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Comparing projections of future changes in runoff and water resources from hydrological and ecosystem models in ISI-MIP

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Abstract

Projections of future changes in runoff can have important implications for water resources and flooding. In this study, runoff projections from ISI-MIP (Inter-sectoral Impact Model Intercomparison Project) simulations forced with HadGEM2-ES bias-corrected climate data under the Representative Concentration Pathway 8.5 have been analysed. Projections of change from the baseline period (1981–2010) to the future (2070–2099) from a number of different ecosystems and hydrological models were studied. The differences between projections from the two types of model were looked at globally and regionally. Typically, across different regions the ecosystem models tended to project larger increases and smaller decreases in runoff than the hydrological models. However, the differences varied both regionally and seasonally. Sensitivity experiments were also used to investigate the contributions of varying CO_2 and allowing vegetation distribution to evolve on projected changes in runoff. In two out of four models which had data available from CO_2 sensitivity experiments, allowing CO_2 to vary was found to increase runoff more than keeping CO_2 constant, while in two models runoff decreased. This suggests more uncertainty in runoff responses to elevated CO_2 than previously considered. As CO_2 effects on evapotranspiration via stomatal conductance and leaf-area index are more commonly included in ecosystems models than in hydrological models, this may partially explain some of the difference between model types. Keeping the vegetation distribution static in JULES runs had much less effect on runoff projections than varying CO_2, but this may be more pronounced if looked at over a longer timescale as vegetation changes may take longer to reach a new state.

1 Introduction

Assessments of future hydrological changes are important due to the effects that changes in water availability, flooding and drought can have on society (Kundzewicz et al., 2007). At the global scale, projections of future freshwater availability may be provided by a number of different modelling approaches (Bates et al., 2008), each of which may potentially produce different results, even when driven by the same forcing data. The WaterMIP intercomparison (Haddeland et al., 2011) studied two types of impact model. They classified the models into global hydrological models (GHMs, which tend to be focused on water resources and represent lateral transfers of water), and land surface models (LSMs, which typically calculate vertical exchanges of heat, carbon and water), although these categories are not exclusive and some GHMs contain features of LSMs and vice-versa. These two categories of model showed differences in simulating aspects of the present-day water balance (Haddeland et al., 2011), linked both to the representation of snow processes in mid-high latitudes, and canopy evaporation over the Amazon. Similarly, a recent study comparing multiple GHMs driven by an ensemble of GCMs (Hagemann et al., 2012) found a large spread in future runoff responses, with GHM choice being an important factor. The spread in future runoff projections was dominated by GHM choice over central Amazonia and the high latitudes (Hagemann et al., 2012). This suggests that differences between models are a major source of uncertainty, and that climate change impact studies need to consider both multiple climate models and multiple impact models. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2013) is a community-driven modelling effort with the goal of providing cross-sectoral global impact assessments, based on the newly developed climate (Representative Concentration Pathways, RCPs) and socio-economic (Shared Socio-Economic Pathways, SSPs) scenarios (Moss et al., 2010). Based on common background scenarios (climate and socio-economic), a quantitative estimate of impacts and uncertainties for different sectors and from multiple impact models were derived. Within ISI-MIP, future projections of runoff (Schewe et al., 2013) were provided by both hydrological models (which mostly do not include ecosystem/vegetation dynamics) and ecosystem models (which do include vegetation dynamics).

Vegetation dynamics may alter the future response of runoff since changing vegetation patterns (in response to future climate) may alter the fluxes of energy and water in several ways. Firstly, plant structural changes, such as changing plant functional types (PFTs), or changes in leaf area index (LAI) may alter evapotranspiration rates and albedo. Secondly, changes in plant productivity and leaf area index may result from the changing climate, which may similarly alter evapotranspiration rates and albedo. Thirdly, increased CO_2 concentrations will alter plant growth and photosynthesis, and water use efficiency, which may also alter evapotranspiration rates (Falloon and Betts, 2006; Gedney et al., 2006; Betts et al., 2007), and albedo. Since any changes in evapotranspiration caused by plant responses to increasing CO_2 have to be balanced by runoff, changes in runoff may result. Elevated CO_2 is generally considered to have two opposing impacts on runoff through changes to evapotranspiration. Firstly, CO_2 fertilisation of photosynthesis, may increase plant productivity and leaf area index, thereby also increasing the possible evapotranspiration from the canopy (Betts et al., 2007; Alo and Wang, 2008), and thus decreasing runoff. Secondly, CO_2 may also inhibit evapotranspiration by reducing stomatal conductance at the leaf-level (Gedney et al., 2006; Betts et al., 2007; Cao et al., 2010). Recent studies have generally found overall increases in runoff resulting from elevated CO_2 concentrations (Gedney et al., 2006; Betts et al., 2007), although the relative size of the two opposing effects may vary (Alkama et al., 2010), particularly regionally and seasonally. The CO_2 fertilisation of photosynthesis and reduced stomatal conductance can also lead to increased soil moisture contents (Niklaus and Falloon, 2006), leading to further increases in NPP (Friend et al., 2013). Even within one hydrological model, estimates of future water stress are highly sensitive to CO_2 impacts on runoff (Wiltshire et al., 2013).

Further impacts may occur as a result of climate feedbacks (Falloon et al., 2012b; Martin and Levine, 2012). For example, projected high latitude forest expansion may warm the land surface (Falloon et al., 2012b) more in models with vegetation change than in those without (including hydrological models), which may further enhance the advancement of the spring snowmelt peak seen in some high latitude basins due to climate warming (Falloon and Betts, 2006). For instance, Martin and Levine (2012) found a reduction in Eurasian snow mass resulted from future vegetation changes.

On the other hand, the projected loss of Amazon forest cover reduces evaporation, with less marked seasonal differences (Falloon et al., 2012b), so the impact on runoff may also be more even seasonally. For the Amazon, differences between hydrological models and ecosystem models may therefore also result from differing vegetation cover (and impacts on evaporation). However, in stand-alone models which are not coupled to the climate (such as those in the present study), these changes will not feedback to the climate and result in further changes (such as the temperature increases driven by high latitude vegetation expansion and resulting albedo reduction, and evaporation reductions resulting from Amazon forest loss; Falloon et al., 2012b).

