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Comparison of impact model projections – off-line and on-line

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Executive summary

This study compares two methodologies for using climate model projections to assess the impacts of climate change on hydrology and ecosystems; (i) application of the meteorological outputs of the climate model to separate impacts models, including adjustments of the meteorological outputs to account for systematic biases, and (ii) simulation of hydrological and ecosystem changes within the climate model itself, accounting for feedbacks to the climate and maintaining internal consistency of the water cycle and land surface effects on climate. Projections of climate change with the 2nd Hadley Centre Global Environment Model, Earth System version (HadGEM2-ES) are used, driving the Joint UK Land Environment Simulator (JULES) as a separate model and also using JULES within HadGEM2-ES itself. The impacts in each are assessed at specific levels of global warming. It is found that the relationship of key impacts processes to global mean temperature differs according to whether JULES is used within or outside of HadGEM2-ES, often due to differences in regional impacts responses especially in cold regions where thresholds such as the freezing point of water are either passed or not depending on whether climatic biases have been corrected. While climate models continue to exhibit systematic biases, impacts assessments will need to involve a judgment about whether it is more important to correct these biases or maintain conservation and internal consistency in key processes such as water and energy fluxes.

1. Introduction

Projections of the impacts of climate change often involve the use of meteorological outputs of climate models to drive models of impacts such as changes in land hydrology and ecosystems. , In recent years climate models have become more comprehensive in their representation of processes in the Earth System, and many of these 'impacts' processes can now be simulated within the climate models themselves. If all models involved were perfectly realistic, it would be expected that these two approaches would give identical results. However, since models are inevitably imperfect and subject to approximations and assumptions, it is more likely that these different methods may lead to different results. In particular, when impacts models are run it is common to bias correct the driving climate data. This is because human and ecosystem impacts are very often sensitive to thresholds in the climate system, for example the temperature threshold 0°C. However, this bias-correction may itself introduce problems in comparison with the approach of modelling all processes within one large modelling system, as the process of adjusting input data may break the internal consistency within climate models and the conservation within certain processes, such as the hydrological cycle. Moreover, other methodological issues such as averaging climate model output data over longer periods for practical reasons may also cause differences in the impacts simulations. Hence there may be unknown uncertainties in projections of climate change impacts arising from the choice of methodology, in addition to the more widely-recognised uncertainties arising from other issues such as emissions scenarios and robustness of individual models.

This study begins to examine these issues by comparing two sets of simulations with the HadGEM2-ES climate system model and JULES land surface model. JULES forms the land surface component of HadGEM2-ES, and has also been used outside of HadGEM2-ES driven by meteorological outputs from this model as part of a wider set of impacts model simulations. While the two approaches do not use exactly the same version of JULES, this nevertheless provides an opportunity for a preliminary study of the different results arising from these two approaches, which may provide some insights into the uncertainties in climate impacts assessments arising from the choice of approach. The focus here is on projected impacts at specific levels of global warming, as part of the HELIX framework.

2. Method

This study compares results from JULES associated with climate projections performed with HadGEM2-ES for the 5th Coupled Model Inter-comparison Project 5 (CMIP5). One set of results are from JULES 'online' within HadGEM2-ES, and the other are 'offline' JULES simulations (outside of HadGEM2-ES) driven by the CMIP5 HadGEM2-ES simulations as part of the Inter Sectoral Impacts Model Inter-comparison Project (ISIMIP) [4]. The underlying climate projection in both cases is therefore the same – however, one key difference between the data used as input to JULES either within or outside of HadGEM2-ES is that the 'offline' simulation in ISIMIP are made with bias-corrected climate data [1]. 30-year periods were identified within the climate projections at which the global warming simulated by HadGEM2-ES reached specific levels of global warming at 1, 2, 3, 4, 5 and 6°C (K) relative to pre-industrial – impacts on key components of the water cycle (runoff and evaporation) were then quantified at these levels of warming.

Figure 1 shows the global land, annual mean values of surface air temperature, precipitation, wind speed and relative humidity plotted against time, and global annual mean temperature change. Figure 2 shows the maps of the difference or ratio between the two models and observations over the historical period, and together, these plots illustrate the impact of the bias correction. Figure 1 shows that the temperature and wind speed are both changed considerably by the bias correction. Figure 2 shows that the difference between the model and observations is reduced by the bias correction.

