responsible for the reduction in rainfall in Southern Europe. There the signal is smaller due to smaller gradients in MSLP, and an already low climatological precipitation amount that can not be reduced strongly anymore. Vautard et al (2007) noted the northward propagation of dry conditions during hot summers and explained this by the northward transport of anomalously warm and dry air from Southern Europe during southerly wind episodes. Our results indicate that this northward propagation is dynamically reinforced by the heat low response that blocks the inflow of moist maritime air. Vautard et al (2007) also noted that hot summers are preceded by winter rainfall deficits over Southern Europe. Their results are supported by the ESSENCE data indicating that dry conditions in June are related to reduced rainfall in January-May (Fig. 6f). This points towards an important role for reduced winter and spring rainfall for the development of an anomalously hot summer and accompanying Mediterranean heat low.

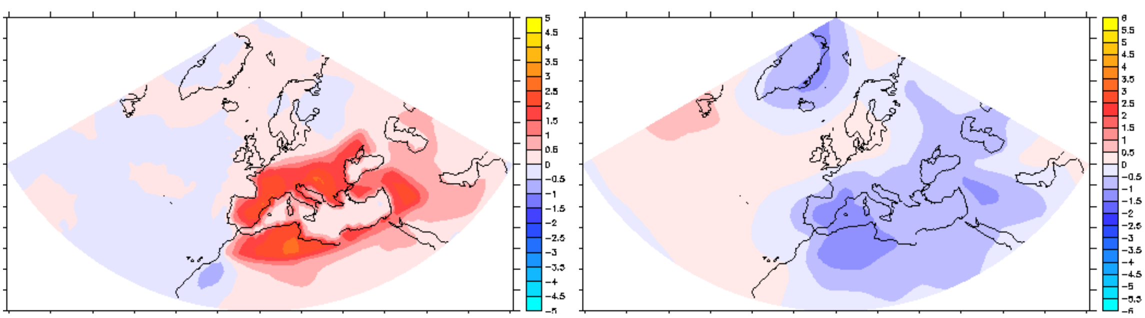

Figure 7: Change in SAT [°C] (left) and MSLP [hPa] (right) for JJA in the ECMWF model experiment where 20 Wm-2 was added in the Mediterranean area.

To check whether enhanced heating over the Mediterranean generates a low similar as observed in the simulations for the future climate, we carried out a new model simulation in which SAT in the present climate was artificially enhanced by adding 20 Wm^{-2} to the net downward surface flux over the Mediterranean region (30-50ºN, 10ºW-40ºE). The resulting increase in SAT during summer, shown in Fig. 7a, is 2-3 ºC which is comparable to the enhanced SAT over the Mediterranean simulated by ESSENCE and ECMWF caused by greenhouse warming. Forced by this increase in SAT a Mediterranean heat low of about 1 hPa has formed (Fig. 7b) comparable to the lows formed in the ECMWF and ESSENCE experiments (Fig. 5ab).

The relatively large increase of SAT over the Mediterranean is related to the depletion of the soil moisture resulting in a strong decrease in latent heat flux. The decrease in latent heat flux, especially in the countries along the north coast of the Mediterranean, is clearly seen in Fig. 8a. The drying is not confined to the Mediterranean; in fact Fig. 8b shows that the largest drying occurs in western and central Europe. The drying has, however, the largest impact on the latent heat flux and the SAT in the Mediterranean because of the semi-arid conditions in summer with soil wetness index *S* in the order 0.2. When soil moisture is the limiting factor for evaporation (which is the case in semi-arid conditions with abundant radiation) a further reduction of *S* has a large impact on the evapotranspiration. This process is amplified during prolonged spells of high temperatures and drought. Over central Europe there is a widespread increase of subsidence (Fig. 8d) resulting in a reduction of cloud cover and an increase of solar radiation. For central Europe this increase of solar radiation is the dominant term in the surface heat balance that causes the increase of SAT. For the Mediterranean where the increase in subsidence is less or absent, the decrease in latent heat flux is the main contributor to the increase in SAT.

