

# 1 Anonymous Referee #1

- a ) The manuscript entitled “Resolution-dependence of future European soil moisture droughts” by Eveline C. van der Linden presents differences between low (standard) resolution and high-resolution runs of EC-Earth with respect to drought conditions over central Europe. They find that droughts happen to be more severe and durable in the high-resolution experiments and explore potential causes leading to the differences between the model runs.

The manuscript is generally in a good shape, mostly well structured and well written. The overall presentation of the results is good with mostly concise and high quality figures. The methodological approach is well explained and technically sound, but some clarifications are needed in this context. However, the considered ensemble is relatively small and some of the conclusions might not be robust. The authors thus need to discuss some limitations of their approach before final publication.

We wish to thank the reviewer for this positive evaluation, and for the constructive comments and insightful suggestions on our paper. They have helped us to substantially improve the quality of the manuscript. Our detailed responses to the comments are presented below.

## 1.1 Major comment

- b ) The ensemble used in this study consists of 6 ensemble members, each containing 5 years of simulation, resulting in a sample size of 30 years. This is mostly fine for assessing the averaging land surface water and energy balance components. However, I doubt the sample size is large enough for assessing droughts. Droughts are extreme events. An extreme drought event is thus defined as a 1/30 year event, which does not correspond to the 1st quantile, simply because the sample size is too small. It would be good if the authors could discuss the robustness of their results and provide a concise reasoning why the ensemble is not larger. Please also provide some insights into why you choose the years 2002-2006 for present day climate conditions. Maybe because these are the last years of the CMIP5 historical runs? I was just wondering because in 2003 central Europe experienced a major drought and heatwave.

Thank you for these questions. We agree that, ideally, extreme drought events as discussed in this paper should be studied with longer model runs. Unfortunately, there are currently no longer runs at this high resolution available for EC-Earth and we currently do not have the resources to increase the ensemble size. This experiment with exceptionally high spatial resolution for a global climate model is computationally very expensive and was therefore performed for multiple research questions. The larger ensemble approach with shorter runs was motivated by a study on the impact of climate change on teleconnection responses to specific tropical SST patterns (Haarsma et al.

2013). As you suggest, the focus of the current paper should therefore be on average changes in the land surface water and energy balance components and on the underlying physical processes rather than on extreme drought events. Therefore we will shift the focus from soil moisture droughts, which are extreme events by definition, to mean changes in soil drying and the associated physical processes, for which 30 years are sufficient. In the revised paper, we will change the title and text accordingly. We will discuss the impact of soil drying on droughts shortly as an impact in the final section of the current paper and we will add a note in which we clarify that a larger sample size is required to obtain robust answers.

Years 2002-2006 are indeed chosen for present-day conditions since these are the last years of the CMIP5 historical runs. This choice was made for multiple research questions and therefore did not consider the major drought and heatwave of 2003. Since this is a model ensemble with perturbed initial conditions, there will not be a major heatwave in each 2003 ensemble member though.

## 1.2 More comments

- c ) Introduction: It might be good to add a few more references in the first part of the introduction. Especially regarding the uncertainty in European drought trends, such as e.g. Samaniego et al., 2018 (DOI: 10.1038/s41558-018-0138-5)

We will add more references in the first part of the introduction, including your suggestion.

- d ) p. 1, l. 22-25: You write that potential evaporation is enhanced through larger atmospheric moisture demand due to the increasing temperatures. You also write that humidity and wind speed might affect evapotranspiration. This is all a bit confusing, since the atmospheric moisture demand is also defined through humidity and wind speed. Maybe consider to rephrase this part.

Thank you for this comment. We understand that this part could be a bit confusing. In the first part of this paragraph we focus on global mean changes (higher temperatures and the associated increase in saturation vapour pressure), whereas the second part focuses on regional changes such as wind speed and associated moisture transports. We will rephrase this paragraph to make the clear distinction between global mean and regional effects.

- e ) p. 2, l. 3: What do you mean by hydroclimatic components?

Precipitation and evaporation. We will clarify this in the text.

- f) P. 2, l. 12-14: This is also a bit confusing. You write about quantifying drought severity, and later drought characteristics (such as e.g., severity). Seems redundant.

Thank you for pointing this out. We will remove the redundancy.

- g) p. 2, l. 18: Please outline what variables are needed to compute PDSI.

Following the suggestions of the second reviewer, we have decided to limit the discussion on the PDSI and other off-line drought metrics and we will concentrate more on studies of actual soil moisture changes. The introduction paragraph focusing on PDSI will therefore be replaced.

- h) p. 2, l. 26-27: The north-south wetting vs. drying pattern in Europe is actually a well-known feature which was assessed in many studies.

We agree that this large-scale pattern has been shown in many studies. However, our point is that the magnitude of these changes is highly uncertain and that over many land areas in the transition regions between north and south it is even uncertain whether there will be a wetting or drying trend. Regionally, there are still large uncertainties. We will rephrase this part to avoid confusion.

- i) Sec. 2.1 and 2.2: Why do you choose the years 2002-2006? How do the model runs differ? Why don't you use more recent SST data? What version of HTESSEL do you use? Does HTESSEL include river routing or where does the runoff go? Are there open water bodies in HTESSEL?

We choose years 2002-2006 because these are the final years of the CMIP5 historical runs. Since the individual ensemble members have perturbed initial conditions, the exact years are not of major relevance. We will explain this more extensively in the text.

The model experiments were performed about five years ago, therefore the SST data are not the most recent ones. However, our purpose is to demonstrate the effect of model resolution on future soil moisture changes. To demonstrate this effect these experiments were suitable.

Open water bodies in HTESSEL are represented by open (or frozen) water tiles in the land surface scheme, as described in the data and methods section. HTESSEL does not include river routing. For each grid cell, runoff is transferred to a designated region in the ocean.

We will add these explanations to the 'data and methods' section.

j ) p. 5, eq. 1: Do you really mean  $d\theta$  within the integral? Shouldnt it just be  $\theta$ ?

Thank you for noticing this mistake. We will correct it in the revised manuscript.

k ) p. 8, l. 15: The validation period is 1982-2011, right? Might be worth to mention this here as well. What happens if you choose just 2002-2006 as validation period? How is an event like 2003 represented in the model?

Thank you for these questions. We understand that this period could be confusing. We will add the section on model validation to the observations description, since this is what the observations are used for. Please note that we use an ensemble of model simulations with perturbed initial conditions (we will explain this in the experimental setup). This indicates a ‘present-day’-like forcing similar to 2002-2006, but due to the perturbed initial conditions these years are (and should) not be exactly the same as the observed 2002-2006 conditions. The initial conditions create climate variability, so the simulated 2002-2006 years are not supposed to be exactly the same as the observed 2002-2006 state. Moreover, using only 2002-2006 as a validation period is not statistically robust, since the period only represents five years. The impact of internal climate variability on such a time scale is large, both in the model and in observations. To compare the climatology, you need to compare about 30 years of data. That is why we use a validation period of 30 years for the observations as well. We will explain this in the text.

l ) p. 9, eq. 4: Well,  $dS/dt$  is not necessarily just soil moisture. This might include also snow/ice water storage and water in open water bodies. How is this represented in HTESSEL?

In HTESSEL, a grid box is either 100% land or 100% sea. Each non-land point (grid point with less than 0.5 land cover) can have two fractions, open and frozen water. Open water bodies are thus not included in  $dS/dt$ , which only takes land grid points into account. Each land point (grid point with 0.5 or more land cover) can have six fractions of which two include snow (snow on low vegetation/bare ground and high vegetation with snow underneath). Snow is treated as an additional surface layer on top of the upper soil layer. You are therefore right that snow and ice (permafrost) are part of the soil water  $S$  in this context and a melt term should be added. However, since we focus on the warm season months and choose our study region outside mountainous regions, ice and snow can be neglected in the land surface water balance. We will add this explanation in the text.

m ) p. 9, l.10-11: Does the soil water content determines runoff?

We understand that this sentence implies a causal relation between soil water content and runoff, which is only partly correct (as described under the next comment) since it is rather a negative feedback. We will rephrase this paragraph.

- n ) p. 9, l. 23-27: Here it would help if you could provide more information on how runoff is treated in HTESSEL.

Runoff consists of two parts: surface runoff and subsurface runoff. Whenever precipitation or snow melt occurs a fraction of the water is removed as surface runoff. The ratio runoff/precipitation scales with the standard deviation of orography, and depends on the complexity represented in the gridbox, as well as on soil texture and soil water content. Subsurface runoff is associated with free drainage at the bottom. We will add this information in the description of the land surface scheme and will rephrase these sentences accordingly.

- o ) p. 12, l. 19: remove "is"

Thank you, we will correct this sentence.

## 2 L. Samaniego (Referee #2)

### 2.1 General comments

- a ) In this manuscript, the authors use a high resolution 6-member ensemble of the general circulation model EC-Earth to get a better and more realistic position of the storm track, which in turn leads to improved representation of the soil moisture (SM) conditions in the future and characterization of SM droughts. The study domain is the central-western Europe under the RCP4.5 emission scenario. One of the major claims of the authors is that high resolution CMIP5 GCMs leads to an underestimation of soil drought characteristics.

The subject covered by this paper is a highly relevant research topic for practitioners and researchers in hydro-climatology and climate change impacts. I welcome this study because I am convinced that high resolution GCMs will improve the estimates of future precipitation and temperature patterns because of better parameterization of convective precipitation and land-atmosphere feedbacks.

In the present state of the manuscript, nevertheless, there are many shortcomings that have to be clarified before publication.

We thank L. Samaniego for his positive evaluation and the constructive and valuable comments concerning our manuscript, which helped to considerably improve the quality of the paper. We have studied the comments carefully and made major corrections. Our detailed responses to the comments are presented below.

## 2.2 Specific comments

The following technical shortcomings should be addressed in the revised manuscript:

- b) The literature of future soil moisture drought projections should be updated and the insights of these studies should be put in context of this interesting study. I recommend to include:
- Samaniego, L., S. Thober, R. Kumar, N. Wanders, O. Rakovec, M. Pan, M. Zink, J. Sheffield, E. F. Wood, and A. Marx (2018), Anthropogenic warming exacerbates European soil moisture droughts, *Nature Climate Change*, 5, 111721, doi:10.1038/s41558-018-0138-5.
  - Hanel, M., O. X. I. Rakovec, Y. Markonis, P. M. X. ca, L. Samaniego, J. Kysely, and R. Kumar (2018), Revisiting the recent European droughts from a long-term perspective, *Scientific Reports*, 8(1), 111, doi:10.1038/s41598-018-27464-4.
  - Hirschi, M. et al. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nat. Geosci.* 4, 1721 (2010).
  - Huang, J., Yu, H., Guan, X., Wang, G. & Guo, R. Accelerated dryland expansion under climate change. *Nat. Clim. Change* 316, 847171 (2015).
  - Berg, A., Sheild, J. & Milly, P. C. D. Divergent surface and total soil moisture projections under global warming. *Geophys. Res. Lett.* 44, 236244 (2017).
  - ... and references therein.

Thank you for these recommendations. We will update and revise the introduction with these relevant recent insights and add the suggested references in the text.

- c) L7, P4. Parametric uncertainty plays a very strong role in soil moisture predictions and corresponding drought characteristics (see Samaniego et al, JHM, 2013). For this reason, I consider that a ensemble of 6 members and a single land surface model is too small an ensemble to provide conclusive evidence.

We agree that a larger ensemble of different models should be used to obtain robust answers about the impact of model resolution. The use of a single model allowed us to put emphasis on mechanistic explanations for the differences between model resolutions. Certainly, these results should be verified with a larger systematic ensemble of high resolution model simulations such as the CMIP6-endorsed HighResMIP, which are currently not available. Therefore, we will add notes in the manuscript to emphasize that a larger ensemble is required to obtain conclusive evidence.

- d) L17 ff P2: Please clarify in the revised manuscript that the PDSI should not be used for climate impact studies because it does not perform well un non-stationary climate.

See the explanation provided in the methods section of Samaniego et al. NCC 2018 and in its supplementary information (Fig S8, S9). Contrary to what Sheffield et al. stated in his Nature paper, the reason of the poor performance of PDSI is more likely related to the autoregressive formulation of this index rather than in the temperature-based PET formulation used in the original formulation of PDSI. The text as it written, put in context with these recent insights, is misleading or at least incomplete.

Thank you for this insightful suggestion. We will add the explanation provided by Samaniego et al. NCC 2018 in the introduction. In addition, we will strongly reduce the paragraph that discusses the PDSI results and will shift the focus to soil moisture projections instead.