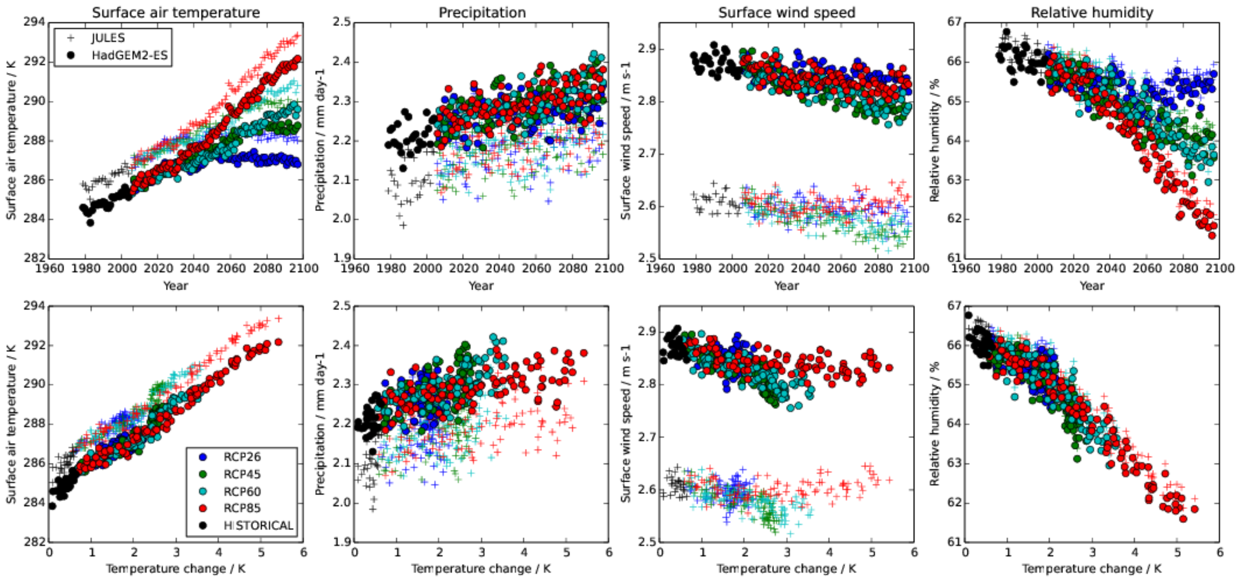

Figure 1. Global land, annual mean of climate variables: temperature, precipitation, and wind speed as modelled by HadGEM2-ES (round points) and as they are input to the offline JULES model in ISI-MIP after bias correction (crosses). Values are plotted against time (top panels) and against global mean temperature change from pre-industrial levels (bottom panels). The global mean temperature change is calculated from HadGEM2-ES CMIP5 simulations. The black points show the simulations over the historical period (1971-2005) and the colours show the climate change simulations (dark blue: RCP2.6, green: RCP4.5, light blue: RCP6.0 and red: RCP8.5).