The aim of this study is to use the ISI-MIP ensemble to assess differences in future runoff response between the two types of model (hydrological and ecosystem model), and investigate the relative roles of vegetation and CO_2 changes in the ecosystems model responses. We focus only on simulations driven by the HadGEM2-ES RCP8.5 experiments for several reasons. This setup provided the largest dataset for analysis in ISI-MIP, and the largest impacts of vegetation change on runoff may be expected under the stronger RCP8.5 forcing scenario. While the application of non-bias-corrected GCM data can result in large uncertainty in impacts simulations (Gosling et al., 2010; Ehret et al., 2012), the application of bias correction in the ISI-MIP forcing dataset may largely remove any impact of differences between GCMs in the present day baseline (Hempel et al., 2013). This study first focuses on differences between model responses using all of the available runoff data from the ISI-MIP “minimal” settings simulations. In order to better understand the drivers of these differences, the available simulations with fixed CO_2 were next studied. Finally, a set of sensitivity experiments using the JULES model were used to assess the relative roles of changing vegetation and CO_2 on runoff; JULES was the only model to perform a full set of these sensitivity experiments.

2 Methodology

Runoff from a selection of impacts models involved in ISI-MIP from both the hydrological and ecosystems sectors was analysed. Unrouted runoff, as opposed to (routed) discharge was analysed in the present study since discharge data was not available from all of the ecosystems models studied here. The model selection was based on the availability of monthly runoff output from runs forced with HadGEM2-ES (Collins et al., 2011; Jones et al., 2011; Martin et al., 2011) bias-corrected climate data (Hempel et al., 2013) for the historical period (1971–2004) and the RCP 8.5 future climate scenario (2005–2099). For 2100 compared to the baseline period (1861–1990), in the original HadGEM2-ES simulations, global mean temperatures increased by approximately 6 K and precipitation by around 6 % (Caesar et al., 2012). The model runs were set up according to the ISI-MIP simulation protocol (Warszawski et al., 2013) so the models were run with comparable setups. As common forcing data is used in all of the model runs, differences between their output have (the uncertainty that they show has) to come from differences in the model – and therefore show the uncertainty in projections based only on the model selected or the setup of the model in the case of sensitivity experiments.

The models whose data was used are described in Table 1. The data used here are global gridded datasets mainly on a 0.5° latitude-longitude grid, with JULES and JeDi on a 1.25° × 1.875° latitude-longitude grid.

Using the full model dataset described above, 30 yr averages of annual and monthly runoff for 1981–2010 and 2070–2099 were calculated and the difference between them analysed. Precipitation is identical in all of the models since they were driven by the common forcing data, which had a global mean of 893 mm yr^{-1} for the land surface and the baseline period (1981–2010), within the range of 743–926 mm yr^{-1} suggested by Biemans et al. (2009), although the latter used a baseline period of 1979–1999. Data was analysed on annual and monthly timescales for land Giorgi regions (Fig. S1 in the Supplement: Giorgi and Bi, 2005; Ruosteenoja, 2003), in order to compare differences between models across large regions with different climates. As discussed in Meehl et al. (2007), the Giorgi regions have simple shapes and are no smaller than the horizontal scales on which current global climate models are useful for climate simulations (typically judged to be roughly 1000 km). These regional averages may have some deficiencies Meehl et al. (2007). For instance in some cases, the simple boxes used results in spatial averaging over regions where precipitation is projected to increase and decrease. In some sub-regions where the case can be made for a robust and plausible hydrological response, information about which is lost in the regional averages.

The main simulations analysed in this study were the ISI-MIP "minimal settings" simulations (ISI-MIP project description paper). A subset of ecosystems models were also further analysed in order to investigate the importance of including individual processes, depending on the availability of sensitivity experiments. These included models with both a varying CO_2 and a constant CO_2 run (LPJmL, JeDi, JULES and VISIT), and four JULES runs, which include the ISI-MIP minimal setting run (Warszawski et al., 2013) and sensitivity experiment runs, with and without varying CO_2 and dynamic or non-dynamic vegetation. Table 2 gives an overview of the experiments analysed in this study.

In order to identify spatial patterns of model agreement, consensus plots (Kaye et al., 2012; McSweeney and Jones, 2013) were created for the ecosystems models and hydrological models separately as well as for the full set of models. This was done since averaging over model groups may compromise the physical consistency between variables, and does not show the true behaviour of any particular model outcome (Taylor et al., 2012; Ehret et al., 2012).

3 Results and discussion

3.1 Runoff changes across all models

There is a large spread in projections of runoff, with uncertainty arising from climate models, future scenarios and impacts models (Nohara et al., 2006; Hagemann et al., 2012; Tang and Lettenmaier, 2012). The choice of impact model is often an important source of uncertainty (Haddeland et al., 2011; Hagemann et al., 2012). In this study, we used model results generated by a common forcing data-set and scenario, so the variation in future runoff projections only results from differences between the impacts models themselves. In common with Hagemann et al. (2012), our study also found a large spread in projections across different models; in the present study notable differences were produced by hydrological models and ecosystems models. Differences between the models within each category were relatively large compared with differences between the categories, so the inter-class differences may be within inter-model uncertainty. Haddeland et al. (2011) also found that differences between models in each class were larger than inter-class differences. The parameterisations used within different impact models to represent certain processes such as evapotranspiration, snowmelt or the different treatment of soil moisture (Hagemann et al., 2011; Hagemann et al., 2012; Haddeland et al., 2011) may also affect future runoff projections.