- e ) L30 ff P2: I strongly suggest to avoid comparisons with the PDSI index (see last point) in future projections. EDgE results (<http://edge.climate.copernicus.eu>), which are based on downscaled CMIP5 forcings and a multi model ensemble, may be more interesting and realistic than the PDSI estimates. Data is available in nc format upon request (contact L. Samaniego if required).

We clearly understand your point. We will remove the paragraph in which a comparison of PDSI results is made and we will revise the introduction to shift the focus to actual soil moisture projections instead of drought metrics.

- f ) L35 ff P2: More recent insights on the future soil moisture droughts can be found in Samaniego et al, NCC 2018, e.g., an increase drought area by  $40 \pm 24\%$  by an increase of 3 K. This study also offers a regional perspective that can be put in contrast with the present study.

We will add a regional comparison with this study in the conclusions section.

- g ) L9 P4 Why only the RCP4.5 is used in this study? In my opinion RCP6.0 or 8.5 would be more interesting in the context of future impacts.

Although we would have liked to include other RCPs, we did not have the resources to repeat the runs at this very high resolution for other RCPs as well. Therefore, RCP4.5 was chosen since it is one of the middle scenarios. If changes are significant in RCP4.5, they are very likely also significant in the higher RCPs. Our aim is to demonstrate the impact of spatial resolution on future soil drying and to provide a mechanistic explanation. For this goal, one RCP was considered sufficient.

- h ) L9, P5 I strongly suggest to use the soil moisture index (see Samaniego et al. JHM 2013, code written in Fortran, it is open source) instead of a soil moisture anomaly. The

advantage of SMI is that the SM is mapped to a 0-1 space that allows comparison over time and space. It facilitates the calculation of drought area, duration and magnitude as presented in Samaniego et al. JHM 2013, Vidal et al. HESS 2010, Andreadis et al. JHM 2005, Sheffield et al. JGR, 2004). The index used in eq.3 is difficult to put in context with past studies.

Thank you for this suggestion. We understand your point and agree that SMI (as calculated in Samaniego et al. JHM 2013) is a good measure for multi-model and regional intercomparison studies. In our study, however, we mainly focus on mean changes in soil drying (aridity) rather than on soil moisture droughts (extremes). In addition, we do not focus on regional patterns but on a regional average value over central-western Europe. From your comment, we have realized that this main focus was not clear enough from the paper as written. Therefore, we will revise the paper accordingly by changing the title and structure of the paper. We will remove the term ‘drought’ from the title and replace it with ‘soil moisture changes’. Furthermore, we will include more specifically the study region ‘central-western Europe’ rather than ‘Europe’ in the title. We will also restructure the paper by moving the section on droughts towards the impact section at the end of the paper. The main body of the paper will be clearly focused on regional average soil moisture changes and its underlying mechanisms. The absolute drying measure (expressed in soil moisture changes) facilitates the quantitative comparison of different water balance components (precipitation, evapotranspiration, runoff, soil moisture storage) in terms of magnitude.

- i) L10 P7. Please estimate the severity as used in literature (see previous references). Very interesting will be the changes of the curve area-severity relationship with the resolution of the GCM. The code to estimate this curve as presented in Samaniego et al. JHM 2013 is open source.

Thank you for this suggestion. We have computed the severity based on percentile thresholds of the soil moisture anomaly distribution, as is done in for example Burke (2007, JHM) and Zhao (2015, J. Clim.) for CMIP5 models. The results show that broad change pattern in EC-Earth is similar to other CMIP5 simulations. We will add this in the text. Considering the area-severity relationship, we believe this would be very interesting. However, we did not concentrate on drought area in our study since we focus on a regional average value over the Rhine-Meuse drainage basin and not on the entire European continent. We believe that your suggestion would be an excellent idea for a study focusing on the continental scale changes, but in our current study we only focus on a relatively small region in central-western Europe. Therefore, we will take your suggestion into account for a future study focussing on the impact of model resolution on future European patterns of droughts with multiple global climate models.

- j) L5 P9. The term anomaly as defined in this paragraph is misleading. It is an average change over the domain. I recommend to estimate the change in aridity as defined in



Samaniego et al. NCC, 2018 since it is a better estimate of the changes in soil moisture under extreme conditions (droughts). A similar index can be developed to wetter events (just the opposite of the distribution function). I recommend to estimate changes over natural regions to avoid compensation. Some regions experience increases in wetting (Scandinavia), others the opposite (Mediterranean).

We understand that this terminology could be a bit misleading, therefore we will not call future mean changes in soil moisture or other water balance components ‘anomalies’. We will change this terminology throughout the text.

As mentioned before, we believe that there was some confusion in the text about ‘droughts’ (extreme conditions) and ‘drying’ (mean changes). The main focus of our paper is not on extreme conditions but on mean future changes. Where appropriate, we will clarify this in the text.

Our focus region is roughly over the Rhine-Meuse drainage basin in central-western Europe, which is a natural region. In Figure 2 we show that the changes in aridity over this region are not compensating but have the same sign.

- k ) L22 P5, the selection of percentiles is a bit ad-hoc. Why not round numbers like 1, 2, 5, 10, 90, 95, 99 percentiles. Remaining analysis should be updated.

We understand that these percentiles could be confusing, since they are indeed not round numbers. This is because we only have 30 years of data. Therefore we can only compute e.g. 1/30, 2/30 or 6/30 year events, which we classified as extreme, severe, and moderate droughts, respectively. To avoid confusion we have rewritten this paragraph to make this clear. In addition, we have moved this subsection to the final part of the paper which focuses on extremes rather than mean changes in soil moisture.

- l ) L11 P14, This hypothesis is highly interesting and should be done as proposed in the future. In this study, however, authors should compare the results existing CMIP5 models (e.g., based on EDgE data ) to see if the hypothesis holds with present insights (see above).

Thank you for this suggestion. Unfortunately, we do not (yet) have future simulations of other high resolution models to test our hypothesis at the moment, since the model runs were performed with only one global climate model. Existing CMIP5 models do not have this high spatial resolution. In fact, EC-Earth in its ‘standard’ CMIP5 resolution has already a high spatial resolution compared to other CMIP5 models. In a future study, in which we will have systematic model simulations with multiple high resolution GCMs, we will be able to make this comparison.

# ~~Resolution-dependence~~ Impact of future European climate model resolution on soil moisture droughts projections in central-western Europe

Eveline C. van der Linden<sup>1</sup>, Reindert J. Haarsma<sup>1</sup>, and Gerard van der Schrier<sup>1</sup>

<sup>1</sup>Royal Netherlands Meteorological Institute, De Bilt, Netherlands

*Correspondence to:* Eveline van der Linden (linden@knmi.nl)

**Abstract.** Global climate models project ~~an intensification of future soil moisture droughts~~ widespread decreases in soil moisture over large parts of Europe. This paper investigates the impact of model resolution on the ~~severity and seasonal cycle of future European droughts~~ magnitude and seasonality of future soil drying in central-western Europe. We use a ~~6-member ensemble of~~ the general circulation model EC-Earth to study two 30-year periods representative of the start and end of the 21st century under low-to-moderate greenhouse gas forcing (RCP4.5). In our study area, central-western Europe, at high spatial resolution (~25 km) ~~droughts are soil drying is~~ more severe and ~~start starts~~ earlier in the season than at standard resolution (~112 km). Here, changes in the large-scale atmospheric circulation and local soil moisture feedbacks lead to enhanced evapotranspiration in spring and reduced precipitation in summer. A more realistic position of the storm track at high model resolution leads to reduced biases in precipitation and temperature in the present-day climatology, which act to amplify future changes in evapotranspiration in spring. Furthermore, in the high resolution model a stronger anticyclonic anomaly over the British Isles extends over ~~our study region~~ central-western Europe and supports soil drying. The resulting drier ~~soil~~ future land induces stronger soil moisture feedbacks that amplify drought drying conditions in summer. In addition, soil moisture-limited evapotranspiration in summer promotes sensible heating of the boundary layer, which leads to a lower relative humidity with less cloudy conditions, an increase of dry summer days, and more incoming solar radiation. As a result a series of consecutive hot and dry summers appears in the future high resolution climate. The enhanced drying at high spatial resolution suggests that future projections of central-western European ~~droughts~~ soil drying by CMIP5 models have been potentially underestimated. Whether these results are robust has to be tested with other global climate models with similar high spatial resolutions.

## 1 Introduction

~~Soil moisture drought constitutes a serious hazard to regional European crop yields, water resources, and energy supplies, with major economic impacts (???)~~ Global climate models project that global aridity over land will increase in response to anthropogenic climate warming (Feng and Fu, 2013; Scheff and Frierson, 2015; Huang et al., 2016). Nevertheless, there remains considerable uncertainty concerning ~~trends in European droughts in response to anthropogenic climate warming~~ regional trends in soil moisture (Greve and Seneviratne, 2015). Soil drying is a result of complex interactions between ~~precipitation, water storage in the soil, and evapotranspiration, which are presumably affected by climate warming~~ the land surface and the

atmosphere (Seneviratne et al., 2006; Hirschi et al., 2011; Seneviratne et al., 2010). Anthropogenic climate change expectedly induces enhanced potential evaporation enhances global mean evaporation and precipitation due to the larger moisture demand of the atmosphere with higher air temperatures (Feng and Fu, 2013; Scheff and Frierson, 2014). Under conditions with sufficient soil moisture, this will lead to an increase in actual evapotranspiration, assuming other variables remain the same. However, atmospheric humidity and wind speed could also change with climate warming and might affect evapotranspiration the net impact of these increases on land aridity and droughts remains difficult to predict (Sherwood and Fu, 2014). Projections of soil moisture in Europe for the 21st century indicate pronounced soil drying and an associated increase in drought area and intensity, but these changes are strongly dependent on season and location (Ruosteenoja et al., 2018; Samaniego et al., 2018). Regionally, future changes in evaporation over land will depend on the local soil water content and surface characteristics, but also on changes in available energy, wind speed, air temperature, and air humidity. At the same time, changes in precipitation are spatially variable between different future projections, leading to enhanced uncertainty at regional spatial scales (Kumar et al., 2013). Moreover, soil moisture itself interacts with the hydroclimatic components through various feedback processes (Seneviratne et al., 2006, 2010). How these processes will change under climate warming in individual regions is highly uncertain, whereas reliable regional information is especially important in order to assess future drought risks.

Studying drought changes under climate warming is further complicated by the limited quality and length of observations on historical drought changes. Profile measurements of past soil moisture are sparsely distributed and too short to encompass robust trends (Seneviratne et al., 2010), while satellite-based retrievals are less detailed and only depict up to the top 10 cm of soil (?). As an alternative for in situ and remote sensing measurements, reconstructions of soil moisture have been developed by forcing soil moisture models with historical meteorological data from observations or reanalyses. Using a soil moisture reconstruction, ? revealed a significant soil moisture drying trend for the Czech Republic between the period of 1961–2012 in late spring and early summer. A more essential for adaptation planning.

A frequently used approach to study historical changes in drought land aridity or droughts is to use various drought indices to quantify drought severity, corresponding to different types of drought (e.g., meteorological, agricultural, or hydrological) and drought characteristics (e.g., severity and duration)(??). Owing to the variety of drought indices, assessments of recent dryness trends show large inconsistencies (?).

A prominent metric to characterise soil moisture drought is the off-line computed indices, for example, the prominently used Palmer Drought Severity Index (PDSI) (Palmer, 1965), which is essentially a simple water balance model. In the PDSI, potential evaporation is often simplified to the parameterisation of Thornthwaite (PDSI<sub>th</sub>)(?), which is only based on temperature and latitude. ? showed that the PDSI<sub>th</sub> suggests global drying over the past 60 years, but that it may be too simplistic to assess large-scale droughts. They repeated the analysis with the more elaborate Penman-Monteith parameterisation for potential evaporation (PDSI<sub>pm</sub>)(??), which indicates that there have been little changes in global droughts over the past 60 years. Moreover, different forcing data of the PDSI<sub>pm</sub> index add to the uncertainty of European drought response to climate warming. For example, ? pointed at high disparities between precipitation datasets used in the calculation of drought indices. After excluding precipitation datasets with low coverage over land, ? computed spatial patterns of drying with the self-calibrated version of PDSI<sub>pm</sub> (sc\_PDSI<sub>pm</sub>). They reported a consistent drying trend for southern Europe and a wetting

trend for northern Europe between the period of 1950–2012. In addition, they demonstrated that climate warming and the associated vapour pressure deficit over land have enhanced global drying trends since the 1980s. However, recent studies show that these metrics often overestimate future increase in drought and decrease in water availability (Roderick et al., 2015; Milly and Dunne, 2016). Swann et al. (2016) and Berg et al. (2017) argue that projections of future aridity should therefore be based on direct output of the simulated land water balance (precipitation, evapotranspiration, runoff, and soil moisture) rather than on off-line aridity metrics.