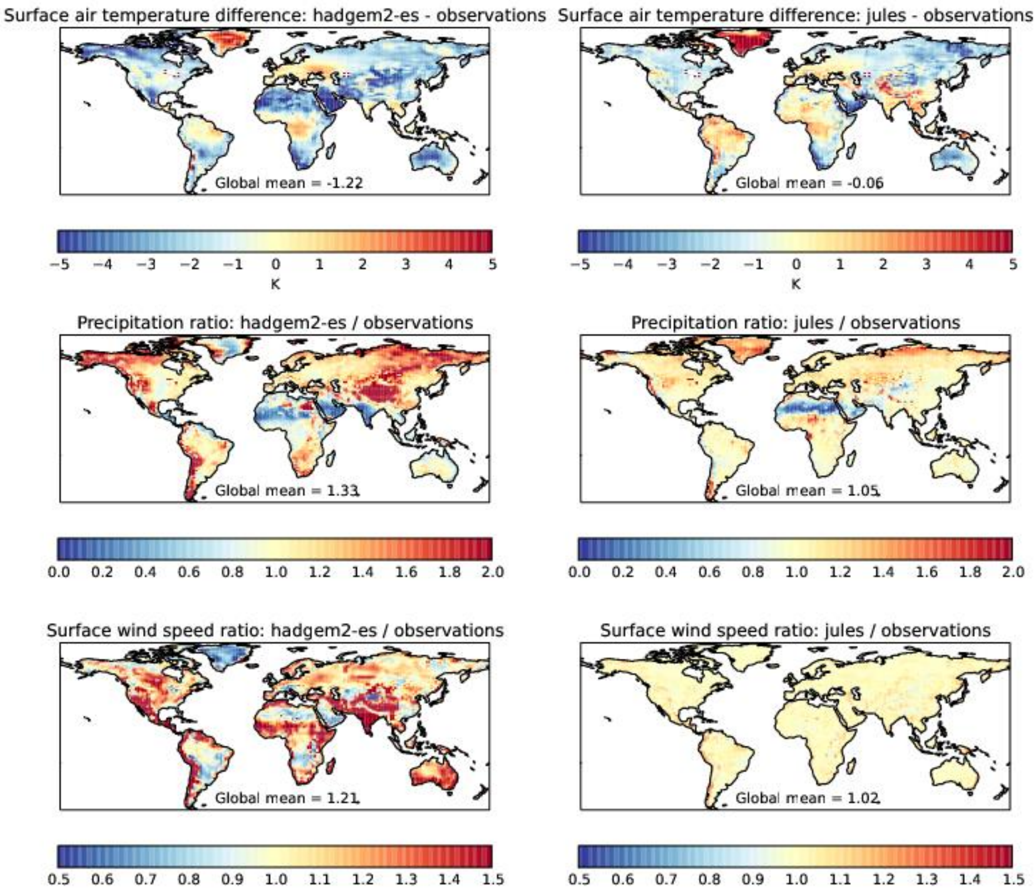

Figure 2. Maps comparing the 1971-2004 mean modelled and observed climate fields before and after bias correction. The top column shows the difference between the modelled and observed temperature, the middle and bottom columns show the ratios between the modelled and observed precipitation and surface wind speed fields respectively. The left columns show the climate data simulated by HadGEM2-ES before bias-correction, and the right columns show the HadGEM2-ES data after bias corrections. It is the bias-corrected fields that are the inputs to the impacts model for the ISIMIP simulations.

2.1 Warming Levels

In order to investigate the impact of different levels of climate change, the simulations are averaged at different warming levels. The warming is defined as the ensemble, global, decadal mean temperature increase of the HadGEM2-ES climate change simulations with respect to the pre-industrial control simulations. The decade with the global mean temperature change closest to the ``target'' is found, and the 30 year mean is taken around this. For example if the decade is the 2060, the 30 year period around this runs from 2050 to 2079.

The bottom row of Figure 1 shows the driving climate data plotted against the global annual mean temperature change relative to the pre-industrial simulation. It shows that all the scenarios show very similar behaviour when plotted in this manner, and the effect on the climate appears not to depend on how quickly the radiative forcing change takes place.

3. Water cycle changes

Figure 3 shows the simulation results of the water cycle components from HadGEM2-ES and JULES, plotted against global mean temperature change.