Across all models (Fig. 1), there was consensus for annual runoff increases over high latitudes and India, parts of China, the Great Lakes and Eastern Canada, and for decreases in runoff over Southern and Central Europe, the Amazon and Indonesia. The ecosystems models showed less agreement in runoff changes over Europe, Central Africa and the Amazon, compared to the hydrological models. Figure S2 in the Supplement shows the runoff changes for individual models. The consensus plots showed a broadly similar spatial pattern of runoff change to results found in Nohara et al. (2006) for the A1B scenario, however, in central, particularly Western, Africa, whilst the ecosystems models tended to project increases in runoff which is in agreement with Nohara et al. (2006), the hydrological models projected decreases. Patterns of the sign of runoff change from the hydrological models agreed with those found by Hagemann et al. (2012) based on 3 GCMs and the A2 scenario in high latitudes and the extra-tropics. However, there were opposing signals in the Tropics, with Hagemann et al. (2012) finding increasing runoff and this study forced only by HadGEM2-ES finding a drying. Although the present study has only used one future scenario, Tang and Lettenmaier (2012) found that spatial patterns of runoff change are stable across emissions scenarios.

Regionally, the hydrological models tended to show greater decreases and smaller increases in annual mean runoff between 1981–2010 and 2070–2099 than the ecosystem models used (Fig. 2). This was particularly evident in regions where there was a large spread across the models and when the projected change was of a greater magnitude. JeDi tended to show lower annual mean runoff increases than the other ecosystems models, in some cases producing the lowest runoff increases across all of the models. VISIT also tended to produce higher decreases in runoff in some regions. There was an approximately linear positive relationship between annual mean precipitation change and annual mean future runoff change (Fig. 2) which is in agreement with Betts et al. (2007) that runoff change in the future will be dominated by precipitation changes. However the points are not on a 1 : 1 line, which indicates regional variations.

Differences between runoff projections from ecosystems and hydrological models varied with region (Fig. 1). The regions showing the most pronounced differences between the types of model (Fig. 1) were Amazonia, Western Africa, Southern Asia and Alaska and Western Canada. Hagemann et al. (2012) also found that spread in runoff projections largely came from GHM choice over the Amazon and high latitudes. In our simulations, over the Amazon there was less consensus for a drying from the ecosystems models than from the hydrological models. Similarly, over Southern Asia, the hydrological models projected smaller runoff increases than the ecosystems models. Over Alaska and Western Canada, the hydrological models tended towards runoff increases, while the ecosystems models showed smaller changes.

The more marked difference between hydrological and ecosystem models for these regions suggests that runoff responses there may be strongly controlled by vegetation effects, particularly evapotranspiration. The differences between models in how and whether these effects are included results in further uncertainty between the model projections. The patterns of vegetation change differ across the ISI-MIP ecosystems models (Friend et al., 2013). For example, Haddeland et al. (2011) found that runoff results for the Amazon were sensitive to the representation of canopy evaporation.

Seasonal differences between runoff projections from ecosystems and hydrological models also varied with region (Fig. 3). The patterns of change from hydrological and ecosystems models over the year were broadly similar, but with different magnitudes, particularly at times when a large change in runoff was projected. This may be because the precipitation changes will be common to all models and dominates the changes in runoff. Over Amazonia, runoff was generally reduced throughout the year in all models, with larger decreases projected by the hydrological models used than the ecosystems models, with the largest spread in model projections between January and April, when precipitation rates are greatest. During the rainy season, evapotranspiration is not limited by soil moisture availability so that plants usually may transpire at their potential rate. Thus, limits on transpiration imposed by the stomatal conductance will directly impact the total amounts of evapotranspiration and, hence, runoff. A general increase in runoff was found over Southern Asia, with the main change to the annual cycle being one peak month becoming two peak months, likely to be from changes to the monsoon, but with differing magnitudes of change across models. The ecosystems models showed larger increases during these months than the hydrological models. Differences over Western Africa were fairly constant throughout the year. However, during August, the runoff peak, the hydrological models projected increases more similar to those of the ecosystems models. Less marked differences between model types were found over Alaska and Western Canada, with most models suggesting earlier and reduced (spring) peak runoff.

3.2 The impact of varying CO_2 in ecosystems models

Figure 4 compares the effect of precipitation change on runoff change from varying CO_2 runs and constant CO_2 runs, from those models for which these simulations were available. The impact of CO_2 on runoff was not consistent across the four models presented here. For example, the JULES and LPJmL simulations with varying CO_2 produced higher runoff than those with constant CO_2, although the impact in LPJmL was less marked. However, the JeDi and VISIT runs showed the reverse, with constant CO_2 producing greater increases in runoff than varying CO_2. There was less spread in projected runoff changes between the constant CO_2 runs than between those runs with varying CO_2. This suggests that the treatment of CO_2 in the models leads to some of the uncertainty between different models' projections of runoff change and that the effects of CO_2 on transpiration differ strongly between the models. It may be that stomatal conductance has a greater effect on reducing transpiration than the positive impact of CO_2 fertilisation on transpiration in both JULES and LPJmL. However, compared to the other models, JeDi has a weaker coupling between CO_2 and stomatal closure, leading to smaller reductions in transpiration while the CO_2 fertilisation effect is similar, resulting in overall runoff decreases.

The impact of varying CO_2 on runoff projections also varied regionally. In Amazonia, it appears that there was more difference between the runoff changes with varying CO_2 and with constant CO_2 in the early part of the year (Fig. 5), from January to April, which is also when runoff is typically highest. Over Western Africa, the impact of CO_2 was largest in summer, and most ecosystems models projected larger increases in runoff than hydrological models. The only exception to this was JeDi, which projected the strongest decreases of all models. Throughout the year, JULES and LPJmL varying CO_2 simulations projected higher runoff than constant CO_2 simulations. However JeDi projected the reverse pattern, and VISIT agreed with JeDi on the sign of the difference between varying and constant CO_2, apart from during peak runoff, the varying CO_2 run gave higher runoff than the constant CO_2 run. The impact of elevated CO_2 on runoff was small over Alaska and Western Canada in most models, except for JULES which projected larger runoff increases during summer and autumn.

