SIMULATIONS OF THE HYDROLOGICAL RESPONSE TO THE CLIMATE CHANGE FOR THE IBERIAN PENINSULA THROUGH A LAND-SURFACE MODEL

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ABSTRACT

The objective of this work has been to evaluate the ability of the VIC model to simulate the hydrological response of the Iberian Peninsula under different climate scenarios. Taking as forcing several outputs from the WRF model for present and for future climate in the study area, three simulations have been carried out and the behavior of the distinct components of the water balance equation has been analyzed. For this purpose, the terms of this equation have been interpreted as the sum of three adimensional indices: a runoff index (i_R), an evapotranspiration index (i_E), and a storage index (i_S). Results of the three simulations show that most of the annual precipitation is lost to the atmosphere through evapotranspiration in almost all the regions. Headwaters, though, constitute the areas with the highest runoff index. The hydrological response of the Iberian Peninsula to climate change reveals that the mountainous areas are sensitive to the changes in the runoff generation, with decreases of i_R of up to -0.3 and for which a decrease of the precipitation is also predicted.

Key words: climate change, VIC model, water balance, runoff index, evapotranspiration index.

RESUMEN

El objetivo de este trabajo ha consistido en evaluar la capacidad del modelo VIC para simular la respuesta hidrológica de la Península Ibérica ante diferentes escenarios climáticos. Tomando como forzamientos varias salidas del modelo WRF para el presente y para el clima futuro en el área de estudio, se han llevado a cabo tres simulaciones y se ha analizado el comportamiento de los distintos componentes de la ecuación del balance de agua. Para ello se han reinterpretado sus términos como la suma de tres índices adimensionales: un índice de escorrentía (i_R), un índice de evapotranspiración (i_E) y un índice de almacenamiento (i_S). Los resultados obtenidos en las tres simulaciones demuestran que la mayor parte de la precipitación anual se pierde hacia la atmósfera por evapotranpiración en casi todas las regiones. Las zonas de cabecera, sin embargo, constituyen aquellas áreas con el mayor índice de escorrentía. La respuesta hidrológica de la Península Ibérica al cambio climático revela que las áreas montañosas son sensibles a los cambios en la generación de escorrentía, con disminuciones de i_R de hasta -0.3 y para las que se prevé, además, un descenso de la precipitación.

Palabras clave: cambio climático, modelo VIC, balance de agua, índice de escorrentía, índice de evapotranspiración.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) states that warming of the climate system is unequivocal (IPCC, 2014). The Mediterranean Basin constitutes a region where the effects of climate change are already evident. The Iberian Peninsula (IP), as part of the Mediterranean Basin, has been identified as a hotspot, particularly vulnerable to global warming (Diffenbaugh and Giorgi, 2012).
Climate models are powerful tools developed to analyze the effect of green house gases (GHGs) emissions over variables such as the precipitation and the temperature. In order to properly represent the land-atmosphere interaction, Land-Surface Models (LSMs) have been designed to be coupled to Global Circulation Models (GCMs) and Regional Climate Models (RCMs). LSMs make it possible to incorporate the surface and subsurface hydrological processes into the climate modeling framework. However, LSMs are slightly different from classical hydrologic models (Clark et al., 2015): while the former put the emphasis on the biophysical processes (e.g., evapotranspiration), the latter mainly focus on simulating streamflows.
The Variable Infiltration Capacity (VIC) model (Liang et al., 1994, 1996) has played the role of both a LSM and a hydrologic model in many previous studies. Here, the potentialities of VIC as a hydrologic model have been tested in an exploratory analysis of the hydrological response of the IP to a set of climate scenarios.

2. METHODS

2.1 Climate dataset

The meteorological forcings for the hydrological modeling have been taken from high resolution (0.088º) simulations carried out with the Weather Research and Forecasting (WRF) model driven by the bias-corrected outputs from version 1 of NCARs Community Earth System Model (CESM1). These last simulations were conducted under historical concentrations and for two different representative concentration pathway (RCP) scenarios, RCP4.5 and RCP8.5. Table 1 summarizes the main climate dataset characteristics (García-Valdecasas Ojeda et al., 2017).

Study periods	RCP scenarios	Climate fields
1980 – 2014	Historical	- Daily precipitation in mm - Daily maximum temperature in ºC - Daily minimum temperature in ºC
2071 – 2100	RCP4.5	
	RCP8.5	

Table 1: Main climate dataset characteristics.