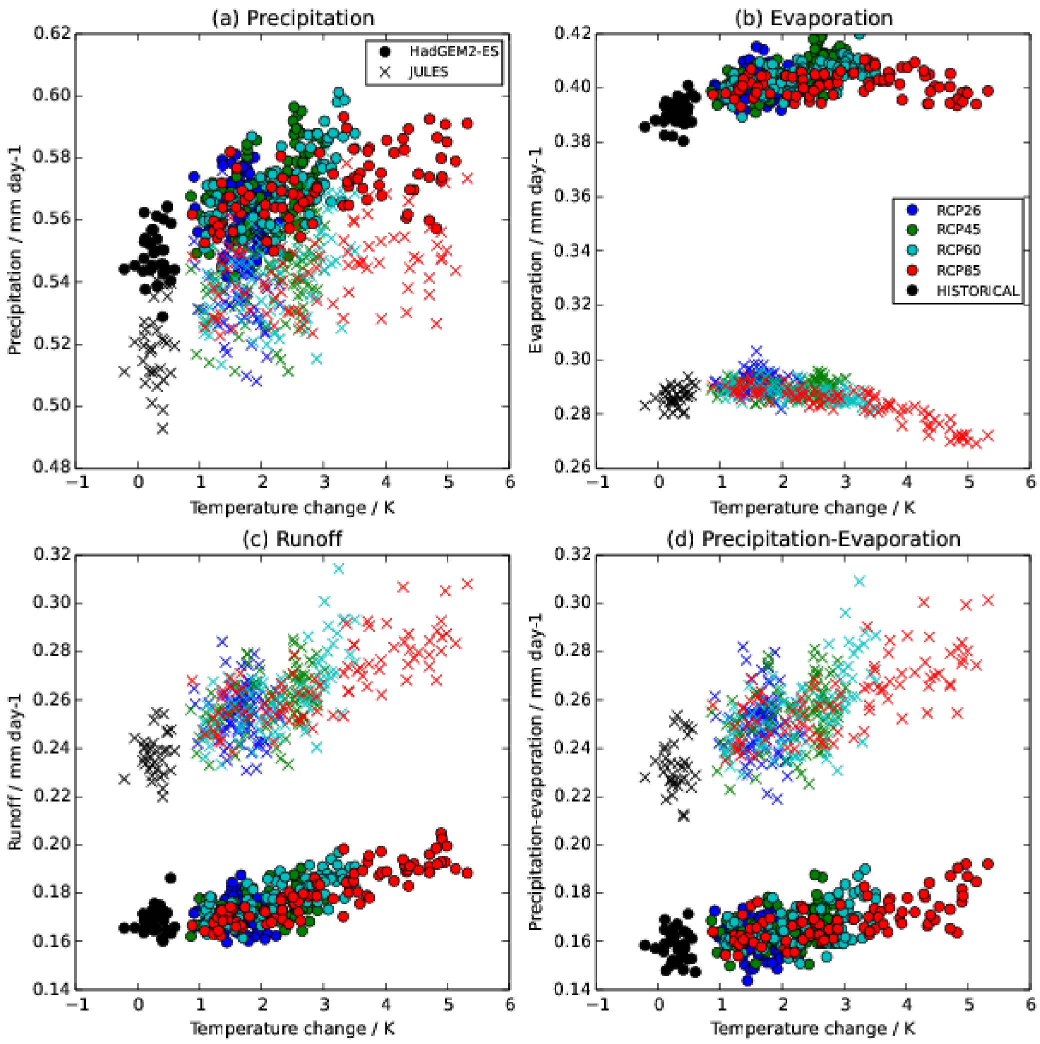

Figure 3 Global land, annual mean water cycle variables as simulated by HadGEM2-ES for the CMIP5 (circular points), and JULES in the ISIMIP driven by bias-corrected HadGEM2-ES data (crosses), plotted against global mean temperature change with respect to the pre-industrial control simulation. The black points show the simulations over the historical period (1971-2005) and the colours show the climate change simulations (dark blue: RCP2.6, green: RCP4.5, light blue: RCP6.0 and red: RCP8.5).

As in the bottom rows of Figure 1, it shows that the scenarios are similar to one another when plotted in this way, in both HadGEM2-ES and JULES. When considering the impact of climate change on ecosystems, and human systems, this is very relevant, as the timescales for adaptation is very different between the scenarios. Figure 3 also shows that there is a large, systematic difference in the evaporation simulations between the two models. This difference is then propagated through the hydrological cycle and is seen in the runoff. The difference in the evaporation could be caused by different aspects of the climate driving data. The bias correction of the temperature makes JULES 1.5K warmer. This would imply that JULES should show higher evaporation rates than HadGEM2-ES. This is the opposite of what is seen. This bias correction of the wind speed, and precipitation, causes a reduction in both cases, which is consistent with lower evaporation rates. Figure 4 shows the other impacts models run as part of ISIMIP and driven by the same bias corrected HadGEM2-ES climate simulations. For simplicity, only the RCP8.5 scenario is shown.

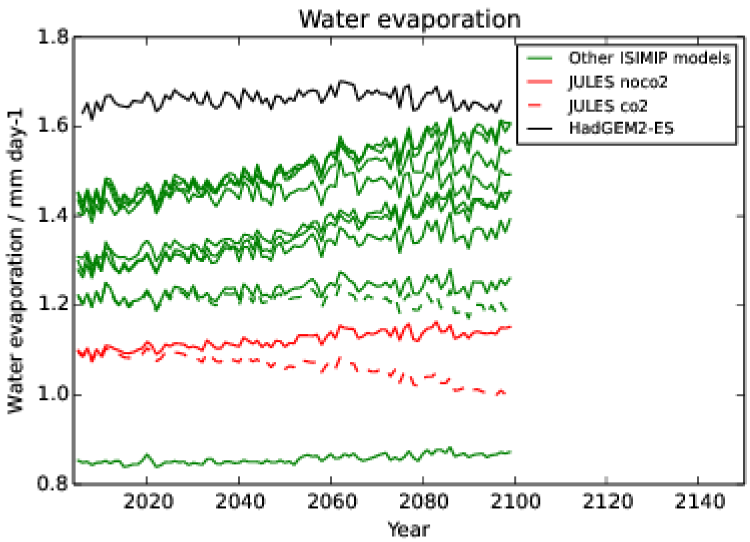

Figure 4. Global land, annual mean evaporation simulated when driven by HadGEM2-ES climate projections under RCP8.5. The black line represents the HadGEM2-ES simulation, the green lines show other impacts models driven by HadGEM2-ES data after bias correction, and the red lines show driven by the same data. The dashed lines show the JULES and LPJ models when vegetation can react to the changes in atmospheric CO_2 concentrations.