The effect of increasing CO_2 may therefore partially help explain the differences seen between some ecosystem models, which typically include CO_2 effects, and hydrological models which do not. In some regions the impact of varying CO_2 on runoff was of similar magnitude to the magnitude of overall runoff change. For example in the JULES runs, Amazonia was projected to have an average change of $-88.26\,\mathrm{mm\,yr^{-1}}$ with varying CO_2 and $-191.51\,\mathrm{mm\,yr^{-1}}$ with constant CO_2. Amazonia, and other regions showing a stronger impact of varying CO_2 on runoff, typically have higher LAI than others such as the Sahara, where smaller impacts occurred.

3.3 The impact of varying vegetation and CO_2 in JULES

In the JULES simulations (Fig. 6), greater regional increases and smaller decreases in runoff were found in the varying CO_2 runs compared to the constant CO_2 runs, regardless of whether the vegetation distribution was allowed to change dynamically or not. By comparison, the impact of vegetation change on runoff was smaller and the sign of the difference (for both varying and constant CO_2 runs) differed between regions. In some regions there was little or no impact of dynamic vegetation, particularly in the constant CO_2 runs. However, even within the same region the sign of the impact of vegetation change on runoff vegetation varied depending on whether the run included varying or constant CO_2. This may be due to the ways different vegetation types (PFTs) respond to CO_2 in JULES.

The limited impact of vegetation change may be partly explained by the long timescales required for a vegetation distribution to change significantly (Jones et al., 2009, 2010). Relatively small differences in the vegetation distributions occurred by 2070–2099 (Figs. S4 and S5 in the Supplement) which could account for the small impact on runoff. In agreement with this finding, Falloon et al. (2012a) found only small impacts of vegetation change on future (2080s) surface climate, while much larger impacts have been found for studies of the Holocene (O'ishi and Abe-Ouchi, 2012), Miocene (Micheels et al., 2009; Krapp and Jungclaus, 2011) and in synthetic modelling studies (Fraedrich et al., 2005), where much larger vegetation changes were applied. Another possible reason for the relatively small impact of vegetation change on runoff may be the non-inclusion of feedbacks between the vegetation and climate, which may have a significant effect (Falloon et al., 2012a). For example, expansion of high latitude forests may increase the temperature and therefore enhance evapotranspiration, which in turn may increase precipitation. Falloon et al. (2012a) found that in an Earth System Model, vegetation changes over the Amazon reduced evapotranspiration, leading to greater warming than without vegetation change, although different climate (and vegetation) models may result in different impacts (e.g. Martin and Levine, 2012).

The effect of vegetation distribution change on runoff projections varied regionally. Vegetation change had the largest impact over Amazonia and Alaska and Western Canada. In some regions vegetation change increased runoff (Sahel, Southeast Asia, Southern Australia), in others runoff was decreased (Europe, Eastern North America, Southern and Eastern Africa, Northern Australia and India), while only small changes occurred elsewhere. In this study, the impact of vegetation change on relative runoff change was greater in regions with lower precipitation, but the impact of changing CO_2 concentrations was greater than that of vegetation change (Fig. S3 in the Supplement). Leipprand and Gerten (2006) also found that changes in vegetation distribution had more effect in dry regions than wet regions. However, they found that vegetation distribution had larger effects on runoff in dry regions than physiological effects do, which was not found here.

Annual evaporation is generally higher in forested catchments compared to non-forested catchments (Zhang et al., 2001); similarly evaporation may generally be greater under shrub vegetation compared to grasses (depending on the composition). Therefore, all other factors being equal, a change in vegetation type from tree to shrub, or grass would generally be expected to increase runoff, and vice versa. The regions experiencing little change in runoff due to vegetation change appear to be those regions where runoff is not controlled as much by vegetation, for example in desert areas such as the Sahara Giorgi region, or where vegetation is not projected to change significantly. The direction of vegetation changes (Figs. S4 and S5 in the Supplement) do not always explain the regional differences in runoff changes in the JULES simulations with and without interactive vegetation, and in some cases elevated CO_2 altered the sign of response (Fig. S6 in the Supplement).

Over Amazonia, larger runoff decreases were found throughout the year for simulations including constant CO_2 compared to those with varying CO_2 (Fig. 7). The largest decreases were found during low runoff periods. In the constant CO_2 simulations, keeping vegetation static affected the runoff response over Amazonia particularly between January and April, which was not found in the varying CO_2 simulations. This suggests that the greatest difference in transpiration rates between vegetation types occurs during this period. Replacement of shrubs with trees in the Amazon led to runoff increases due to vegetation change in the simulations with changing CO_2, suggesting that reduced transpiration rates (due to elevated CO_2) outweighed increases in evaporation due to increases in tree cover and changes in productivity. In the runs with fixed CO_2, the opposite effect occurred, with a decrease in runoff resulting from tree replacement by shrubs, which would be expected to reduce evapotranspiration (and increase runoff), all other factors being equal. The runoff reductions in this experiment may therefore be due to either warming-related increases in evapotranspiration, or reduced moisture supply, or productivity increases.

In Alaska and Western Canada, the simulations gave a shift to an earlier month of peak runoff, which is likely to be from earlier snowmelt, and increase in the runoff at that peak. This was also when a changing vegetation distribution was more evident, with larger increases in peak magnitude when it and CO_2 were allowed to evolve than when they were kept static.

The impact of elevated CO_2 on runoff over Western Africa was fairly even throughout the year, while the greatest runoff increases due to vegetation change were projected during July–September. C4 grasses were replaced by shrubs and tree types, with increases in runoff resulting from vegetation change and a greater increase in the simulations with changing CO_2 concentrations. Since the direction of vegetation change would be expected to increase evapotranspiration rates and decrease runoff, CO_2 and productivity-related reductions in evapotranspiration appear to have outweighed the increases due to increased tree and shrub cover. In the fixed-CO_2 simulations, tree cover was replaced by grasses, but decreases in runoff due to vegetation were found, also suggesting that the role of warming, productivity changes, or reduced moisture supply may have been dominant.