2.2 Hydrological modeling

The VIC model (Liang et al., 1994, 1996) is a semi-distributed macroscale hydrologic model that computes both the water and the energy balance within the grid cell. Different algorithms for the runoff generation process must be contemplated depending on the number of soil layers defined. The three-layers VIC (VIC-3L) model is the most common with recent applications and has been chosen for this work since it is a modification of the two-layers VIC (VIC-2L) model developed in order to better represent the runoff generation process (Liang et al., 1996). A simplified schematic diagram of the conceptualization of the hydrological model is shown in Fig.1. For a certain time step, P is the precipitation in mm, AET the actual evapotranspiration in mm, R_s the surface runoff in mm and R_b the subsurface runoff in mm. Hence, the hydrological system implemented by the VIC model consists of a grid cell with three soil storages in its simplest form, being P the input of the system and AET, R_s and R_b the outputs.

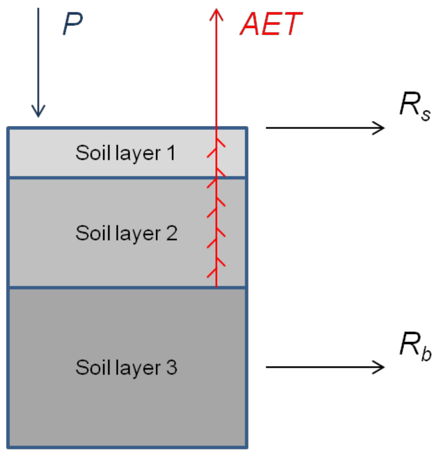

Fig. 1: Simplified conceptualization of the VIC model

Surface runoff is generated via an infiltration excess following a formulation based on a variable infiltration capacity curve (Zhao et al., 1980) applied to the first two soil layers. This formulation assumes a spatially heterogeneous structure for the infiltration capacity and takes into account the subgrid variability in the soil moisture storage. On the other hand, subsurface runoff is calculated in the third layer through an ARNO scheme (Francini and Pacciani., 1991) that divides the baseflow into two parts with different behaviors: for low moisture contents, the baseflow follows a linear law, while a parabolic function is adopted for higher soil moisture values.
Once the runoff generation process has been completed, a routing model may be coupled to VIC in order to determine the streamflow values at the outlet of a given catchment. Usually the outputs of the VIC model are post-processed with the routing scheme proposed by Lohmann et al. (1996).

2.3 Model implementation
The spatial domain of the VIC model (Fig.2) consists of a grid of 25269 cells covering the IP with a spatial resolution of 0.05º (~ 5 km). The soil parameters have been taken from two sources: the European Soil Hydraulic Database at 1 km resolution (Tóth et al., 2017) and SoilGrids1km (Hengl et al., 2014). The vegetation parameters come from the UMD Land Cover Classification at 1 km resolution (Hansen et al., 2010).

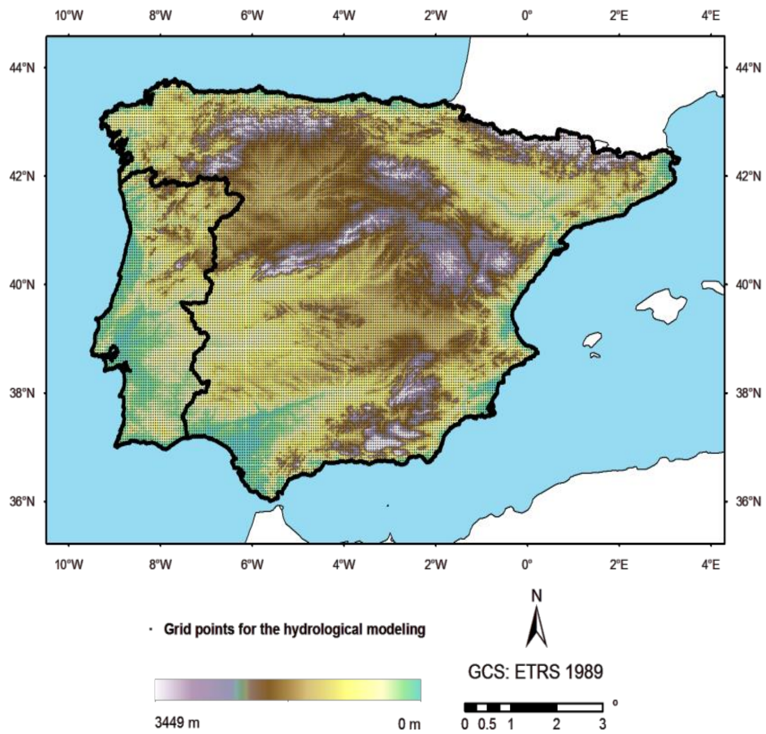

Fig. 2: Spatial domain for the hydrological modeling

A total of 3 simulations with a daily time step have been carried out taking as the boundary conditions of the hydrologic model the climate data described in Table 1. The model was implemented in the water balance mode and the outputs of VIC were then aggregated in an annual scale for interpreting the results.