This figure shows that the evaporation is systematically lower than the HadGEM2-ES climate model in all impacts models. This supports the hypothesis that the bias correction of the climate data is causing some of the difference. It is interesting to note that the evaporation simulated by JULES is one of the most different to HadGEM2-ES. This is not what is expected when it is considered that JULES is coupled to HadGEM2-ES and run interactively to simulate the evaporation in this model. The dashed lines in this figure show the two models (JULES and LPJ), that can simulate the reaction of the vegetation to atmospheric CO_2 levels. When CO_2 levels are enhanced, plants can photosynthesis more efficiently, meaning not as much evapotranspiration occurs from leaves, leading to reduced evaporation rates. This can be seen with the two red lines showing the different JULES simulations diverging towards the end of the simulation. This was noted by Prudhomme et al (2014) [3] who found negative trends in runoff simulations in all the ISIMIP models they analysed with the exception of JULES. This was attributed to the interactive vegetation reducing the evaporation rates and therefore increasing the runoff. This counteracted the underlying tenancy of the reduction on runoff, leading to no substantial trend.

3.1 Impact of temporal resolution of climate driving data

Another possible source of difference between the JULES and HadGEM2-ES simulations is to do with the coupling. With the fully coupled model within HadGEM2-ES, the energy and water fluxes are exchanged with the surface at every 30-minute model time step, and therefore precipitation can be simulated as short-term events within the diurnal cycle. When JULES is driven offline however, the climate data are provided at daily resolution. In this situation it is necessary to make an assumption as to how the precipitation is spread across the day. This will have an impact on evaporation, as if there is more surface water when the temperature is largest (during the day), that water will be more readily evaporated. This effect was investigated by Williams and Clark [5], and found to have the largest impact on evaporation over the tropics. This is where the precipitation is most convective in nature, therefore high temporal resolution is needed to capture its characteristics. The method used in ISIMIP was to concentrate daily convective precipitation into a 2 hour period, and other large scale precipitation into 5 hours. Simulations were run for a 6 year period with time step temporal resolution (20 minutes), here termed the ``control'', and with the disaggregation of daily means following the ISIMIP method, referred to as ``experiment''. This resulted in a global land, annual mean difference in evaporation of 0.1 mm day^{-1}. When comparing this impact to Figure 4, this accounts for a significant proportion of the systematic difference.

3.2 Evaporation drivers

As well as showing the large systematic bias, Figure 3 also shows that the climate change trend is different between the two modelling methods. The evaporation increases in HadGEM2-ES with global mean temperature change until about 4°C then decreases. The JULES simulations however have a peak at much lower global mean temperature change, and decreases after about 2°C. This might imply that the variables constraining the evaporation (for example: temperature, soil moisture, wind speed) might be different.

Global evaporation trends in recent decades were investigated by Jung et al (2010) [2], who concluded that soil moisture limitation, particularly in the southern hemisphere was behind the halt in the increasing trend in evapotranspiration since 1998. The change in evaporation drivers is investigated here. Figure 5 shows the correlation between monthly evaporation and four other variables: temperature, soil moisture, wind speed and relative humidity. The colour indicates the variable for which the correlation is highest.