Over Southern Asia, where shrubs replaced C4 grasses, runoff decreases resulted from vegetation change, with greater changes in both vegetation and runoff in the simulations including both changing vegetation and CO_2 concentrations. This suggests that the role of vegetation change may have dominated over that of CO_2 in this region.

Elsewhere, runoff reductions were found over Europe and parts of Eastern North America where broadleaf trees replaced needleleaf trees. This suggests that vegetation change may have led to increased evapotranspiration in these simulations. When fully leafed out, broadleaf trees have twice the albedo and 50–80 % greater evapotranspiration rates than needleleaf trees (Swann et al., 2010). The magnitude of the difference in runoff change due to vegetation change was generally smaller than the magnitude of the projected change in runoff over time.

The runoff increases due to both changing vegetation and CO_2 over the Amazon found in the JULES simulations agree with the finding that smaller decreases in runoff were found in the ecosystems models, compared to the hydrological models. In Alaska and Western Canada, the ecosystem models showed less agreement on an increase in runoff, and there was a less marked difference between runoff from simulations varying CO_2 and keeping CO_2 constant. Western Africa was projected to have increased runoff by ecosystems models compared with decreases in the hydrological models, and the effects of varying CO_2 and allowing vegetation to change also showed this increase. Over Southern Asia, the ecosystem models projected slightly higher runoff than the hydrological models, with varying CO_2 compared to constant CO_2 also having this difference.

4 Limitations and future work

Only changes in annual and monthly means have been considered, which do not account for changes in extremes linked to runoff, such as floods (Dankers et al., 2013) and drought (Taylor et al., 2012; Prudhomme et al., 2013). Differences between ecosystem and hydrological model projections may not show the same patterns for the extremes as they do for the mean changes. Nevertheless, in the ISI-MIP simulations, Prudhomme et al. (2013) noted smaller runoff deficits under elevated CO_2, compared to fixed CO_2, while JULES with both fixed vegetation distribution and CO_2 behaved most like the hydrological models.

We have found that there are differences in runoff projections between models, but in order to determine the causes of these differences, other variables contributing to runoff rate such as evapotranspiration, snow mass, leaf area index and plant functional type fractions could be investigated systematically (Haddeland et al., 2011), even though the complicated interactions between the various processes make it infeasible to explain the causes of many simulation differences in detail, as noted in previous model intercomparisons (e.g., Koster and Milly, 1997).

Key uncertainties in projections of future runoff come from the possible changes in climate (GCM uncertainty), changes in vegetation and the runoff responses determined by the impacts models. As these findings used HadGEM2-ES bias-corrected climate forcing data, runoff responses using forcing data which has not been bias corrected may differ (Kahana et al., 2013) and using forcing data from other GCMs and Representative Concentration Pathways may also influence runoff projections differently to HadGEM2-ES RCP 8.5 (Schewe et al., 2013). Comparison of simulated water balance terms with observational data (e.g, Haddeland et al., 2011; Falloon et al., 2011) may provide further insight into the reasons for differences between the model projections discussed here. However, for land surface processes, validation does not necessarily help to constrain the future spread of projections – a wide range of future outcomes may result, despite reasonable simulation of present-day values (e.g. for water: Haddeland et al., 2011; Hagemann et al., 2012, and for ecosystems and the carbon cycle: Good et al., 2012; Nishina et al., 2013).

This study has only assessed runoff projections and not any of the associated socioeconomic impacts (for example, assessing impacts on water stress – Schewe et al., 2013). Human interventions through land use change, irrigation and construction of dams and reservoirs may also affect future runoff, but have not been considered. Different impacts may also result from ecosystem/hydrological models when fully coupled to GCMs (e.g. Falloon et al., 2012a; Martin and Levine, 2012).

5 Summary and conclusions

Our study has found notable differences in runoff projections between hydrological and ecosystems models; this is expected because ecosystems models tend to include other processes which affect runoff, such as by the treatment of carbon dioxide in the models and the effects this has on evapotranspiration and therefore runoff. In general, the hydrological models tended to produce larger decreases and smaller increases in annual mean runoff than ecosystems models.

The difference in runoff response between ecosystems and hydrological models varied regionally, related to the strength of vegetation influence on runoff in different regions, with some regions such as the Sahara not showing differences between the types of model. In some regions large differences in projections of changes in average runoff were found between impacts models, despite using common climate forcing data, as also found by Hagemann et al. (2012). Interestingly, the impact of elevated CO_2 on runoff in the three ecosystems models studied here was not consistent – two showed increases and two decreases in response to varying CO_2. The difference in model behaviour appears to result from the impact of two competing processes which vary in strength across the models – that of elevated CO_2 on stomatal conductance, and the fertilising impact on transpiration. This suggests more uncertainty in runoff responses to elevated CO_2 than in previous studies (e.g. Gedney et al., 2006; Betts et al., 2007).

In the JULES simulations, the impacts of vegetation change on runoff varied with region, and were generally smaller than overall future projected changes. On the other hand, for some regions, inclusion of varying CO_2 had an effect on runoff with a magnitude similar to that of the change projected over time. In the JULES simulations across all Giorgi regions, increased CO_2 concentrations led to increases in annual average runoff. The impact of elevated CO_2 on runoff may therefore partly explain the differences between ecosystems and hydrological models, because of the processes typically included in each type of model.

This indicates that a range of impacts models should be considered in impacts studies due to the range of uncertainty, and that ecosystems models should be used in conjunction with hydrological models in planning for water resource management in the future as they may produce different findings.

Supplementary material related to this article is available online at: http://www.earth-syst-dynam-discuss.net/4/279/2013/esdd-4-279-2013-supplement.pdf.

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Table 1. Models used in the present study and their main characteristics (in part, after Haddeland et al. 2011).