2.4 Water balance equation

The law of conservation of mass applied to the system depicted in Fig.1 leads to the following expression:

$$P = R_t + AET + \Delta S \qquad (1)$$

where R_t is the total runoff in mm, calculated as the sum of R_s and R_b, and ΔS is the increment of the total storage in the hydrological system in mm. Dividing each term of Eq. 1 by the precipitation P yields:

$$1 = \frac{R_t}{P} + \frac{AET}{P} + \frac{\Delta S}{P} = i_R + i_E + i_S \qquad (2)$$

Here, i_R is a runoff index, i_E an evapotranspiration index and i_S a storage index. The relative contribution of each of these indices to the water balance depends on the time interval in which the equation above is applied and interpreted.

3. RESULTS AND DISCUSSION

3.1 Annual water balance

The indices i_R and i_E in Eq. 2 have been computed using the mean annual (from October to September) values of P, R_t and AET for each grid cell and for each simulation. The values of both indices are displayed in Fig.3. There is a clear predominance of low values of i_R and high values of i_E in the IP. This suggests that most of the annual precipitation is lost to the atmosphere through evapotranspiration, with little contribution to the runoff generation process for the vast majority of the study area. The highest values of i_R (and the lowest ones of i_E) take place over mountainous areas located in the headwaters of the different IP catchments, reaching maximum values of 0.8-0.9. These areas also constitute the greatest contribution to the runoff generation, not only for the high value of i_R, but also for presenting the largest annual precipitation means. Therefore, the headwaters in the IP are of particular interest in the complex process of the transformation of precipitation into runoff.

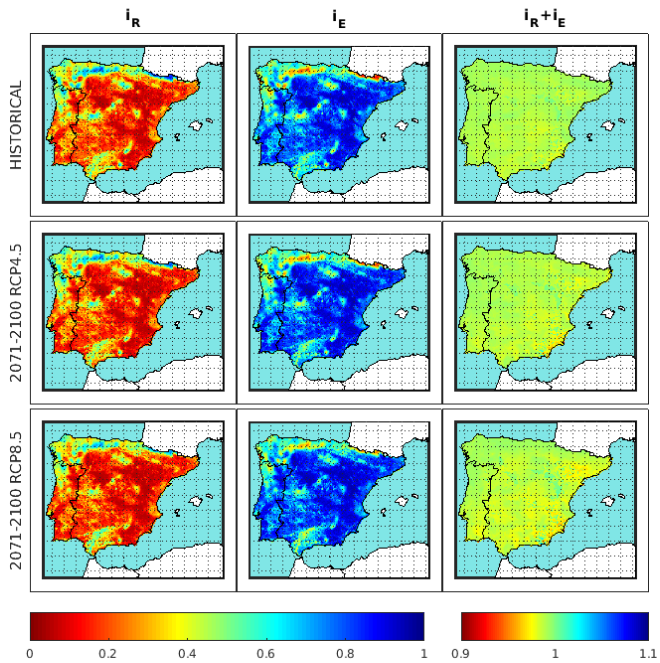

Fig. 3: Mean annual values of i_R, i_E and their sum for present (1980-2014) and future (2071-2100) for RCP4.5 and RCP8.5 from WRF simulations driven by CESM1.

The sum of i_R and i_E is also depicted in Fig.3. At an annual time scale one can expect that the relative contribution of i_S in Eq. 2 is almost negligible because the soil moisture follows an annual cycle, with minimum values at the end of the hydrological year (Oct – Sep) and maximum values in winter (that is, Jan-Feb-Mar). As a matter of fact, the sum of i_R and i_E is close to 1 for the full spatial domain in all the simulations. Therefore, it is possible to consider that after the summer the water balance is closed.