Regions with consistent increases in observed drought conditions are only partly consistent with climate model simulations from the fifth phase. Various studies have used direct model output to assess future changes in aridity. Climate model simulations of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) based on the PDSI<sub>pm</sub> model-simulated historical drying appears to be consistent with observation-based estimates over some regions, including southern Europe, but regional changes are still dominated by natural variability (?). For the RCP4.5 emission scenario (low-to-moderate greenhouse gas forcing), model projections of PDSI-based drought frequencies show an increase over nearly all land areas (Zhao and Dai, 2015). Accordingly, the simulated top 10 cm project a decline of the upper 10 cm soil moisture content is projected to decline over most of Europe (Zhao and Dai, 2015). However, using the Berg et al. (2017) state that soil moisture changes near the surface are more negative than total column soil moisture changes, and can be even of opposite sign in middle and high latitude regions. Using the same suite of models (CMIP5) but including the entire soil moisture profile in their analyses, Orłowsky and Seneviratne (2013) indicate a large inter-model spread over central-western Europe, with drought projections ranging from pronounced drying to wetting conditions. Therefore the vertical distribution of drying should be taken into account when studying future soil drying and water availability. Focusing on seasonality of soil drying, Ruosteenoja et al. (2018) show that summer and autumn exhibit strong drying trends in central and western Europe, while all-season drying occurs in southern Europe. This emphasises the necessity to study seasonal instead of annual mean values for future drying.

Orłowsky and Seneviratne (2013) indicate that by the end of the 21st century, model formulation of global climate models (GCMs) will become the dominant source of spread in drought projections, especially for soil moisture drought and at the regional scale. This suggests that improvements of GCMs could considerably reduce the intermodel-spread in future drought inter-model spread in future soil moisture projections. Several studies have shown that high resolution (~25 km horizontal resolution) GCMs mimic the present-day climate state more realistically than standard resolution models, since they resolve physical processes more explicitly (Delworth et al., 2012; Jung et al., 2012). Therefore, high resolution simulations are generally expected to be more reliable in their representation of future climatic changes. For example, post-tropical cyclones and mid-latitude storm tracks that bring precipitation towards Europe could change their path in a future climate and are dependent on model resolution (Baatsen et al., 2015; Willison et al., 2015). Furthermore, atmospheric blocking frequencies (Jung et al., 2012; Berckmans et al., 2013) and atmospheric moisture transport from the ocean to the continents (Demory et al., 2014) are better represented at finer model resolution. Also local-scale land surface-atmosphere feedbacks related to soil moisture are arguably dependent on model resolution (Lorenz et al., 2016). Using high resolution simulations thus could improve our physical understanding and provide potentially better estimates of future changes in drought soil drying. This will lead to enhanced confidence in future drought soil moisture projections at a regional level.

Motivated by these studies, this paper investigates for central-western Europe the consequences of climate warming for the regional hydrology with a high resolution global climate model. To investigate the role of resolution we have repeated the experiment and analyses at standard CMIP5 resolution for the same climate model. The use of a single high-resolution model allows us to put emphasis on mechanistic explanations for the differences in regional hydrological changes between model resolutions. We assess what the role is of local feedbacks and the large-scale circulation on the response of regional soil moisture storage to climate warming. The study area is central-western Europe, concentrated on a relatively small spatial scale and therefore riddled with large inter-model differences in future hydrological projections. While most studies focus on annual mean changes, our analysis focusses on ~~warm-season~~ warm season months (April–September). Furthermore, we will analyse changes in the total soil moisture column, which are most relevant for water availability and have been shown to exhibit large inter-model uncertainty in future drying over central-western Europe in standard resolution GCMs (~~Orlowsky and Seneviratne, 2013~~)(Orlowsky and Seneviratne, 2013; Berg et al., 2017).

The present paper is outlined as follows. Section 2 presents the data~~and methods, including a description of droughts definitions, methods, and a validation of the present-day climate~~. Section 3 describes the simulated soil ~~moisture drought drying~~ characteristics, including climate- and resolution-induced changes in its spatial distribution ~~, seasonal cycle, and severity~~. ~~The evolution and seasonal cycle. The drivers~~ of central-western European ~~droughts is soil drying and resolution-induced differences are~~ presented in section 4. Here, the land surface water balance components and their interaction with the surface energy balance are examined in detail. Also the effect of changes in the large-scale atmospheric circulation is studied. Thereafter, section 5 shortly describes climatic impacts that are closely related to ~~droughts~~soil drying, including soil moisture droughts, warm extremes, and dry days. Finally, section 6 contains a summary and conclusions.

## 20 2 Data and methods

### 2.1 Model and experimental setup

This study is based on high-resolution climate model simulations that were also used in previous studies to assess the impact of high resolution on several climatic processes (e.g., Haarsma et al., 2013; Baatsen et al., 2015). The simulations were carried out using the EC-Earth V2.3 model (Hazeleger et al., 2012) at a resolution of T799L91 (~25 km horizontal resolution, 91 vertical levels), which was the operational resolution at the European Centre for Medium Range Weather Forecasts (ECMWF) from February 2006 until January 2010. Different model runs were performed for the present-day (2002–2006, final years of historical CMIP5 run) and future (2094–2098) climate. Each of these datasets consists of a 6-member ensemble spanning 5 years with perturbed initial conditions, resulting in a 30-year dataset for each climate state. In the present-day simulations, observed greenhouse gas and aerosol concentrations were applied, while future concentrations were derived from the RCP4.5 scenario (Van Vuuren et al., 2011). Sea surface temperatures (SSTs) were imposed using daily data at 0.25° horizontal resolution from NASA (<http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php>) for the 2002–2006 period. The SSTs for the future were calculated by adding the projected ensemble mean change using the 17 members of the coupled climate model ECHAM5/MPI-OM in the ESSENCE project (Sterl et al., 2008) under the SRES A1B emission scenario (Nakicenovic, 2000).

This scenario is compatible with the RCP4.5 scenario but the median global temperature increase by the end of the twenty-first century is about 1 °C smaller (Rogelj et al., 2012). Further details on model setup and spin-up procedures can be found in Haarsma et al. (2013) and Baatsen et al. (2015). The simulations were repeated at the standard CMIP5 resolution of T159L62 (~112 km horizontal resolution, 62 vertical levels) for the same climate model configuration. The generated data have been stored on 5 pressure levels (850, 700, 500, 300 and 200 hPa) at 6-hourly intervals, while surface fields have been saved on a 3-hourly basis.

## 2.2 Land surface scheme

The land surface scheme plays a central role in simulating soil moisture ~~droughts~~changes. The land surface scheme used in EC-Earth is HTESSEL (Balsamo et al., 2009). Up to six tiles are present over land (i.e., bare ground, low and high vegetation, intercepted water, and shaded and exposed snow) and two over water (i.e., open and frozen water), with separate energy and water balances. Considering the water balance, precipitation is initially collected in the interception reservoir until it is saturated. Then, excess precipitation is partitioned between surface runoff and infiltration into the soil column. ~~When the imposed water flux exceeds the maximum possible soil infiltration rate, excess water is taken as surface runoff~~The ratio runoff/precipitation depends on the terrain complexity represented in the grid cell as well as on the soil texture and soil water content. The vertical discretization of the land surface scheme considers a four-layer soil that can be covered by a single layer of snow. The depths of the soil layers are in an approximate geometric relation (0.07 m for the top layer and then 0.21, 0.72, and 1.89 m for the layers underneath). HTESSEL does not include river routing. Instead, runoff is collected in pre-defined river basins and distributed instantaneously into ocean points nearby the outlets of major rivers, without considering delayed river transport. At both model resolutions all soil and vegetation characteristics of HTESSEL are kept constant. An evaluation of HTESSEL in the Transdanubian region in Hungary by Wipfler et al. (2011) reveals that HTESSEL slightly underpredicts the seasonal evaporative fraction as compared to satellite estimates. The underestimation is most prominent for low evaporative fractions with a maximum prediction error of 30% for individual grid cells.

## 2.3 Observations and validation

To ~~evaluate the EC-Earth simulations we have used the~~gain some confidence in the model performance we have validated the present-day climate over central-western Europe. This is done for simulated present-day precipitation and near-surface air temperature. The latter is used instead of evapotranspiration since observations of evapotranspiration are scarce and air temperature mainly determines the evaporative demand of the atmosphere. For the validation we have used the observational E-OBS gridded dataset (0.5° horizontal resolution; version 11.0) for precipitation and 2 m-temperature. The E-OBS data originated from the EU-FP6 project ENSEMBLES (Haylock et al., 2008) and is now maintained and updated by the data providers in the ECA&D project (<http://www.ecad.eu>). The dataset is based on meteorological station measurements and is designed to provide the best estimate of gridbox averages to enable direct comparison with climate models. The period used to compare the observational E-OBS data against EC-Earth simulations is 1982–2011. This period covers 30 years to make a robust comparison of the climatology.

## 2.4 Drought definitions

Figure 1a and 1b show the annual cycle of precipitation and near-surface air temperature over the analysis domain (the black box in Fig. 2) for E-OBS observations and the EC-Earth model simulations at high and standard resolution. Precipitation biases of present-day climate simulations show that it is too wet over the study region (Fig. 1c). As discussed in Van Haren et al. (2015b), this is due to a too zonal position of the storm track over the east Atlantic Ocean and Western Europe. This is a common bias in CMIP3 and CMIP5 models (Haarsma et al., 2013; Van Ulden et al., 2007). The wet bias is reduced in the high resolution version of EC-Earth primarily due to a less zonal orientation of the storm track (Van Haren et al., 2015b).

Surface air temperature biases show that the T159 version is a bit too cold compared to observations (Fig. 1d), whereas T799 is somewhat warmer, especially in summer. The warmer temperature is associated with the less zonal orientation of the storm track which makes the summer climate less maritime and more continental. The high resolution simulations thus perform better with respect to the E-OBS precipitation and temperature data than the standard resolution model. We shall see later that this contributes to enhanced future drying at high resolution.

## 2.4 Definitions

~~Soil moisture droughts, also referred to as agricultural droughts, are characterized by soil water availability.~~ Throughout this paper we quantify the intensity of ~~agricultural droughts soil drying~~ by the soil moisture anomaly ( $S'S'$ ). To compute this ~~drought aridity~~ index, first the soil water content ( $SS$ ) is computed from integrating volumetric soil moisture content ( $\theta$ ) over the total soil profile in the land surface scheme:

$$S = \int d\theta dz \quad (1)$$

For comparison of soil moisture in the present and future climates, the present climatology of soil moisture content averaged over all ensemble members ( $S_0S_0$ ) is used to compute soil moisture anomalies in both the current and future climate. For each ensemble member and year, anomalies of soil moisture content ( $S'S'$ ) are computed for each grid point by subtracting  $S_0S_0$  from the simulated soil moisture content:

$$S' = S - S_0 \quad (2)$$

Threshold values for soil moisture droughts are based on distributions of monthly-mean soil moisture anomalies for the present climate consisting of 30 years of data. They are computed per month, considering each individual year as ~~independent~~independent. Seasonal threshold values are based on three-monthly averages. For each grid cell, extreme, severe, and moderate droughts are classified to be ~~the 1st, 5th, and 20th percentile of the  $S'$  distribution, respectively. With 30 years of data per period, the nearest percentiles that can be calculated are 3.3% (1 out of 30), 6.7% (2/30, and 6/30 )year events, corresponding to percentiles 3.3, 6.7, and 20 % (6/30) of the  $S'$  distribution, respectively.~~ As a result, by definition, for the current climate each land surface grid cell is for each individual month on average for 3.3%, 6.7%, and 20% of the ~~ensemble members sampling years~~ in the extreme, severe, and moderate drought severity class (s), respectively.

Drought frequency ( $f$ ) is defined as the percentage of months with soil moisture anomalies below a certain drought threshold value. To measure the impact of resolution on the frequency of future droughts we define the resolution factor (RF). RF is defined as the ratio of frequency of droughts in T799 ( $f_{T799,s}$ ) to T159 ( $f_{T159,s}$ ) for each drought severity class:

$$\text{RF} = \frac{f_{T799,s}}{f_{T159,s}} \quad (3)$$

5 Also computed is the corrected resolution factor (CRF) to correct for differences in the present-day climate between T159 and T799. CRF is defined similarly to RF but uses the threshold values of the T159 present-day climate to compute the frequency of future droughts at T799 resolution. If CRF and RF are significantly different, this means that differences in the present-day soil moisture climatology could partly explain differences in the frequency of projected droughts.