Model Name	Model time step	Meteorological forcing variables[a]	Energy balance	ET scheme[b]	Runoff scheme[c]	Snow scheme	Vegetation dynamics	CO_2 impacts	References
Hydrological models									
DBH	1 h	P, T, W, Q, LW, SW, SP	Yes	Energy balance	Infiltration excess	Energy balance	No	No	Tang et al. (2006, 2007)
VIC	Daily/3 h	P, T_{max}, T_{min}, W, Q, LW, SW, SP	No	Penman-Monteith	Saturation excess/beta function	Energy balance	No	No	Liang et al. (1994)
WBM	Daily	P, T	No	Hamon	Saturation excess	Empirical T and P based formula	No	No	Vörösmarty et al. (1998)
MacPDM.09	Daily	P, T, LW_{net}, SW	No	Penman-Monteith	Saturation excess/beta function	Degree-day	No	No	Arnell (1999); Gosling et al. (2010)
MPI-HM	Daily	P, T, W, Q, LW, SW, SP	No	Penman-Monteith	Saturation excess/beta function	Degree-day	No	No	Hagemann and Gates (2003); Stacke and Hagemann (2012)
WaterGAP	Daily	P, T, LW_{net}, SW	No	Priestley-Taylor	Beta function	Degree-day	No	No	Alkama et al. (2003); Döll et al. (2003, 2012); Flörke et al. (2013)
H08	Daily	R, S, T, W, Q, LW, SW, SP	Yes	Bulk formula	Saturation excess/beta function/ subsurface flow	Energy balance	No	No	Hanasaki et al. (2008a,b)
Ecosystem models									
LPJmL	Daily	P, T, LW_{net}, SW	No	Priestley-Taylor	Saturation excess	Degree day	Yes	Yes	Bondeau et al. (2007); Rost et al. (2008)
JULES	1 h	R, S, T, W, Q, LW, SW, SP	Yes	Penman-Monteith	Infiltration excess/Darcy	Energy balance	Yes	Yes	Clark et al. (2011); Best et al. (2011)
VISIT	Monthly	P, T, Q, SW, W	Yes	Penman-Monteith	Bucket (simplified saturation excess)	Ambient temperature	No	Yes	Ito and Inatomi (2011)
JeDi	Daily	P, T, LW, SW	No	Priestley-Taylor	Saturation excess/beta function	Degree-day	Yes	Yes	Pavlick et al. (2012)

[a] R = rainfall rate; S = snowfall rate; P = precipitation (rain or snow distinguished in the model); T = air temperature; T_{max} = maximum daily air temperature; T_{min} = minimum daily air temperature; W = windspeed; Q = specific humidity; LW = longwave radiation flux (downward); LW_{net} = longwave radiation flux (net); SW = shortwave radiation flux (downward); and SP = surface pressure; [b] bulk formula: bulk transfer coefficients are used when calculating the turbulent heat fluxes; [c] beta function: runoff is a nonlinear function of soil moisture.

Table 2. Model simulations analysed in the present study (all driven by ISI-MIP forcing data for HadGEM2-ES historic and RCP8.5 scenarios).

				Sensitivity experiments			
				Fixed vegetation		Dynamic vegetation	
Model name	Main simulations*	Vegetation dynamics	CO_2 impacts	Fixed CO_2	Varying CO_2	Fixed CO_2	Varying CO_2
Hydrological models							
DBH	nosoc	–	–	–	–	–	–
VIC	nosoc	–	–	–	–	–	–
WBM	nosoc	–	–	–	–	–	–
MacPDM.09	nosoc	–	–	–	–	–	–
MPI-HM	nosoc	–	–	–	–	–	–
WaterGAP	nosoc	–	–	–	–	–	–
H08	nosoc	–	–	–	–	–	–
Ecosystem models							
LPJmL	nolu	Yes	Yes	–	–	Yes	Yes
JULES	nolu	Yes	Yes	Yes	Yes	Yes	Yes
VISIT	nolu	–	Yes	Yes	Yes	–	–
JeDI	nolu	Yes	Yes	–	–	Yes	Yes

* nosoc: naturalized runs, with no human impact, no irrigation, and no population/GDP data prescribed; nolu = no human assumed.

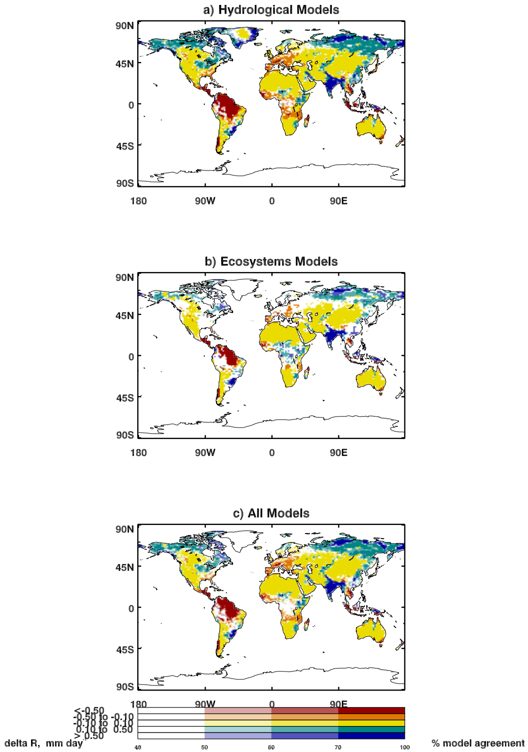

Fig. 1. Ensemble consensus for runoff change between 1981–2010 and 2070–2099 for **(a)** hydrological models, **(b)** ecosystems models and **(c)** all models (with ISI-MIP minimal settings). Each colour shows the category of runoff change, while lighter (darker) shades indicate the proportion of models agreeing with that category of change. Runoff changes were calculated individually for each model, and then the consensus across these individual model changes were calculated for hydrological models, ecosystems models and all models.