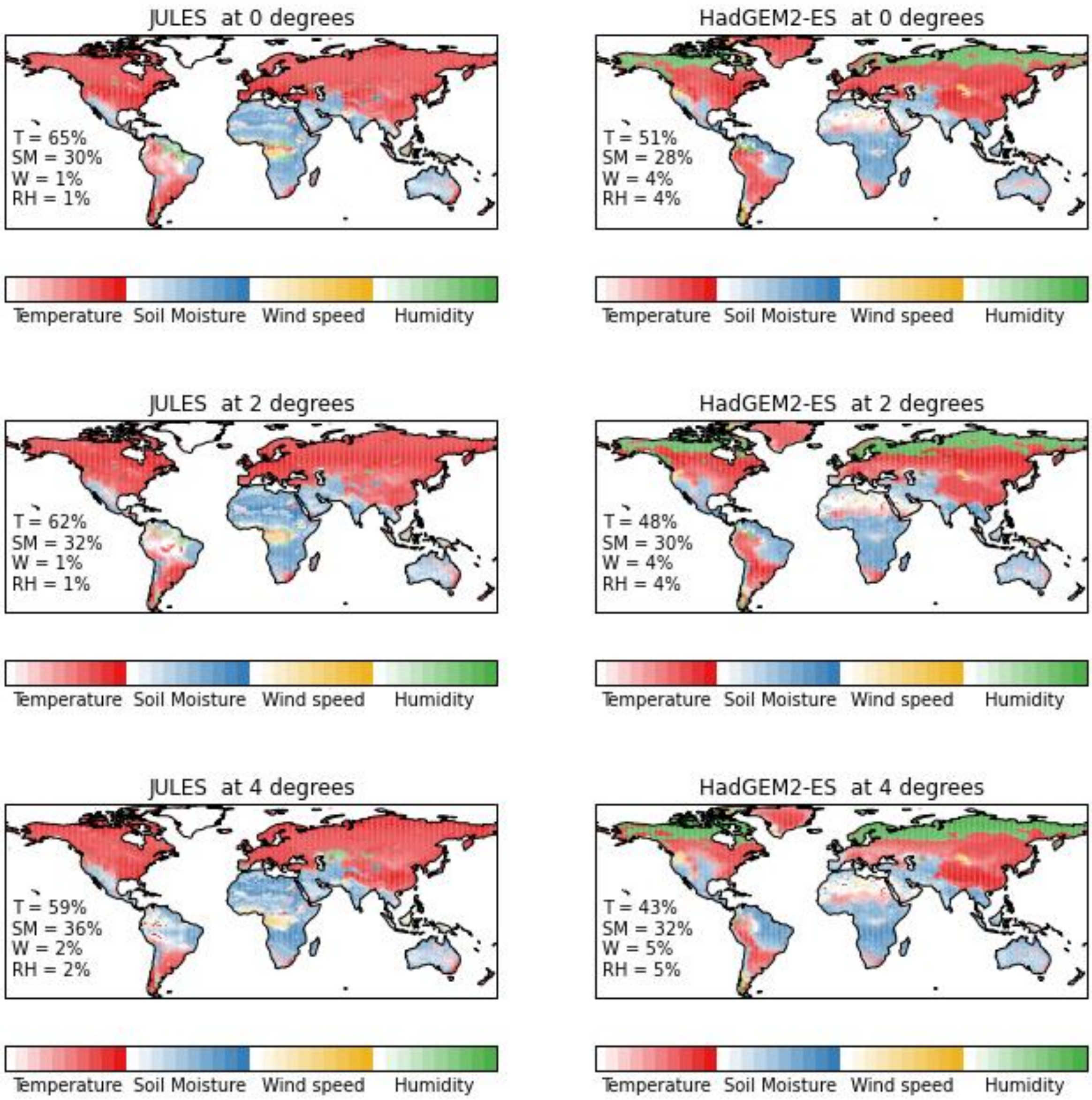

Figure 5. Maps showing the correlation between monthly mean evapo-transpiration and the monthly mean of the variable with the highest correlation (either surface air temperature (T), soil moisture (SM), surface wind speed (W) or relative humidity (RH), indicated by the colours (note the correlation with relative humidity has been multiplied by -1). Also shown is the percentage of land that is dominated by each source. The top row shows the results of the JULES model run offline, driven be bias corrected climate data, and the bottom row shows the results from the HadGEM2-ES CMIP5 simulations. 30 year means are shown in RCP8.5 at global mean temperature changes of 2 and 4 degrees (2020-2049 and 2060-289 respectively) and the historical run (1979-1998) indicated by ``0 degrees''.

This figure shows that evaporation is generally most highly correlated with temperature in the extra-tropics, and soil moisture in the tropics. As the global mean temperature change increased, the proportion of land where the correlation is dominated by temperature consistently decreases, and that of the soil moisture consistently increases. This transition occurs near at the border between the temperature and soil moisture dominated regions, which is consistent with the soil moisture limited regions expanding. The overall picture between JULES and HadGEM2-ES is consistent, with the exception of the very high latitudes in the northern hemisphere. In HadGEM2-ES the correlation is highest between evaporation and relative humidity, whereas in JULES the correlation is highest between evaporation and temperature. This is likely to be related to an issue which is caused by the bias correction of the temperature field which is described in more detail in Section 4.

4. Frozen soil moisture

It was seen in Figure 1 that the bias correction of the climate data increased the temperature by approximately 1.5K, making the offline JULES simulations warmer. Figure 6 shows the frozen component of the soil moisture in JULES and HadGEM2-ES under RCP8.5. An global, annual mean timeseries is shown as well as the 30-year mean when the global mean temperature change is approximately 2K.