### 3 Drought characteristics Soil moisture projections

#### 10 3.1 Spatial-Horizontal distribution and analysis domain

Spring (April–June) and summertime (July–September) European distribution of future soil moisture anomalies for the high resolution model are shown in Figures 2a and 2b, respectively. These seasonal definitions are slightly different from the common definition and chosen to focus on relevant physical processes that will be discussed later in this paper. Differences in the climate change signal between the high and standard resolution simulations are also depicted (Fig. 2e,d,c–d). Both  
15 model resolutions simulate strong increases in future spring and summertime droughts-drying over large parts of the Mediterranean, especially in southeastern Europe. This broad change pattern in EC-Earth is similar to other CMIP5 model simulations (Zhao and Dai, 2015). Furthermore, in the high resolution model a new drought-prone area emerges that is located over central-western Europe, roughly coinciding with the area stretching from southwest Germany into Poland and the northern Balkan. This region experiences more severe droughts-drying in future in the high resolution than in the standard resolution simulations.  
20 Model resolution seemingly plays an important role for projections of future droughts-soil drying over central-western Europe. This partly motivates our choice for the study region in central-western Europe, defined as the area between 47–52°N and 5–10°E (black box in Fig. 2), which roughly encompasses the Rhine-Meuse drainage basin and partly overlaps with the region studied by Van Haren et al. (2015a). The choice for this region is further motivated by the importance of this area for the fresh water supply to the Netherlands and Belgium, which are situated in the lower part of the Rhine-Meuse delta. Consumable  
25 water, shipping, irrigation, and cooling of power plants all depend on sufficient water supply from the Rhine-Meuse basin and could be affected by severe droughts-water depletion.

#### 3.2 Seasonal cycle and vertical distribution

Soil moisture content over central-western Europe exhibits a large annual cycle and reaches its minimum value in September (Fig. 3a). Note that these values depend on the soil depth of the land surface scheme, and therefore are model dependent. For the present-day (baseline) climates, there are no significant resolution-dependent differences in monthly soil moisture content values, except for March. The projected changes in soil moisture content are, however, strongly season and



~~resolution-dependent~~resolution dependent. At both resolutions, the amplitude of the annual cycle is larger in the future climate than in the present-day climate due to drier soils around the annual soil moisture minimum.

Figure 4 depicts monthly volumetric soil moisture anomalies over the four soil layers of HTESSSEL under 2100 conditions, with respect to the current climate. At standard resolution, future soil moisture reduction is mainly confined to late summer and autumn. An almost full recovery of soil moisture occurs in late winter for top soil layers, and in late spring for deeper layers. On the other hand, high resolution simulations exhibit year-round soil moisture depletions compared to the climate at the start of the 21st century. At high resolution, the soil moisture content over the top three soil layers of HTESSSEL restores to its former state in late winter, but the soil in the fourth layer remains drier than current values, suggesting a year-round reduction of ground water. The reduced soil water ~~also impacts~~ is compatible with lower year-round runoff values (Fig. 3b).

As a result, in late spring (April–June), future soil moisture content (Fig. 3a) differs significantly from present-day values at high model resolution ( $\langle S'_{\text{S}} \rangle = -45$  mm) whereas there is no significant change at standard model resolution ( $\langle S'_{\text{S}} \rangle = -6$  mm). At the start of summer, the soil is thus preconditioned towards drier conditions in T799 than in T159. Furthermore, future late summer (July–September) soil moisture depletion is on average more severe in T799 ( $\langle S'_{\text{S}} \rangle = -90$  mm) than in T159 ( $\langle S'_{\text{S}} \rangle = -50$  mm) (Welch t-test:  $p = 0.01$ ). The more severe soil desiccation in late spring at high resolution is thus maintained throughout the late summer months. In the rest of the paper we therefore focus on the modelled differences in late spring (preconditioning phase) and late summer (maintenance phase). For brevity, from now on we will refer to ‘spring’ for the period April to June and ‘summer’ for the period July to September.

### 3.3 Severity

~~The changes in the seasonal cycle of soil moisture content affect the severity of future droughts under climate warming. Consider Figure 10, which depicts the  $S'$  distributions of spring and summer at T799 and T159 resolution, for the present and future climates. The drought threshold values as defined in section 2.4, which are based on these distributions, are also indicated. The associated frequency of extreme, severe, and moderate droughts by the end of the twenty-first century, averaged over central-western Europe, can be seen in the bar charts of Figure 11.~~

~~In spring, model resolution has a high impact on the frequency of extreme, severe, and moderate droughts. In the T159 simulations, extreme future springtime droughts occur about once every thirty years over central-western Europe ( $F_{\text{T159,extreme}} \simeq 3\%$ ) (Fig. 11), which is comparable with the current climate. There is also no significant change in the frequency of springtime severe and moderate droughts in T159. This is clearly visible in the large overlap of the present-day and future climates in the distributions of spring soil moisture anomalies for T159 (Fig. 10a). In contrast, in T799, the springtime soil moisture anomaly distributions indicate that the frequency of extreme droughts increases due to a shift towards drier conditions in a future climate. Future extreme springtime droughts are about seven times more frequent in T799 than in T159 ( $RF_{\text{extreme}} \simeq 7.3$ ) and occur about once every four years ( $f_{\text{T799,extreme}} \simeq 24\%$ ) (Fig. 11). Note here that the threshold value for T799 extreme springtime droughts (red line) is more or less similar to the threshold value in T159 due to the similarity of the baseline soil moisture distributions. Also, the frequency of severe ( $f_{\text{T799,severe}} \simeq 41\%$ ) and moderate ( $f_{\text{T799,severe}} \simeq 71\%$ ) droughts increases in the~~

high-resolution simulations. This is partly due to the increase in extreme droughts, which are by definition included within the threshold values of moderate and severe droughts.

During the summer months, future extreme droughts become more frequent at both resolutions ( $f_{T799,extreme} \simeq 71\%$  and  $f_{T159,extreme} \simeq 21\%$ ). Nevertheless, model resolution is still an important factor in drought frequency with over three times more extreme drought months in T799 than in T159 ( $RF_{extreme} \simeq 3.4$ ). The increase in the number of extreme summertime drought months is partly due to a shift of the threshold value of  $S'$ : in T159 extreme droughts are defined as  $S' \leq -99$  mm compared to  $S' \leq -60$  mm in T799. This is due to a relatively narrow distribution of soil moisture anomalies in the high resolution baseline climate (Fig. 10d). Applying the threshold of T159 to T799 results in 49% of the months being under extreme drought conditions, still more than a doubling in the number of months in extreme drought compared to T159 simulations ( $CRF_{extreme} \simeq 2.3$ ). The resolution factor becomes less pronounced for summertime severe ( $RF_{severe} = 2.6$ ) and moderate ( $RF_{moderate} = 1.5$ ) droughts. This is because the increase in moderate and severe droughts in summer is mainly due to the increase in extreme droughts (Fig. 11). In other words, the high resolution simulations indicate that extreme droughts in the present-day climate will become the normal climatological state in the future.

#### 4 Drought evolution Drivers of soil moisture changes

Under similar soil and vegetation properties, changes in soil moisture content depend largely on precipitation and the evaporative demand of the atmosphere. ~~An accurate simulation of precipitation and evapotranspiration in the current climate would increase our confidence in the model performance of future drought projections. Therefore, in subsection ?? we first compare the simulated climate to the E-OBS observations. After the model validation we study the~~ We study mean changes in the land surface water balance in subsection 4.1, which includes precipitation and evapotranspiration as important factors. The water balance provides more information on the drivers of soil ~~moisture droughts~~ drying. In the last two subsections, the focus is on mechanistic explanations for mean changes in the land surface water balance. These explanations are separately discussed for spring in subsection 4.2 and summer in subsection 4.3. The discussion includes local feedback mechanisms as well as large-scale processes.

##### 4.1 ~~Validation of present-day climate~~

~~To gain some confidence in the model performance we validate the present-day climate over central-western Europe. This is done for simulated present-day precipitation and near-surface air temperature. The latter is used instead of evapotranspiration since observations of evapotranspiration are scarce and air temperature mainly determines the evaporative demand of the atmosphere. Figure 1a and 1b show the annual cycle of precipitation and near-surface air temperature over the analysis domain for E-OBS observations and the EC-Earth model simulations at high and standard resolution.~~

~~Precipitation biases of present-day climate simulations show that it is too wet over the study region (Fig. 1c). As discussed in Van Haren et al. (2015b) this is due to a too zonal position of the storm track over the east Atlantic Ocean and Western Europe. This is a common bias in CMIP3 and CMIP5 models (Haarsma et al., 2013; Van Ulden et al., 2007). The wet bias is reduced~~

in the high-resolution version of EC-Earth primarily due to a less-zonal orientation of the storm track (Van Haren et al., 2015b)

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Surface air temperature biases show that the T159 version is a bit too cold compared to observations (Fig. 1d), whereas T799 is somewhat warmer, especially in summer. The warmer temperature is associated with the less-zonal orientation of the storm track which makes the summer climate less maritime and more continental. The high-resolution simulations thus perform better with respect to the E-OBS precipitation and temperature data than the standard-resolution model. We shall see later that this contributes to enhanced future drying at high resolution.

#### 4.1 Land surface water balance

The land surface water balance gives more information on the drivers of soil water changes:

$$10 \quad dS/dt = P - ET - Q \quad (4)$$

Here, soil moisture-water storage ( $dS/dt$ ) is the change in soil moisture-water content over time,  $P$  is precipitation,  $ET$  is evapotranspiration and  $Q$  is runoff. Since we focus on the warm season months and choose our study region outside mountainous regions, ice and snow can be neglected in the land surface water balance. To study climate-induced changes in more detail, the land surface water balance can also be written in terms of anomalies, linking storage anomalies mean future changes, linking future changes in storage ( $dS'/dt$ ) to flux anomalies changes in water fluxes ( $P'$ ,  $ET'$ ,  $Q'$ ). In our approach anomalies are (future) changes relative to the present-day climatology. Figure 5 shows on the left the average storage anomalies in a future climate future changes in soil moisture storage compared to the current climate from April to September. On the right the contributions of  $P'$ ,  $ET'$ , and  $Q'$  to the changes in  $dS'/dt$  are depicted.

For both model resolutions, the anomalies of changes in evapotranspiration and precipitation clearly show that climate change induces enhanced evapotranspiration in spring and reduced precipitation from June to September. Throughout the entire warm season, the reduced future soil water content yields this results in decreases in runoff, leading to reduced availability of water resources downstream. At the same time, the decreases in runoff restrict the local soil moisture storage anomalies, preventing the soil prevent the soil from further desiccation (Fig. 5).

In the following subsections, we focus on spring and summer averages for mechanistic explanations of the simulated changes in the surface water balance. Individual months are discussed if it adds relevant information to the analyses.

#### 4.2 Spring evapotranspiration increase

The largest resolution-induced differences in soil moisture-drying occur in spring (Fig. 5). Summed over spring months, drying is larger in T799 ( $dS'/dt = -30.9$  mm) than in T159 ( $dS'/dt = -11.1$  mm). Compared to the present, the future shows an intensification of the hydrological cycle with enhanced evapotranspiration from April to June and enhanced precipitation in April and May (Fig. 5). At both model resolutions, evapotranspiration increase is the dominant contributor to spring soil drying (Fig. 5). This increase is stronger in T799 ( $ET' = +55.4$  mm) than in T159 ( $ET' = +21.6$  mm). Contributions of average spring-time precipitation to drying are negligible since rainfall increases in April and May are compensated by a rainfall reduction

in June. Furthermore, runoff plays an essential role in the ~~magnitude of future changes of the land surface water balance~~soil moisture changes since there is close interaction between these two variables. Both model resolutions simulate reduced future runoff, indicating that less water flows away from the study region ~~-(positive value of  $dS'/dt$ )~~. In turn, the reduction in runoff is related to the soil water content, which partly determines the infiltration of water into the soil and therefore the ratio surface runoff/precipitation. Reduced runoff thus ~~counteracts~~acts as a negative feedback on soil drying in central-western Europe (Fig. 5), an effect which is stronger at high model resolution. ~~However, the relative~~This relative local 'moistening' effect (positive value of  $dS'/dt$ ) of reduced runoff does not fully compensate for the strong drying effect of enhanced evapotranspiration in T799. The net result is stronger spring drying in central-western Europe at high model resolution. In the remainder of this subsection, we focus on the dominant contributor to future spring drying, which is evapotranspiration.