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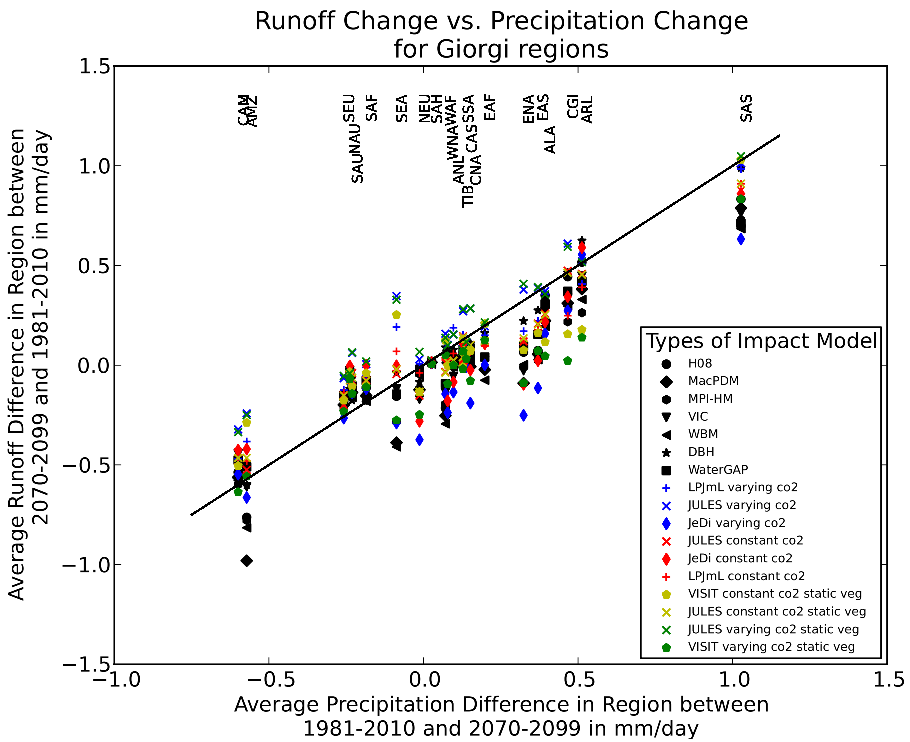

Fig. 2. Scatter plot of precipitation change against runoff change between 1981–2010 and 2070–2099 in mm day^{-1} for the Giorgi regions – including results from all models and configurations.

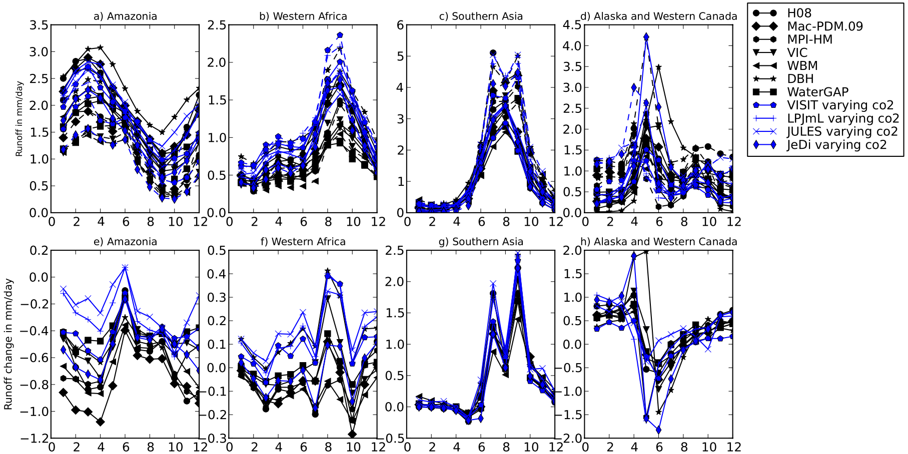

Fig. 3. Annual cycles of runoff for selected Giorgi regions using ISI-MIP (ISI-MIP project description paper) minimal setting model runs, **(a)**–**(d)**: absolute values for 1981–1990 (solid lines) and 2081–2099 (dashed lines); **(e)**–**(h)**: absolute changes between 1981–1990 and 2081–2099. Ecosystems models include varying and constant CO_2.

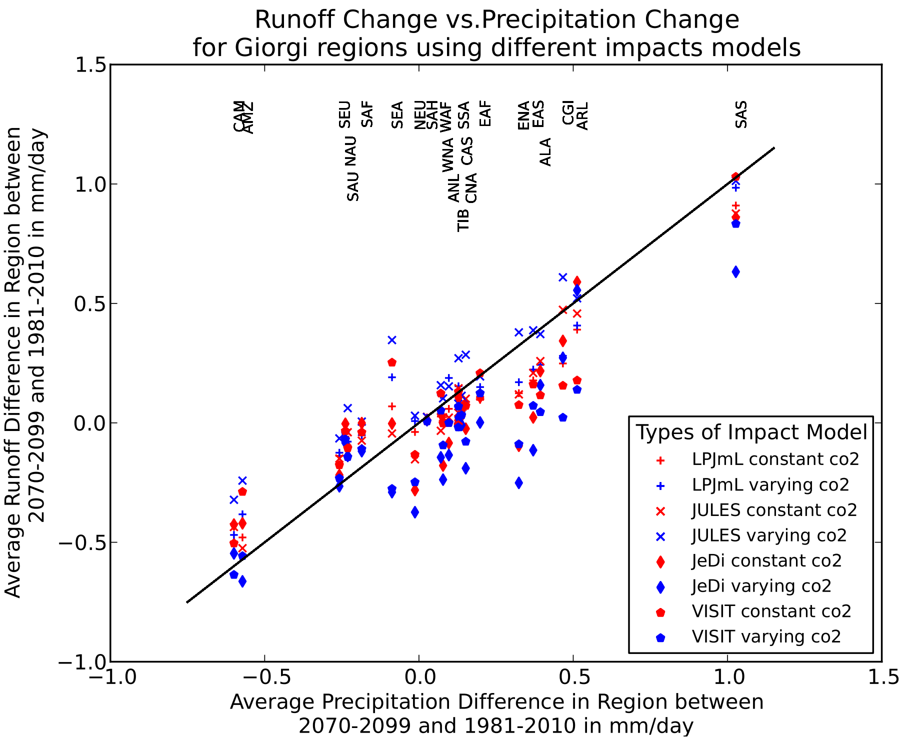

Fig. 4. Scatter plot of precipitation change against runoff change between 1981–2010 and 2070–2099 in mm day^{-1} for the Giorgi regions – for models including both varying and constant CO$_2$.