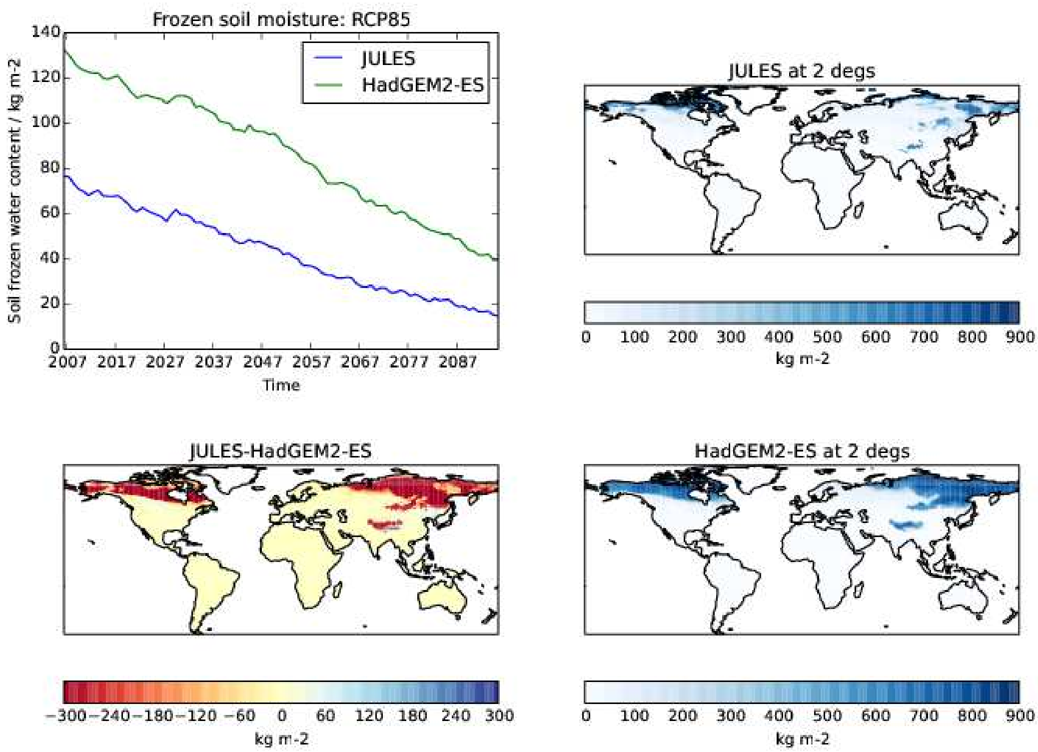

Figure 6. Summary plots of the frozen component of the soil moisture under RCP8.5. The top left panel shows a timeseries of the global land, annual mean frozen soil moisture in JULES (blue) and HadGEM2-ES (green). The right panels show a 30 year mean timeslice of JULES (top) and HadGEM2-ES (bottom) when the global mean temperature change from pre-industrial levels is 2°C. The difference between the models is shown in the bottom left plot.

This figure shows that there is a decreasing trend in frozen soil moisture in both HadGEM2-ES and JULES, but that the volume in JULES is systematically lower. This is consistent with the temperature being higher, therefore a lower fraction of the soil moisture existing in a frozen state. The maps show that this is restricted to the high-latitudes in the northern hemisphere. This corresponds to the area where the correlation with evaporation is dominated by the relative humidity in Figure 5. This shows that the bias correction is having a significant effect on the frozen soil moisture content, which will have implication further down the hydrological cycle.

5. Land Ecosystem Impacts

For a first look at impacts on ecosystems, changes in Net Primary Productivity (NPP) were analysed for JULES online and offline. NPP is the net uptake of carbon by plants, determined by the balance between carbon uptake by photosynthesis and carbon release by respiration, and hence indicates the growth of vegetation. NPP depends on water availability (via soil moisture), temperature and also CO_2 concentration. The offline and online simulations gave different patterns of NPP change and different global mean changes (Figure 7). Global mean NPP increased in both online and offline approaches, as expected due to rising CO_2 driving increased photosynthesis (hence increased carbon uptake) which is only partially offset by a temperature-driven increase in carbon loss by respiration. The global mean NPP increase was larger in HadGEM2-ES than JULES. Changes in atmospheric CO_2 concentration are similar in the offline and online approaches so are unlikely to account for the differences. It is noted that precipitation for a specific warming levels tends to be higher in HadGEM2-ES than ISI-MIP JULES, so this may allow for a greater enhancement of NPP under a given CO_2 rise due to water limitation being less important. However, examination of geographical patterns of the NPP response shows that a substantial aspect of the different responses occurs in the Arctic regions. HadGEM2-ES shows more NPP increase in the Arctic, where differences in temperature and frozen soil moisture are large. The reasons for the differences require further investigation to establish whether the different NPP responses arise from differences in photosynthesis or respiration change.