Since local moisture recycling plays an important role in evapotranspiration over the continents, first we assess resolution differences in evapotranspiration in the present-day climate. The annual cycle of evapotranspiration over central-western Europe (Fig. 3d) indicates that T799 simulates lower evapotranspiration in the present-day climate than T159. As already discussed in ~~subsection ??~~section 2, the precipitation bias over central-western Europe is smaller in T799 than in T159 (Fig. 1b). In spring, the high resolution model simulates significantly less precipitation (2.9 mm/day) than the standard resolution model (3.4 mm/day) (Welch t-test:  $p < 0.01$ ). This is induced by a shift of the precipitation distribution towards more dry days ( $P \leq 1 \text{ mm day}^{-1}$ ) in the high resolution model compared to the standard resolution model (Kolmogorov-Smirnov test:  $p < 0.01$ ). The reduced precipitation likely induces less evapotranspiration in T799 (2.9 mm/day) than in T159 (3.3 mm/day) in the current climate (Welch t-test:  $p < 0.01$ ). In other words, suppressed precipitation in the present-day climate might lead to reduced recycling of moisture over land. This is because in HTESSEL rain is initially collected in the interception reservoir. Before saturation of the interception layer, less rainfall results in less evapotranspiration, which could explain the reduced evapotranspiration in spring in the current climate.

Second, we assess what mechanisms could explain the enhanced increase in evapotranspiration over the 21st century. Assuming that the top soil layer is still saturated at the start of spring (Fig. 4), this implies that the enhanced evapotranspiration in T799 is atmosphere-driven. We start with examining future changes in the atmospheric circulation. In the high resolution model an ~~anomalous~~anomalous high pressure area develops near the British Isles that extends over central-western Europe (Fig. 6). The results show that the anomalous anticyclonic circulation does not significantly affect the wind climate over central-western Europe (Fig. 7a). However, high pressure anomalies promote subsidence, thereby supporting clear skies with more solar radiation reaching the surface (Fig. 7b). This effect is visible in the enhanced solar radiation in June, but not in April and May. As a consequence, more energy is available for future evapotranspiration and surface warming (Fig. 7c) in June in T799.

Third the impact of air temperature on atmospheric humidity is examined. Present-day daily mean springtime temperatures are higher in T799 (12.3 °C) than in T159 (11.8 °C) (Welch t-test:  $p < 0.01$ ) (not shown). These warmer springtime temperatures in T799 are associated with 10% lower cloudiness and 12  $\text{W m}^{-2}$  more surface solar radiation in the baseline climate than in T159. The reduced cloudiness is consistent with the smaller amount of precipitation in the T799 model. In the future climate, these resolution-dependent differences are roughly maintained (9% reduced cloud cover and 15  $\text{W m}^{-2}$  more surface solar radiation than in T159). The specific humidity ( $q$ ) of the atmosphere increases with climate warming (Fig. 7d). However, as

temperature increases, the increase of saturation vapour pressure is larger in a warmer climate due to the nonlinearity of the Clausius-Clapeyron relation. The warmer baseline surface air temperature in T799 leads to a stronger increase in saturation vapour pressure for a similar daily mean temperature change (+2.7 °C in T799 compared to +2.3 °C in T159) and thus a larger increase in the atmospheric demand for moisture. This is clearly visible in the lower relative humidity of the atmosphere at high model resolution (Fig. 7d). Higher baseline surface air temperatures thus contribute to enhanced springtime evapotranspiration in T799 compared to T159 under future climate warming.

In summary, spring drying is larger in the high resolution model version. This is due to a more continental climate in the high resolution model with less precipitation and warmer near-surface air temperatures, which promote enhanced evapotranspiration under climate warming. The main cause of the more continental climate is the less zonal position of the storm track in T799 as explained in Van Haren et al. (2015b).

### 4.3 Summer precipitation decline

~~Summer drying anomalies~~ Changes in summertime soil moisture storage are larger than ~~spring anomalies~~ springtime changes, but the summer differences between the model versions are relatively small. Compared to the present, the future increase of summer drying at T799 resolution ( $dS'/dt = -48.1$  mm) is only slightly larger than the increase at T159 resolution ( $dS'/dt = -44.1$  mm). Consequently, the resolution-induced differences in soil moisture content developed in spring are more or less maintained during summer. The dominant contributor to future soil drying in summer is a decline in rainfall (Fig. 5). Consistent with enhanced drying, the decline in total summer precipitation is larger in T799 ( $P' = -72.3$  mm) than in T159 ( $P' = -59.6$  mm). Similar to spring months, runoff acts as a negative feedback on soil drying. Reduced runoff counteracts local soil drying in both T799 ( $Q' = -21.5$  mm) and T159 ( $Q' = -12.2$  mm). However, runoff is rather a result of the reduced water availability ~~in the soil~~ than an active contributor to the drying. Therefore we focus on the causes of the precipitation decline.

We first study the large-scale changes in the atmospheric circulation. During summer, an ~~anomalous~~ anomalous high pressure area over the British Isles extends over central-western Europe in both model versions (Fig. 8). The anticyclonic circulation anomaly promotes subsidence and decreases convection. This leads to less clouds and reduced summer precipitation (Fig. 7b and 5). In addition, changes in the atmospheric circulation potentially affect horizontal moisture transport through changes in the wind climate over central-western Europe (Fig. 7a). Over this region, eastward winds (U10) typically bring oceanic moisture over land which increases the likelihood of continental precipitation. Due to the anticyclonic circulation anomaly, eastward winds are projected to decrease significantly towards the future at both T159 ( $U10' = -0.50$  m s<sup>-1</sup>) ~~resolution~~ and T799 resolution ( $U10' = -0.30$  m s<sup>-1</sup>) (Fig. 7g), reducing advection of atmospheric moisture from ocean sources. Zonal wind speed changes thus act to enhance summer soil drying over central-western Europe. However, zonal wind speed changes do not induce the resolution-dependent differences in future summer drying, since wind speed reductions in T799 are smaller than in T159 and thus have a counteractive effect on the differences in drying.

Furthermore, future soil drying and precipitation decline ~~anomalies~~ are not uniformly spread over individual summer months. In August and September, changes in soil moisture storage ~~anomalies~~ are larger in T799 than in T159 (Fig. 5). Consistently, in August and September rainfall decline is larger in T799 than in T159 (Fig. 5). Remarkably, in July the climate change-induced

soil moisture drying and precipitation decreases are larger in T159 than in T799 (Fig. 5). The simulations indicate that these monthly precipitation anomalies changes are largely determined by the magnitude and location of the anomalous-anomalous high pressure pattern over the British Isles. In August and September, the anomalous-anomalous high pressure is stronger over central-western Europe in T799 (Fig. 9b-e**b,c**), whereas in July, the high pressure anomaly is larger in T159. It thus  
5 appears that the atmospheric circulation plays an important role in monthly precipitation changes, but is not the main cause of resolution-induced differences averaged over the summer months.

Next to large-scale circulation changes, local feedbacks play a role in the reduced precipitation in summer. The surface water balance is closely connected to the surface energy balance through latent cooling by evapotranspiration. Figure 12 depicts future anomalies-average future changes of the main components of the surface energy balance, including the sensible heat flux (SH'),  
10 latent heat flux ( $\lambda ET'$ ), and the net surface radiation ( $R_{net}'$ ). In future, maximum evapotranspiration is achieved in June for both T159 and T799 (Fig. 3). Thereafter evapotranspiration decreases rapidly, coinciding with a significant decrease of soil moisture in the top layer (Fig. 4). This decrease is stronger in T799 than in T159 (Fig. 6) and shows that from June onward evapotranspiration is limited by soil moisture. In the present-day climate, maximum evapotranspiration occurs one month later (July), for both T159 and T799, closer to the maxima in solar radiation and surface temperature (Fig. 7b,c), indicating that for  
15 the present climate evapotranspiration is not restricted by soil moisture but by available surface energy. As a result, there is no marked change in total summer evapotranspiration towards the future in T799 ( $ET' = +3.9$  mm) and T159 ( $ET' = +4.1$  mm). In turn, the minor increase in evapotranspiration limits the increase in specific humidity of the atmosphere (Fig. 7d) and thereby the local recycling of moisture. In addition, the limited atmospheric moisture content in combination with warmer temperatures leads to reduced relative humidity and less cloudiness with more surface solar radiation (Fig. 7b,d). The resulting warmer and  
20 drier boundary layer (Fig. 7c,d) further diminishes rainfall. This effect is stronger at T799 resolution, presumably caused by the drier soils at the start of summer that alter the partitioning of the turbulent fluxes. Local feedbacks of soil moisture with temperature and precipitation thus seem to dominate the resolution-dependent differences in summer drying.

## 5 Drought impactsImpact on droughts and other extremes

### 5.1 Soil moisture droughts

25 The changes in the seasonal cycle of soil moisture content affect the severity and frequency of future droughts under climate warming. Consider Figure 10, which depicts the  $S'$  distributions of spring and summer at T799 and T159 resolution, for the present and future climates. The drought threshold values as defined in section 2.4, which are based on these distributions, are also indicated. The associated frequency of extreme (1/30 years event), severe (2/30), and moderate (6/30) droughts by the end of the twenty-first century, averaged over central-western Europe, can be seen in the bar charts of Figure 11. When interpreting  
30 these results, it should be noted that the sample size is only 30 years of a single climate model. To obtain more robust answers a larger ensemble of different models is required.

In spring, model resolution has a high impact on the frequency of future droughts. In the T159 simulations, extreme future springtime droughts occur about once every thirty years over central-western Europe ( $f_{T159,extreme} \simeq 3\%$ ) (Fig. 11), which is

comparable with the current climate. There is also no significant change in the frequency of springtime severe and moderate droughts in T159. This is clearly visible in the large overlap of the present-day and future climates in the distributions of spring soil moisture anomalies for T159 (Fig. 10a). In contrast, in T799, the springtime soil moisture anomaly distributions indicate that the frequency of extreme droughts increases due to a shift towards drier conditions in a future climate. Future extreme springtime droughts are about seven times more frequent in T799 than in T159 ( $RF_{\text{extreme}} \simeq 7.3$ ) and occur about once every four years ( $f_{T799,\text{extreme}} \simeq 24\%$ ) (Fig. 11). Note here that the threshold value for T799 extreme springtime droughts (red line) is more or less similar to the threshold value in T159 due to the similarity of the baseline soil moisture distributions. Also, the frequency of severe ( $f_{T799,\text{severe}} \simeq 41\%$ ) and moderate ( $f_{T799,\text{severe}} \simeq 71\%$ ) droughts increases in the high resolution simulations. This is partly due to the increase in extreme droughts, which are by definition included within the threshold values of moderate and severe droughts.

During the summer months, future extreme droughts become more frequent at both resolutions ( $f_{T799,\text{extreme}} \simeq 71\%$  and  $f_{T159,\text{extreme}} \simeq 21\%$ ). Nevertheless, model resolution is still an important factor in drought frequency with over three times more extreme drought months in T799 than in T159 ( $RF_{\text{extreme}} \simeq 3.4$ ). The increase in the number of extreme summertime drought months is partly due to a shift of the threshold value of  $S'$ : in T159 extreme droughts are defined as  $S' \leq -99$  mm compared to  $S' \leq -60$  mm in T799. This is due to a relatively narrow distribution of soil moisture anomalies in the high resolution baseline climate (Fig. 10d).

Applying the threshold of T159 to T799 results in 49% of the months being under extreme drought conditions, still more than a doubling in the number of months in extreme drought compared to T159 simulations ( $CRF_{\text{extreme}} \simeq 2.3$ ). The resolution factor becomes less pronounced for summertime severe ( $RF_{\text{severe}} = 2.6$ ) and moderate ( $RF_{\text{moderate}} = 1.5$ ) droughts. This is because the increase in moderate and severe droughts in summer is mainly due to the increase in extreme droughts (Fig. 11). In other words, the high resolution simulations indicate that extreme droughts in the present-day climate will become the normal climatological state in the future.

## 5.2 Warm extremes

The drier soil at the start of summer limits the evaporative fraction leading to enhanced sensible heat fluxes that amplify near-surface warming (Fig. 7 and Fig. 8). Combined with warmer air temperatures, this decreases the relative humidity of the atmosphere (Fig. 7d). The warmer and drier boundary layer inhibits cloud formation and further enhances surface solar radiation (Fig. 7b). The resulting rise in daily maximum surface air temperature in T799 ( $SAT' = +5.1$  °C) and T159 ( $SAT' = +4.8$  °C) is about two times larger than in spring.