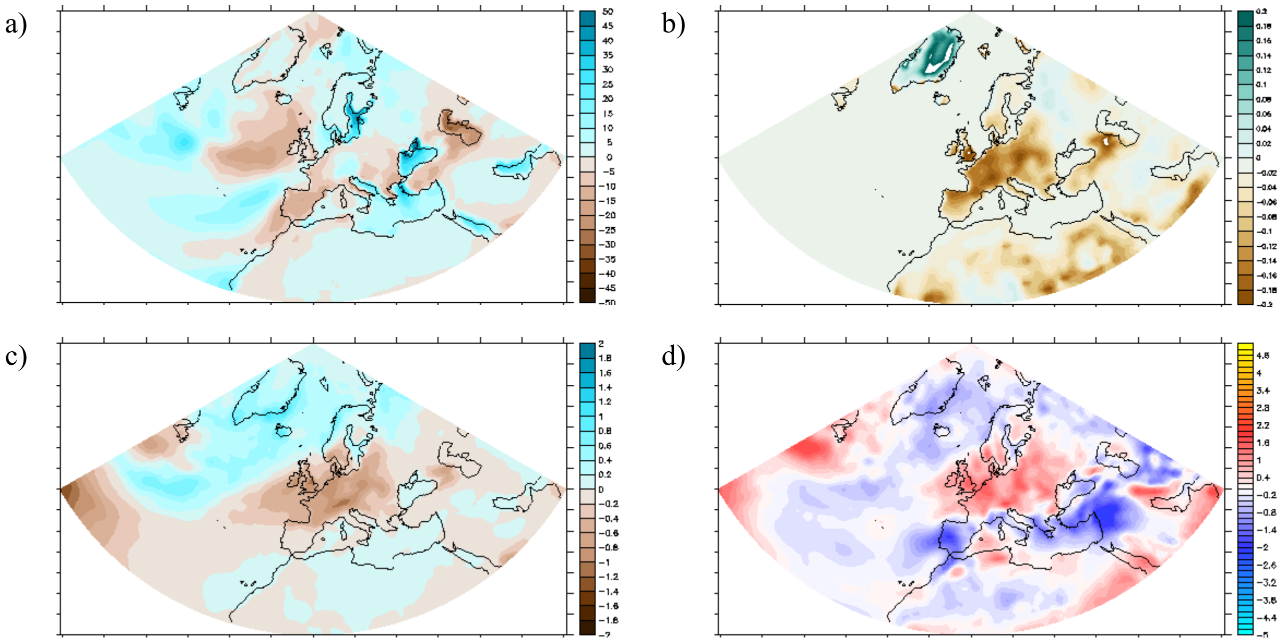

Figure 8: Difference in JJA for ECMWF of (a) surface latent heat flux [Wm^{-2}], (b) soil wetness S, (c) precipitation [mm day^{-1}] and (d) subsidence at 500 hPa [hPa/s] between 1971-2000 and 2071-2100.

Part of the drying in Europe is a direct consequence of the higher temperatures due to greenhouse warming resulting in an increased latent heat flux during the period where soil moisture is still available. In regions of low relative humidity and subsidence like the Mediterranean this enhanced evaporation is not compensated by increased rainfall. The increased subsidence in a warmer climate is counteracted by the development of a heat low due to the strong surface heating, resulting in a relative decrease of the subsidence over that area. A reduction of the subsidence in this area has only minor impact on the solar radiation and precipitation. In central Europe the drying is enhanced by an increased subsidence resulting in a reduction of rainfall (Fig. 8c). This is the result of the north-eastward extension of the subtropical anticyclone over the Atlantic.

5. Wrap up: what did (didn't) we learn from these experiments?

Using the ESSENCE data set a clear relationship has been detected between the depletion of soil moisture and the development of a heat low over the Mediterranean in summer. The connection between reduction of soil moisture and higher SAT in response to greenhouse warming appears to be a robust mechanism (Seneviratne et al, 2006; Vautard et al, 2007; Meehl and Tebaldi, 2004). This enhanced Mediterranean warming generates an anomalous heat low. This is tested by a controlled experiment in which for the present climate the Mediterranean is artificially heated. The resulting increase of SAT and pressure drop over the Mediterranean is comparable to that simulated by the ECMWF and ESSENCE model for the end of this century using an A1b scenario. The development of a heat low at the surface in response to reduced soil moisture and higher SAT is also confirmed in various studies (Ferranti and Viterbo, 2006; Oglesby and Erickson, 1989; Pal and Eltahir, 2003; Fischer et al, 2007). Here we show that the combination of these two mechanisms results in the development of a heat low over the Mediterranean that appears to be the dominant climate response in MSLP over that region.

In contrast, another suggested relationship between soil moisture and atmospheric circulation, the impact on summer blocking characteristics, did not appear to be very strong. Cutting the land-atmosphere interaction in the CLIMSOIL experiment does affect the preferred meridional location of high pressure areas in Europe. This may affect the ability of storm depressions to reach the continent. However, the design of the CLIMSOIL experiment (and similar experiments) does have an undesired impact on the mean state of the climate system (Douville, 2003), which complicates the interpretation of connections between the state of the local soil moisture and remote atmospheric conditions.

The design and scientific arguments of the two studies reported here are very different, and thus the answer to the general question whether soil moisture anomalies have an impact on European atmospheric circulation cannot be expected to be similar. There is an impact on the development of Mediterranean heat low on seasonal timescales (although a significant result is only shown for the large ESSENCE data set, not for the individual members), but the impact on synoptic time scale blockings at higher latitudes is not straightforward.

The feedback mechanisms operating at the synoptic time scales are highly relevant for the assessment of the impact of greenhouse warming on European summer climate. If land-atmosphere feedback indeed contributes to stronger persistence of anomalous (warm and dry) circulation regimes, it is important to investigate this behavior for future climate conditions.

Some additional analyses are still required to demonstrate this mechanism at the synoptic time scale. Apart from the blocking index used here, other circulation characteristics (as those identified by Cassou et al, 2005) may be relevant to address. These can be detected by for instance conditional sampling of these patterns, or by projecting Z500 patterns on predefined (blocked) patterns. Simple measures as the geostrophic wind or horizontal moisture transport may reveal possible non local interactions involving soil moisture anomalies affecting local precipitation rates. This will be the subject of future research.

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