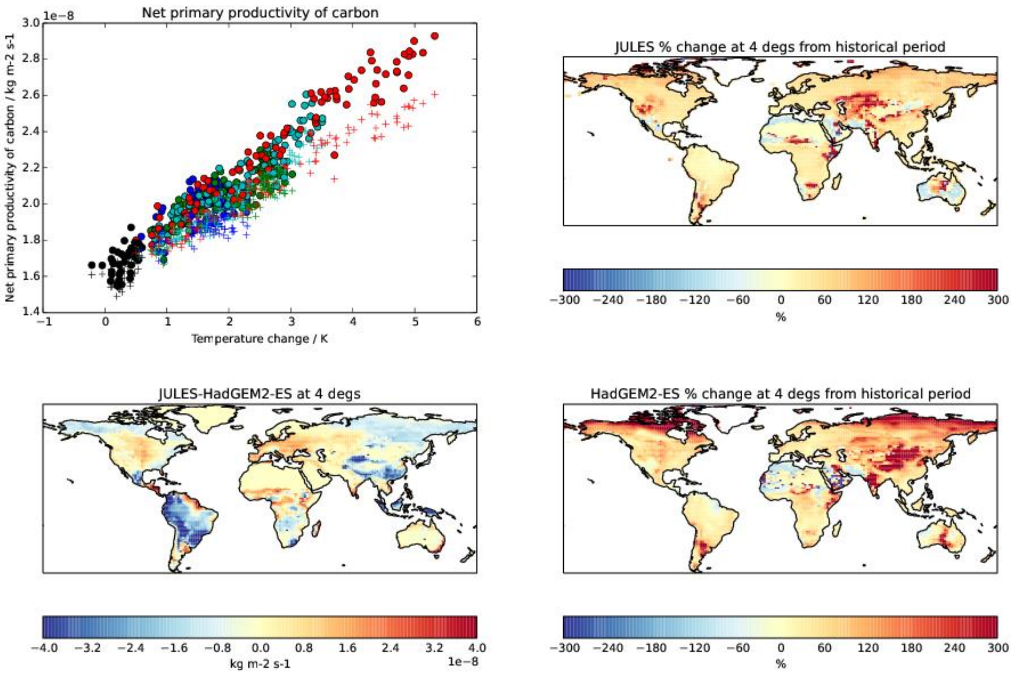

Figure 7. Summary plots of net primary productivity of carbon (NPP). The top left plot shown the global land, annual mean NPP plotted against global mean temperature change relative to pre-industrial levels. The circles represent HadGEM2-ES and the crosses show JULES. The colours show the different scenarios (black: historical, dark blue: RCP2.6, green: RCP4.5, light blue: RCP6.0 and red: RCP8.5). The right panels show the 30 year mean timeslice in JULES and HadGEM2-ES around the decade with a global mean temperature change closest to 4 degrees. The bottom left panel shows the difference between these two plots.

Conclusions

This study has compared simulations of the water cycle under climate change using different modelling methods. The JULES impacts model was run fully coupled to HadGEM2-ES under the CMIP5 protocol, and JULES was driven offline by bias-corrected HadGEM2-ES climate simulations under the ISIMIP protocol.

It has been shown that these two methods lead to significant differences in the simulation of the water cycle. This largest impacts is seen in the evaporation, in the form of a large systematic bias, and a difference in the trends under climate change. A proportion of the systematic change has been attributed to the difference caused by the coupling. When the fully coupled model is run fluxes of water and energy can be exchanged at every time step. This is not possible in an offline system where driving data are on a daily time resolution. Bias correction of the climate data appears to play a key role. Impacts assessments therefore require a judgment about whether it is more important to correct these biases or maintain conservation and internal consistency in key processes such as water and energy fluxes. Reduction of systematic biases in climate models should therefore be a critical long-term goal.

Acknowledgements
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References

[1] S Hempel, K Frieler, L Warszawski, J Schewe, and F Piontek. A trend-preserving bias-correction–the ISI-MIP approach. *Earth System Dynamics*, 4(2):219–236, 2013.

[2] Martin Jung, Markus Reichstein, Philippe Ciais, Sonia I Seneviratne, Justin Sheffield, Michael L Goulden, Gordon Bonan, Alessandro Cescatti, Jiquan Chen, Richard De Jeu, et al. Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature*, 467(7318):951–954, 2010.

[3] Christel Prudhomme, Ignazio Giuntoli, Emma L Robinson, Douglas B Clark, Nigel W Arnell, Rutger Dankers, Bal ´azs M Fekete, Wietse Franssen, Dieter Gerten, Simon N Gosling, et al. Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences*, 111(9):3262–3267, 2014.

[4] Lila Warszawski, Katja Frieler, Veronika Huber, Franziska Piontek, Olivia Serdeczny, and Jacob Schewe. The inter-sectoral impact model intercomparison project (isi–mip): Project framework. *Proceedings of the National Academy of Sciences*, 111(9):3228–3232, 2014.

[5] Karina Williams and Douglas Clark. Hadley centre rechnical note 96. disaggregation of daily data in JULES. http://www.metoffice.gov.uk/media/pdf/2/j/HCTN96.pdf/. Accessed: 2014-10-17.

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