This local soil moisture-temperature feedback starts a few weeks earlier (Fig. 7b) for the high resolution model due to the enhanced soil drying in spring. The strengthening of the soil moisture-temperature coupling is also visible in Figure 12, which shows a steeper regression line between soil moisture content and daily maximum temperature for the future climate than for the present climate. The stronger feedback in T799 leads to a clustering of exceptional dry and hot summers in T799 compared to T159 (clustered in the top left corner in Fig. 12b). The strong link between soil moisture and maximum temperatures is created by reduced soil moisture which strongly restrains latent cooling in summer in both T159 ( $r = 0.78$ ,  $p < 0.01$ ) and T799

( $r = 0.90$ ,  $p < 0.01$ ). In the future, drier future spring soil conditions therefore could potentially act as a precursor for hot summers (e.g., ?).

### 5.3 Heavy precipitation and dry days

In the current climate, T799 simulates a larger fraction of dry days and a larger fraction of precipitation falling as intense rain compared to T159 (Fig. 13), which is presumably caused by the higher surface air temperature. In the future climate, both resolutions simulate an increase in the number of dry days in summer and in the contribution of heavy precipitation to the total precipitation amount. This effect is larger in T799. Unless there is moisture supply from the ocean, after a day with heavy precipitation the air needs to be recharged before a new downpour can start. In between heavy precipitation days, it is therefore relatively dry with little rain. During these dry days there will be less clouds, with more incoming solar radiation, higher temperatures, and less relative humidity inducing a higher evaporative demand. So for the same amount of rain, a shift to more dry days and heavy precipitation potentially increases the evaporative demand of the atmosphere. Dry soils, however, limit the rate of evapotranspiration and slow down the rate at which the atmosphere can recharge with water vapour. The drier soil conditions in T799 thus likely increase the number of dry days between heavy rain events.

## 6 Summary and conclusions

Using two model resolutions of the global climate model EC-Earth we have investigated the impact of model resolution on the occurrence and causes of ~~extreme droughts~~ projected soil drying in the Rhine-Meuse drainage area in central-western Europe. Consistent with previous studies (Berg et al., 2017; Ruosteenoja et al., 2018; Samaniego et al., 2018), both model resolutions project soil drying in the warm season months over central-western Europe. For the present-day climate the high resolution (T799,  $\sim 25$  km) and standard resolution (T159,  $\sim 112$  km) version have similar soil moisture climatologies. However, for the future large differences occur. In spring, enhanced evapotranspiration with respect to the corresponding baseline climatology induces much stronger drying in the high resolution model; ~~which leads to an sevenfold increase in the frequency of extreme soil moisture droughts.~~ The enhanced spring drying preconditions the soil to a drier state at the start of summer. Both resolutions simulate a significant increase in summer drying of similar magnitude. Due to the predrying in spring, this leads to over three times more frequent extreme droughts at high resolution than at standard resolution. Consequently, in the high resolution model, extreme summer droughts in the present-day climate become the normal climatological state in the future.

The analyses revealed that both anomalous circulation patterns and local feedbacks are responsible for the ~~increase in the frequency and severity of droughts~~ decrease in soil moisture in a future climate. A less zonal position of the storm tracks leads to a more continental climate over central-western Europe and a reduction of present-day biases in precipitation and surface air temperature (Van Haren et al., 2015b). The resulting warmer and drier spring promotes enhanced evapotranspiration in the high resolution model. Furthermore, an anticyclonic pressure anomaly over the British Isles extends over central-western Europe. Although no significant changes in wind occur during the preconditioning phase in spring, the high pressure anomaly supports



clear skies with enhanced surface solar radiation reaching the surface. This provides additional surface energy for turbulent fluxes in June.

~~Summer drought characteristics are enhanced~~ Simulated summer drying is mainly caused by a reduction in rainfall. The drying of the ground-land surface results in a reduced evaporative fraction and combined with enhanced solar radiation in higher surface temperatures. This feedback is slightly stronger at high model resolution due to the predrying in spring. The drier soil in the high resolution model at the start of summer induces stronger local feedbacks with precipitation and evapotranspiration, which leads to a clustering of extreme droughts and warm extremes. The impact of soil moisture on observed European warm extremes has also been demonstrated by Whan et al. (2015) using a simple water balance model. Another consequence of ~~the occurrence and clustering of extreme droughts~~ warm season drying is the absence of recovery of the ground water storage in the following winter with consequences for year-round runoff. The stronger local feedbacks open on the other hand possibilities for predictability of summer droughts, heat waves, precipitation, and river runoff.

We argue that both dynamical and local feedback processes are better represented at higher resolution. The cause of the anomalous anticyclonic circulation over the British Isles could be a weakening of the Atlantic meridional overturning circulation (AMOC) under future climate warming as discussed in Haarsma et al. (2015). The stronger response at the high T799 resolution is probably due to enhanced ocean-atmosphere coupling. Because ~~CMIP5-models~~ CMIP5 models underestimate the natural inter-annual-interannual variability of this AMOC-induced UK high (Haarsma et al., 2015), we argue that the stronger response in T799 is more realistic. Furthermore, the additional increase of spring ~~droughts~~ drying in the high resolution simulations is partly due to a better representation of the Atlantic storm track at high model resolution as described in Van Haren et al. (2015b). Whether the simulated ~~droughts~~ soil drying and the impact of resolution is robust has to be evaluated in a larger ensemble of different models. Initiatives as the Horizon 2020 project PRIMAVERA (<https://www.primavera-h2020.eu/>) and the CMIP6-endorsed HighResMIP (Haarsma et al., 2016) will contribute to the hypothesis put forward in this study that the simulated ~~European droughts~~ central-western European soil drying by CMIP5 ~~are~~ is underestimated due to dynamical causes and local feedbacks that can only reliably be simulated at high resolution.

*Competing interests.* No competing interests are present.

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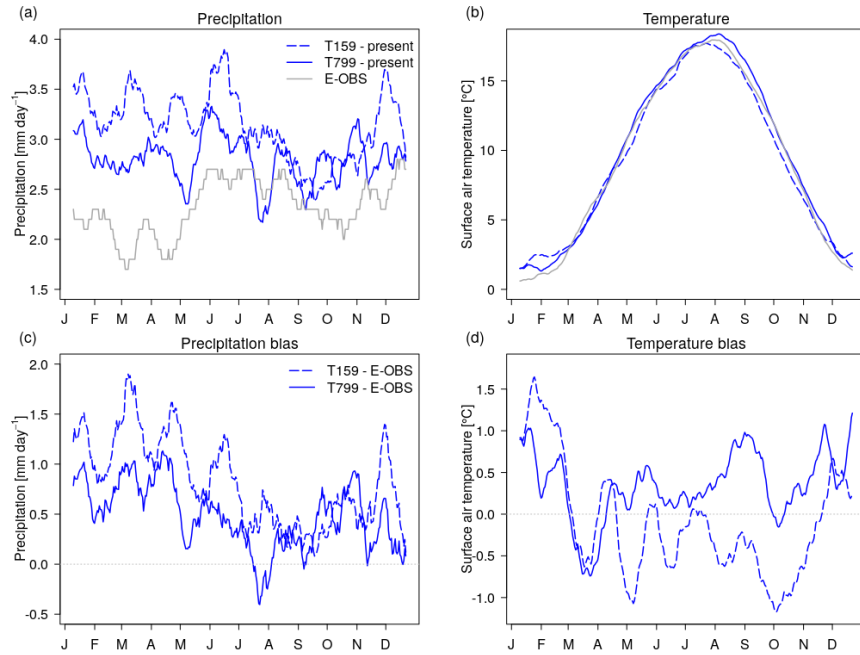
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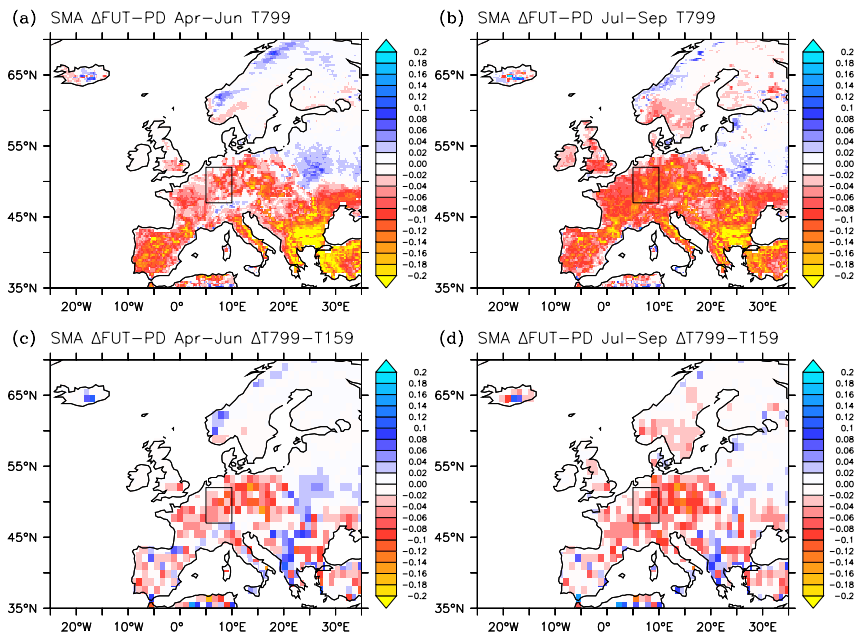
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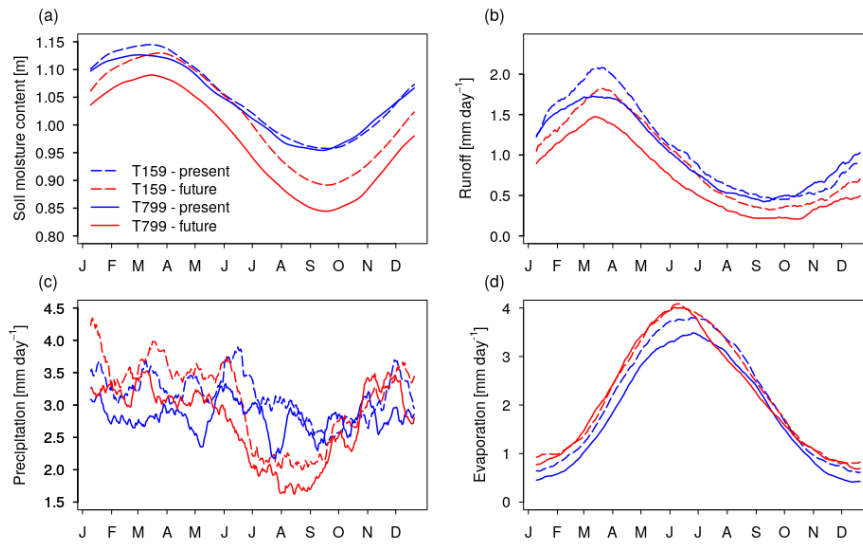
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**Figure 1.** Top: Soil moisture anomaly climate change signal Annual cycle of observed (future—present grey) for and simulated (blue) (a) spring precipitation and (b) summer in the high resolution model. Bottom: daily mean near-surface air temperature at T159 (e-dashed) Same-but and T799 (solid) resolution for difference in climate change signal between the high present-day climate. Annual cycle of biases of (c) precipitation and standard-resolution model (d) daily mean near-surface air temperature with respect to observations. Values are smoothed with a 20-day running mean filter and averaged over central-western Europe. The letters on the horizontal axis correspond with the first day of each month (based on a year with 365 days).

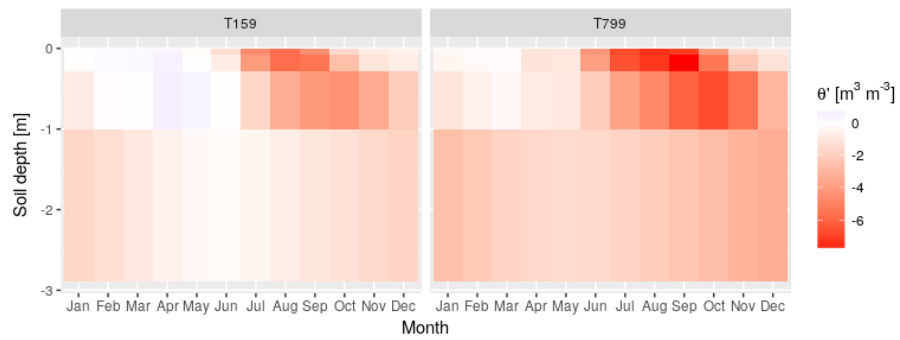


**Figure 2.** Top: Soil moisture content [m] climate change signal (future - present) in for (a) spring and (b) summer in the high resolution model. Bottom: (c-d) Same but for difference in climate change signal between the high and standard resolution model.