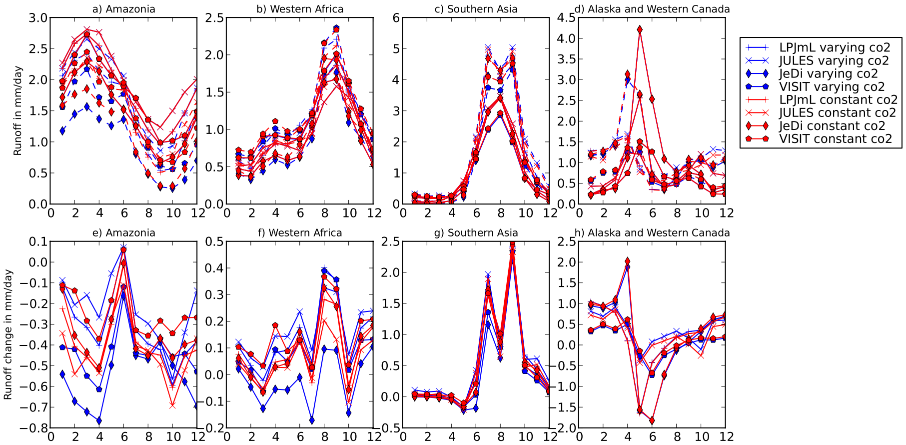

Fig. 5. Annual cycles of runoff for selected Giorgi regions using runs from models including both varying CO_2 and constant CO_2: **(a)–(d)**: absolute values for 1981–1990 (solid lines) and 2081-2090 (dashed lines); **(e)–(h)**: absolute changes between 1981–1990 and 2081–2099.

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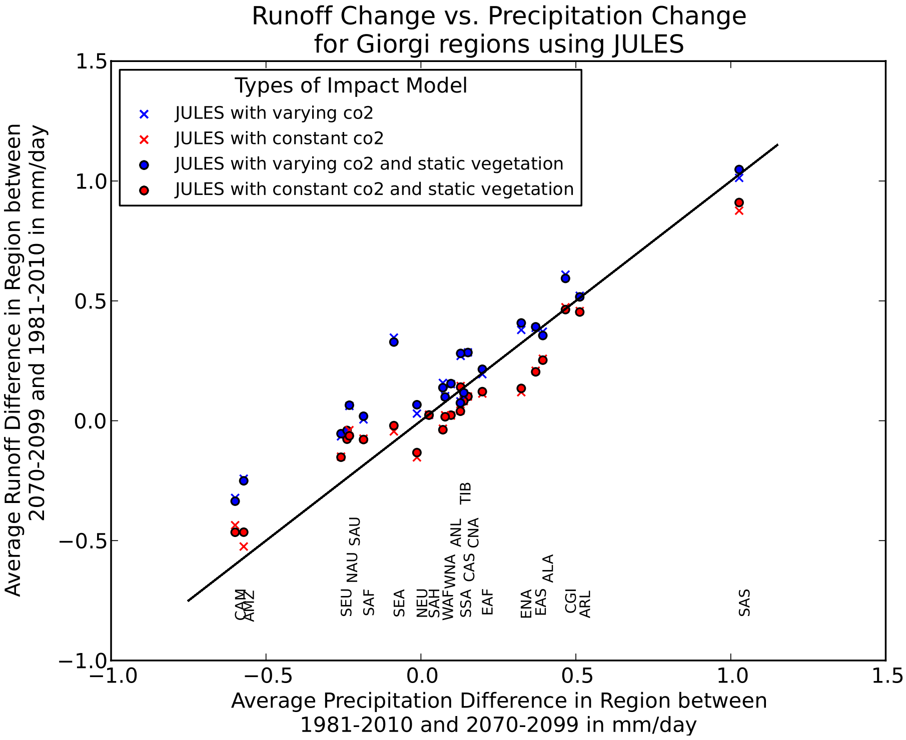

Fig. 6. Scatter plot of precipitation change against runoff change between 1981–2010 and 2070–2099 in mm day^{-1} for the Giorgi regions – for the four JULES simulations.

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Comparing projections of future changes in runoff and water resources

J. C. S. Davie et al.

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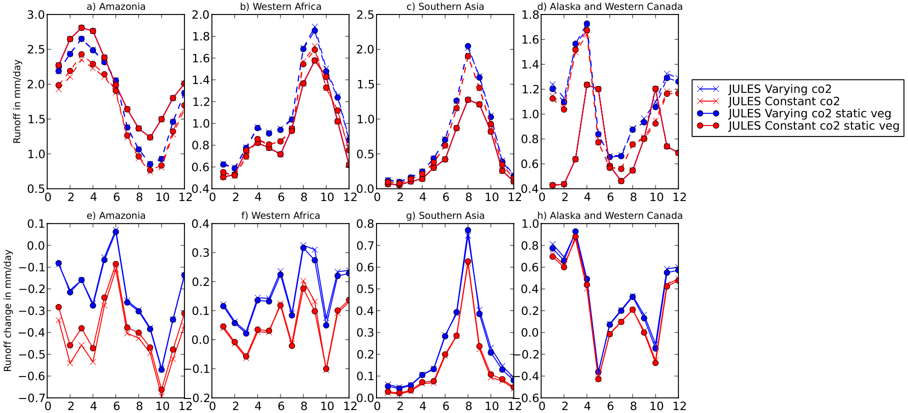

Fig. 7. Annual cycles of runoff for selected Giorgi regions using sensitivity experiment runs from JULES: **(a)–(d)**: absolute values for 1981–1990 (solid lines) and 2081–2090 (dashed lines); **(e)–(h)**: absolute changes between 1981–1990 and 2081–2099.