3.2 Future changes of the water balance indices

The differences between the future, using the two RCPs considered, and the present values of i_R and i_E are shown in Fig.4. A slight and generalized decrease of i_R of about 0.05 has been predicted for the two future simulations with respect to the present. The behavior of i_E, though, is just the opposite, with a little increase in the same amount. However, the most interesting results have been found, again, for the headwaters. Here, the decrease of i_R and the corresponding increase of i_E are more pronounced, with values of up to ±0.3, particularly for the high emission scenario RCP8.5. It is also remarkable the moderate changes found in the Guadalquivir Basin. These findings represent a key result in this work for their implications. First, the changing values of i_R and i_E between the different simulations highlight the complexity inherent to the runoff generation process. The transformation of precipitation into runoff is a highly non-linear process that the VIC model is able to capture satisfactorily. Secondly, precipitation is also expected to decrease for the period 2071-2100 and for both RCPs, especially in the mountainous areas (Argüeso et al., 2012; García-Valdecasas Ojeda, 2018). Finally, and even more importantly, a simple calculation reveals that the reduction in the runoff generation will be much more severe in these zones due to the decrease of both i_R and precipitation.

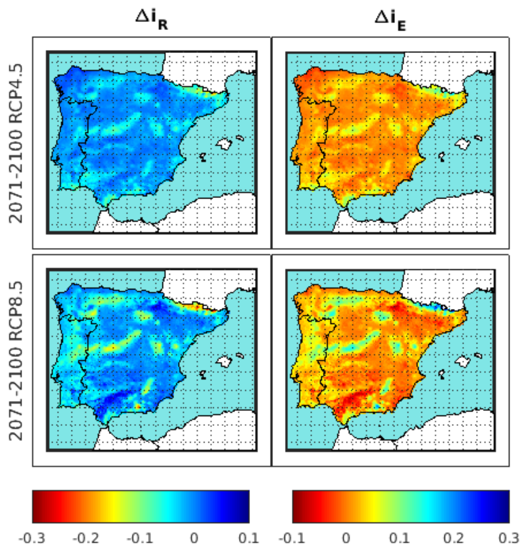

Fig. 4: Changes of i_R and i_E for the period 2071-2100 respect to the present (1980-2014) for RCP4.5 and RCP8.5 computed from WRF simulations driven by CESM1.

4. CONCLUSIONS

The hydrological response of the Iberian Peninsula to climate change has been studied through the VIC model using the water balance equation expressed as the sum of three

adimensional indices: i_R (runoff index), i_E (evapotranspiration index) and i_S (storage index). The results of this analysis can be summarized as follows:
[1] Most regions of the IP are characterized by a high value of i_E, suggesting that most of the annual precipitation is lost to the atmosphere through evaporative fluxes. Mountainous areas show the highest values of i_R, and therefore headwaters represent the largest contribution to the runoff generation process.
[2] i_S is almost null at annual time scale for the three simulations carried out. This can be understood bearing in mind that the soil moisture follows an annual cycle, and therefore its relative contribution to the water balance equation is expected to be low.
[3] Future changes of i_R and i_E are particularly noticeable in the headwaters of the IP, where a decrease of the runoff generation and an increase of the losses to the atmosphere as vapor are predicted. The decrease in the runoff generation is also aggravated by the future values of the mean precipitations, which are predicted to be lower. These changes in the headwaters can affect all the basins, with important implications for the water resources management in the Iberian Peninsula.

5. FUTURE WORK

The results of this work could be the basis of further research about the hydrological behavior of the IP. There are several questions that need to be answered as soon as possible, and there are other ones that will arise in the future. A brief description of the two research lines that could be explored in the future is offered next:
- It is of capital importance to determine if the values of the surface and subsurface runoff predicted are realistic. For this end, a routing model must be applied first for calculating the streamflow values at the outlet of the study catchments. As was stated in the introduction, LSMs are designed to improve the performance of climate models. However, if the estimation of the streamflow is not good enough, we must think if LSMs actually improve the climate predictions. The outputs of the VIC model calculated in this exercise should be analyzed in detail, and additional simulations with observational data will be also carried out.
- Once the ability (or not) of the VIC model to reproduce the streamflow records in the main catchments of the IP is tested, a calibration process will be assessed. The calibration of the parameters of the VIC model will lead to a better prediction of the streamflow. This process must be preceded by a spin-up period that ensures that the effect of the initial conditions (i.e., the initial soil moisture contents in the three soil layers) is not affecting to the calibration period. Finally, the results from the VIC model must be also validated in order to quantify the errors committed and to determine if they are assumable.

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