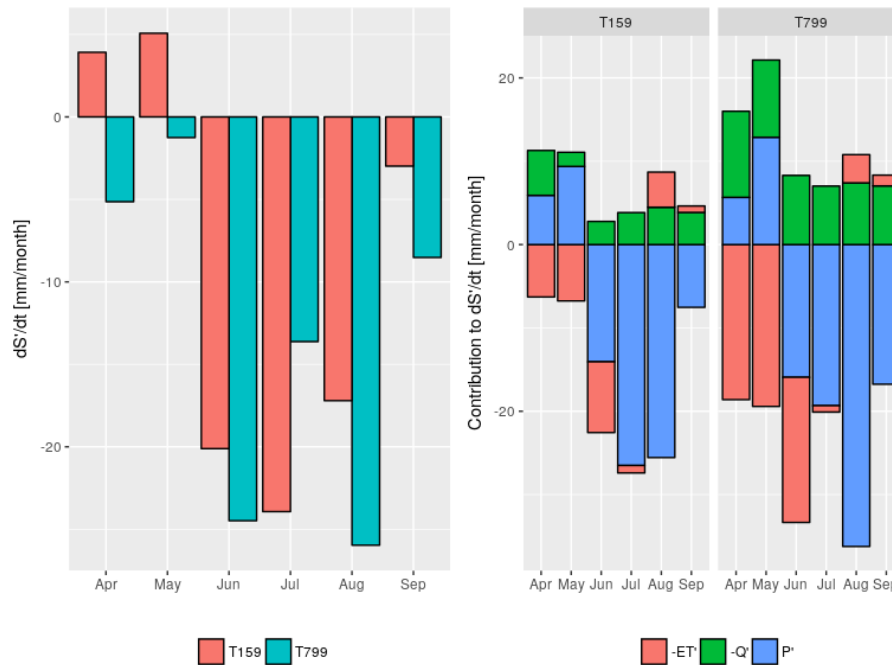
**Figure 3.** Annual cycle of (a) soil moisture content, (b) runoff, (c) precipitation, and (d) actual evapotranspiration. Values are smoothed with a 20-day running mean filter and averaged over central-western Europe. The letters on the horizontal axis correspond with the first day of each month (based on a year with 365 days).



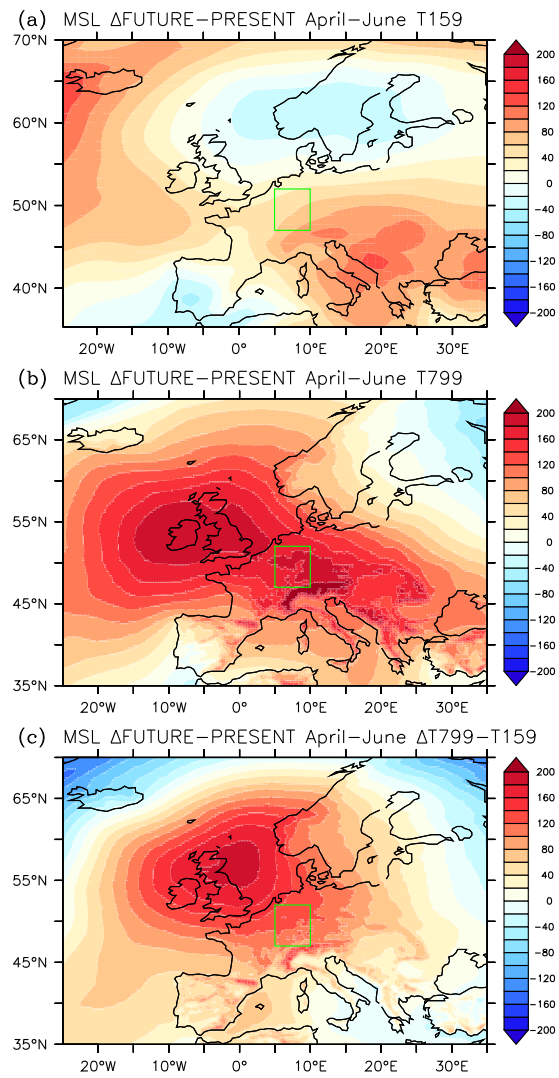


**Figure 4.** Profile of future volumetric soil moisture monthly anomalies changes ( $\theta'$ ) under 2100 conditions with respect to the present-day climatology over central-western Europe for standard and high spatial resolution.

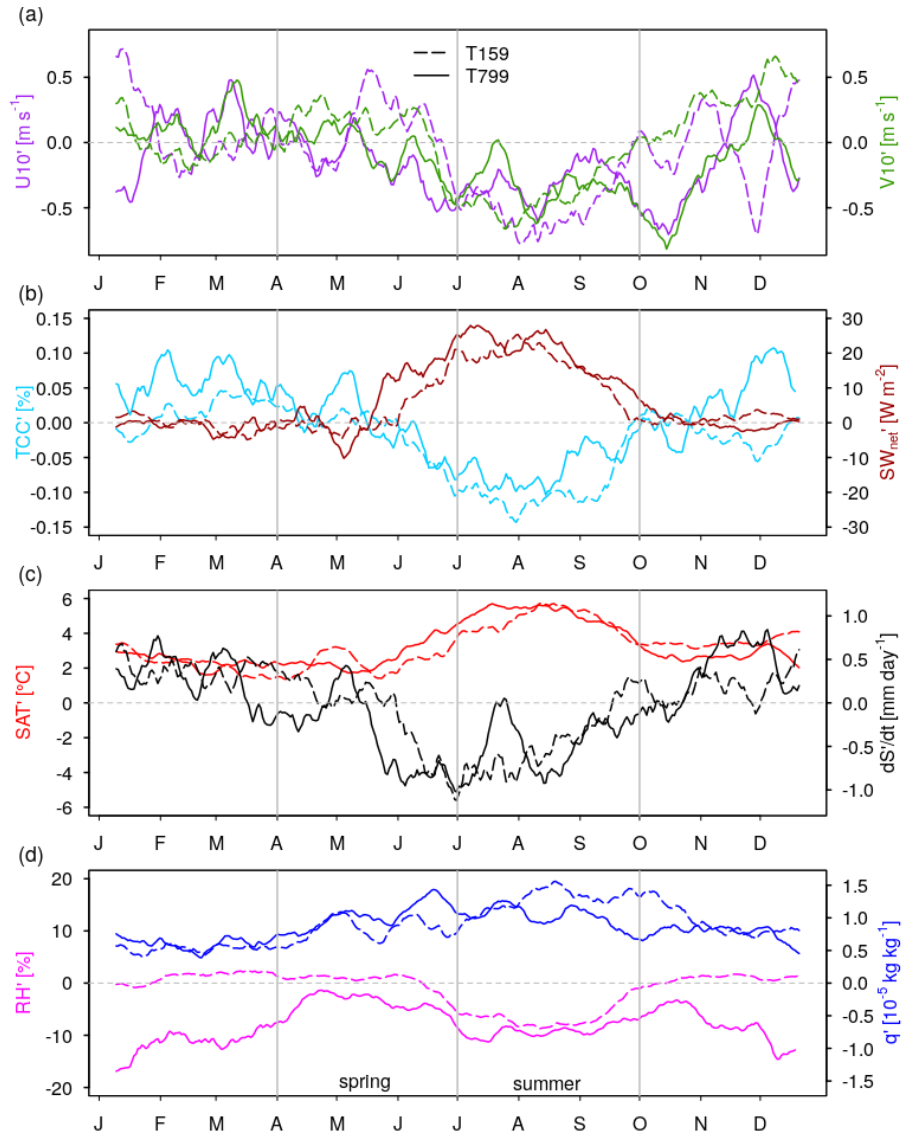
Kernel density distribution of soil moisture anomalies over central-western Europe in (a) April–June at T159 resolution, (b) April–June at T799 resolution, (c) July–September at T159 resolution, and (d) July–September at T799 resolution for the present (blue) and future (pink) climates. Extreme (red line), severe (orange line), and moderate (yellow line) drought thresholds are based on the 1st, 5th, and 20th percentile of the present-day soil moisture anomaly distributions. Top: Frequency of future droughts, expressed as the percentage of months in extreme (red), severe (orange), and moderate (yellow) drought for (left) T159 and (right) T799 over central-western Europe. Bottom: resolution factor and corrected resolution factor for extreme (red), severe (orange), and moderate (yellow) droughts. The resolution factor (RF) indicates what the impact is of resolution and is defined as the ratio of the frequency of droughts in T799 to the frequency of droughts in T159. The corrected resolution factor (CRF) corrects for shifts in the baseline climate due to higher spatial resolution. CRF is computed similar to RF, but uses the thresholds of soil moisture anomalies based on the climatology of T159 for drought thresholds in T799. Annual cycle of observed (grey) and simulated (blue) (a) precipitation and (b) daily mean near-surface air temperature at T159 (dashed) and T799 (solid) resolution for the present-day climate. Annual cycle of biases of (c) precipitation and (d) daily mean near-surface air temperature with respect to observations. Values are smoothed with a 20-day running mean filter and averaged over central-western Europe. The letters on the horizontal axis correspond with the first day of each month (based on a year with 365 days):



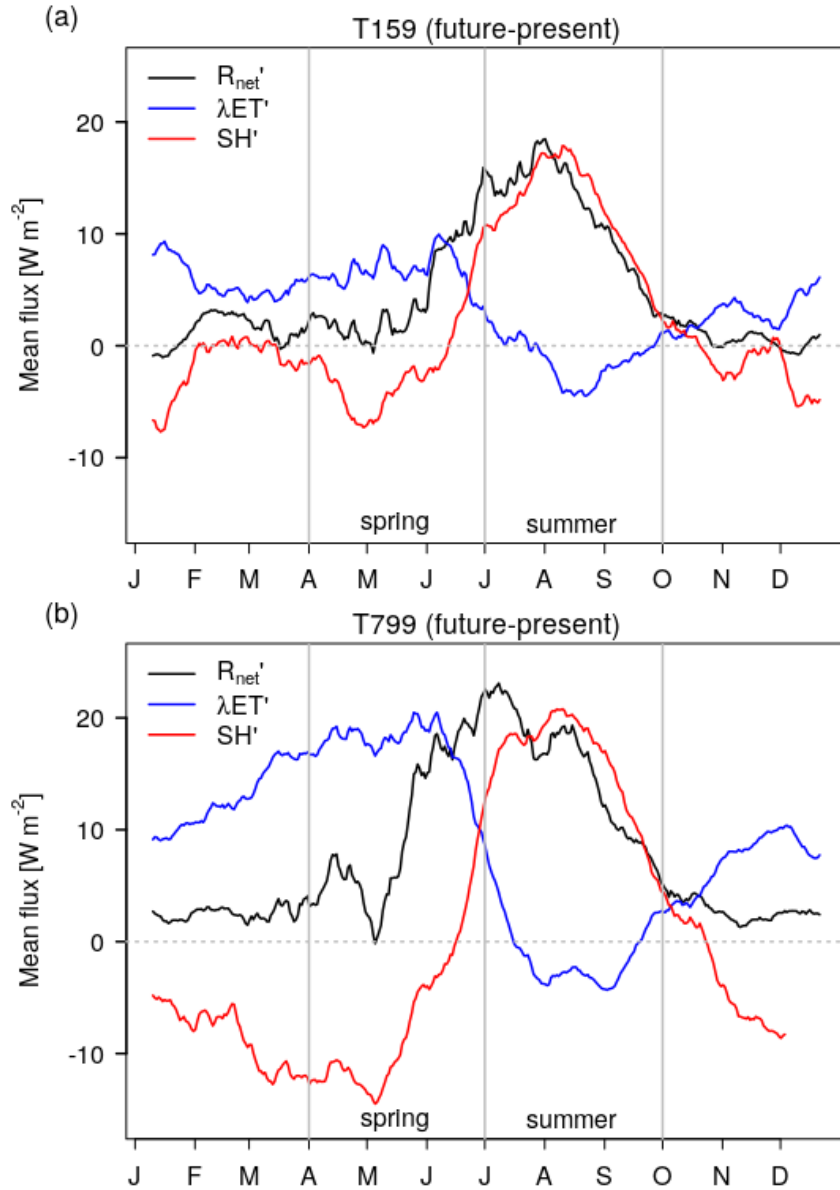
**Figure 5.** Left: Monthly [changes in soil moisture storage anomalies](#) (future – present) under future global warming for (pink) T159 and (cyan) T799. Negative is drying, positive is moistening. Right: Contribution of water balance [flux anomalies fluxes](#) ( $P'$ ,  $Q'$ , and  $ET'$ ) to [changes of soil moisture storage anomalies](#) in the future for (left) T159 and (right) T799. [Water](#) [The changes in the water balance flux anomalies fluxes](#) combine to  $dS'/dt$ . Negative [anomalies values](#) indicate contributions to drying, positive [anomalies values](#) indicate soil moistening.



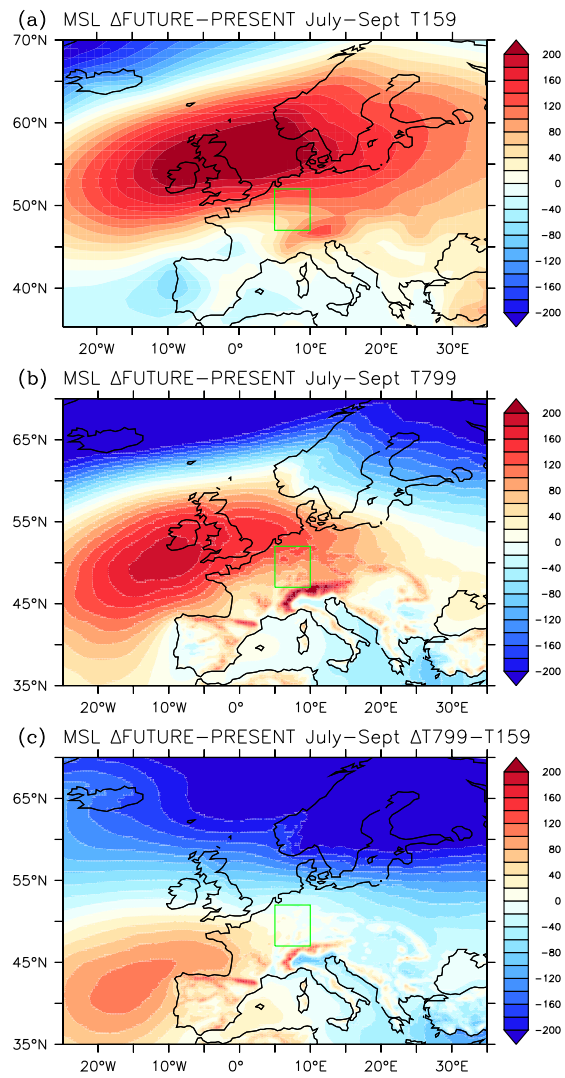
**Figure 6.** Sea level pressure [Pa] climate change signal (future – present) for spring in the (a) standard and (b) high resolution model. (c) Same but for difference in climate change signal between the high and standard resolution model.



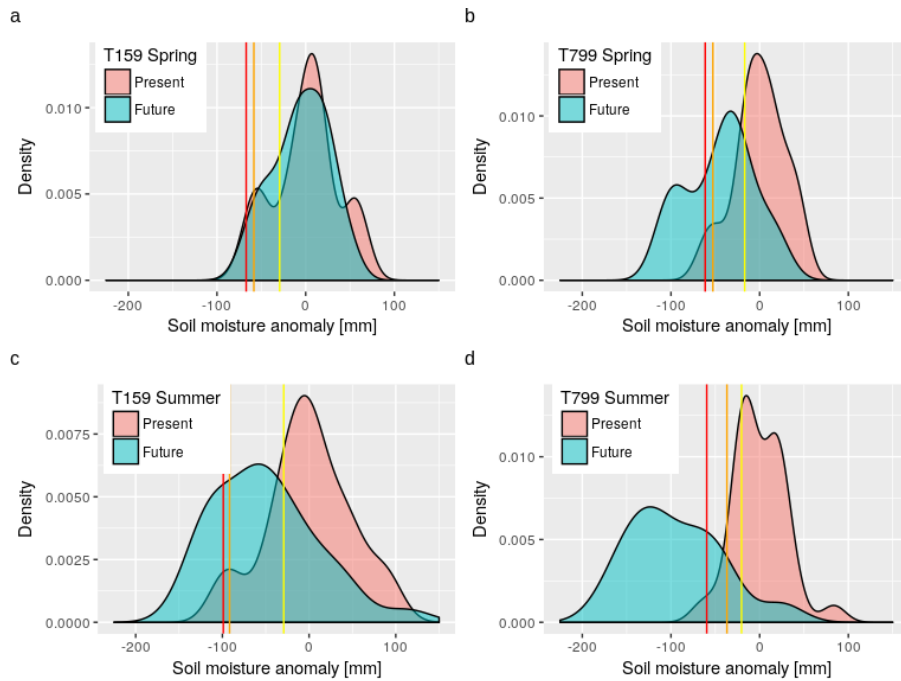
**Figure 7.** Climate change signal (future – present) of (a) zonal ( $U_{10'}$ ) and meridional ( $V_{10'}$ ) wind speed, (b) total cloud cover ( $TCC'$ ) and surface solar radiation ( $SW_{net}'$ ), (c) daily mean surface air temperature ( $SAT'$ ) and soil water storage ( $dS'/dt$ ), and (d) relative humidity ( $RH'$ ) and 850 hPa specific humidity ( $q'$ ) for T159 (dashed lines) and T799 (solid lines). Values are smoothed with a 20-day running mean filter and averaged over central-western Europe. The letters on the horizontal axis correspond with the first day of each month (based on a year with 365 days).



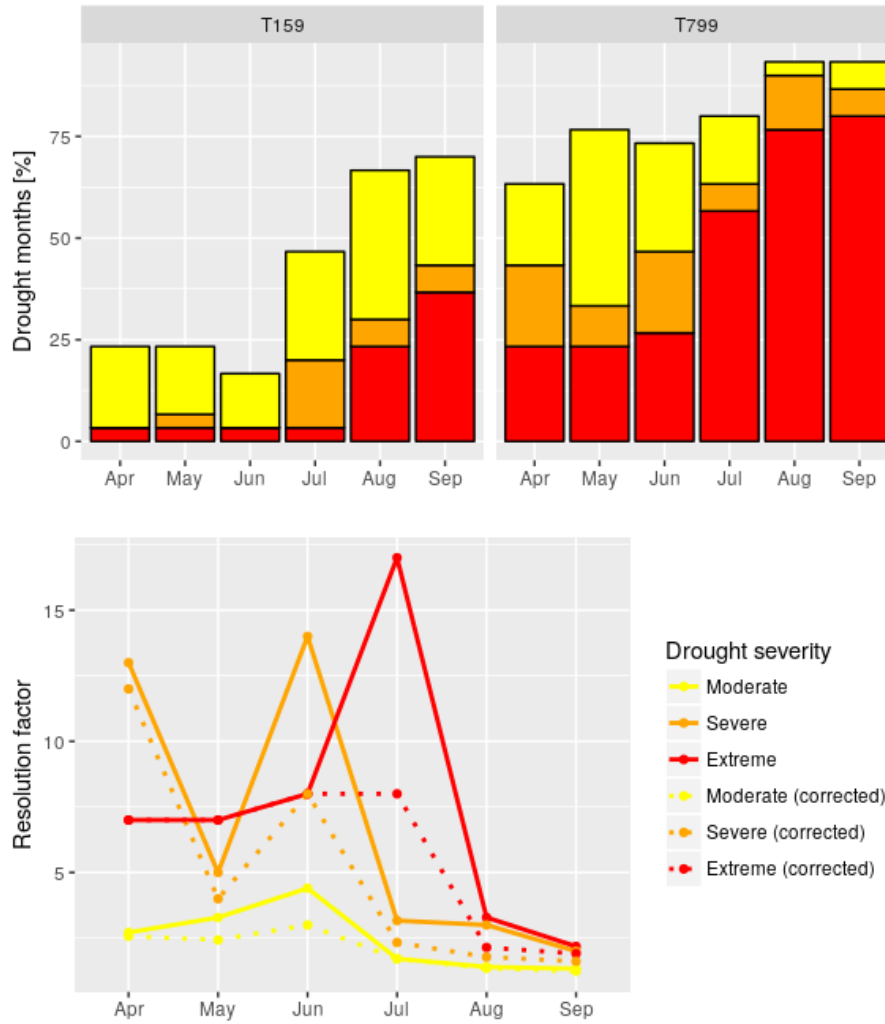
**Figure 8.** Anomalies of surface fluxes under future climate change for (top) T159 and (bottom) T799. Positive indicates enhanced fluxes and negative reduced fluxes. Turbulent sensible heat ( $SH'$ ) and ~~latent~~ latent heat ( $\lambda ET'$ ) fluxes are defined positive upward and net surface radiation ( $R_{net}'$ ) is defined positive downward. Values are smoothed with a 20-day running mean filter and averaged over central-western Europe. The letters on the horizontal axis correspond with the first day of each month (based on a year with 365 days).



**Figure 9.** Sea level pressure [Pa] climate change signal (future – present) for summer in the (a) standard and (b) high resolution model. (c) Same but for difference in climate change signal between the high and standard resolution model.

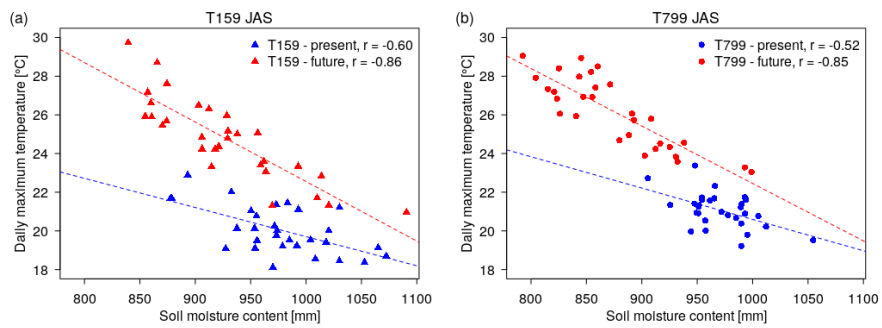


**Figure 10.** Kernel density distribution of soil moisture anomalies over central-western Europe in (a) April–June at T159 resolution, (b) April–June at T799 resolution, (c) July–September at T159 resolution, and (d) July–September at T799 resolution for the present (blue) and future (pink) climates. Extreme (red line), severe (orange line), and moderate (yellow line) drought thresholds are based on 1/30, 2/30, and 6/30 years events of the present-day soil moisture anomaly distributions.

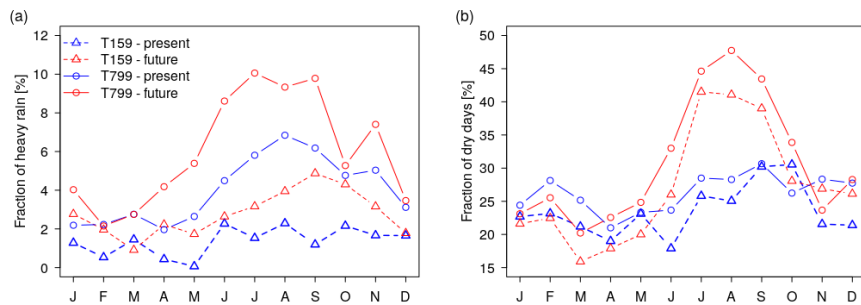


**Figure 11.** Top: Frequency of future droughts, expressed as the percentage of months in extreme (red), severe (orange), and moderate (yellow) drought for (left) T159 and (right) T799 over central-western Europe. Bottom: resolution factor and corrected resolution factor for extreme (red), severe (orange), and moderate (yellow) droughts. The resolution factor (RF) indicates what the impact is of resolution and is defined as the ratio of the frequency of droughts in T799 to the frequency of droughts in T159. The corrected resolution factor (CRF) corrects for shifts in the baseline climate due to higher spatial resolution. CRF is computed similar to RF, but uses the thresholds of soil moisture anomalies based on the climatology of T159 for drought thresholds in T799.





**Figure 12.** Linear regression between summer (July–September) soil moisture content and daily maximum surface air temperature for (a) T159 and (b) T799, for the present (blue) and future (red) climate.



**Figure 13.** (a) Monthly fraction of precipitation falling as heavy rain ( $\geq 30 \text{ mm day}^{-1}$ ) in central-western Europe, computed as the contribution of heavy precipitation falling somewhere in the area to the total amount of precipitation. (b) Monthly fraction of dry days averaged over central-western Europe ( $\leq 1 \text{ mm day}^{-1}$ ). Before the analysis we regridded precipitation values to the T159 model grid and computed the daily sum of precipitation per [gridpointgrid cell](#).