Supplementary material
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Analysis of the dependency between drought indices and hydrological variables

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1 Introduction

We analyze here the dependency between the different drought indices, listed in the main publication, and the corresponding simulated mean annual discharge, water deficit, and hydraulics heads. For this purpose, we use the Pearson's linear correlation coefficient r between the drought indices and the hydrological variables:

$$r = \frac{cov(DI, x)}{\sigma_{DI} \sigma x} \tag{1}$$

where cov is the covariance, DI is the value of the drought index and x is the hydrological variable under consideration. The range of r is -1 to +1, where +1 indicates a perfect positive correlation, -1 is a perfect negative correlation, and a value of zero signifies no correlation.

We conduct the same analysis for present and future climates, and for the different irrigation scenarios. Irrigation and climate scenarios are described in the main publication. The results are summarized in Figure 1 and are subsequently discussed. It is important to note that the correlation coefficients only test whether a linear relationship between two sets exists, regardless of the coefficients of the corresponding linear regression (see Section 7 of the publication).

2 Comparison for present climate conditions

For the present climate, discharge and water deficit are reasonably well correlated with drought indices ($|r| > 0.5$, Figure 1, left column). For hydraulic heads, the correlation coefficient is generally poor (between 0.2 and 0.5, not shown in Figure

1). Hydraulic heads respond slower to drought than discharge and water deficit. Therefore, a lag-time between drought index and hydraulic head response can be expected. This was confirmed by a cross-correlation analysis, which shows a delayed response in some of the wells (e.g., PO8), but no evidence of time-lags in others (e.g., PO10). Correlation coefficients between hydraulic heads and drought indices in Figure 1 incorporate these time-lags, i.e., the correlation coefficients shown are the maximum correlation coefficients between hydraulic heads and the drought indices of 1-16 months before. Because the responses of the aquifer to the meteorological conditions are non-linear, the reasons for these differences between the wells are difficult to explain. Observation wells situated in the highest part of the aquifer (e.g., PO8) are generally more sensitive to drought because the fluctuations of the water table are larger in this part of the catchment. In the lower part of the catchment, dry periods are not sufficient to significantly lower the water table because of the large water storage.

Between the different drought indices, RAI, RDI, and SPEI exhibit the largest correlation with discharge and water deficit. For these indices, the correlation coefficient varies between $r = 0.76$ and $r = 0.82$ for annual discharge and $r = -0.78$ and $r = -0.81$ for water deficit (Figure 1, panels a and c). Indices EDI and PDSI show the smallest correlation (between 0.41 and 0.59 for discharge). PDSI was developed for the climate of the Great Plains in USA (Zargar et al., 2011) and, as our study concentrates on Mediterranean climate, a lower correlation for this index can be expected. In our study, the added information of daily variability of precipitation, as considered by the EDI index, did not improve the quality of the prediction. Correlation of drought indices with hydraulic heads in a particular observation well is similar for all indices, even if large differences were computed between the wells.

Overall, our results for the current climate (Figure 1, left column) are in agreement with earlier studies. For example, Vicente-Serrano et al. (2012) compared the correlation between standardized stream flow at monthly time scale (which is an estimation of average discharge) and 6 drought indices, including SPI, SPEI, PDSI, and PHDI. Similar to our results, SPEI showed the best correlation with discharge. SPI had a lower correlation than SPEI, but the difference was relatively small in both studies. In our case, the correlation coefficient of SPI with mean annual discharge is 0.68, while the correlation with SPEI is 0.83 in the non-irrigated case.

In general, simpler indices based on precipitation only, e.g., SPI or RAI, exhibit similar or larger correlation with the studied hydrological variables than indices that include ET_0 (Figure 1, panels a and c). For example, SPEI has the largest correlation with annual discharge in present climate ($r = 0.81$, average of both land-use scenarios), but RAI exhibits a very similar correlation ($r = 0.80$). This results is consistent with findings of previous studies (e.g., Keyantash and

Dracup, 2002). Indices based only on precipitation also correlate well with water deficit because precipitation correlates strongly with water deficit ($r = -0.75$), and, hence, also with drought indices based only on precipitation (Figure 1, panel c). However, the correlation between the changes of precipitation and water deficit in different climates is low. For example, the water deficit increases in the hydrological simulations driven by the future time series of meteorological inputs from all considered climate models, but the annual mean precipitation increases in some climate models and decreases in others. This situation might be problematic for accurate climate-change impact predictions.

3 Comparison between present and future climates

The correlation coefficients between drought indices and hydrological variables in future climate are computed for each climate scenario (defined by the different regional climate models) and then averaged over the scenarios. The results differ widely between the regional climate models. In the most severe case, the correlation coefficient between discharge and EDI is 0.18 using the ETHZ model, while a value of 0.55 is attained using the MPI model (Figure 1, panel b). This difference between the climate scenarios is nevertheless lower when the drought index correlates well with the hydrological variable. For example, the maximal difference between the correlation coefficient r for the four climate scenarios is 0.2 for the three best indices (RAI, RDI, and SPEI) and discharge.

The correlation coefficients between the drought indices and the hydrological variables for present and future climates are quite similar (Figure 1, left and right columns). The average difference between the present and future correlation coefficients of discharge and drought indices is only 0.02 (average of the four climate scenarios). Moreover, the drought indices which correlate best with discharge in present climate (RAI, SPEI, and RDI, $0.76 <= r <= 0.82$) show also the best correlation with future discharge ($0.73 <= r <= 0.84$). In addition, for water deficit, the indices which correlate well in present climate do so in future climate. The correlation coefficients of hydraulic heads and drought indices are similar in present and future climates, too.

4 Comparison between different land-uses in present and future climates

The correlation of drought indices and hydrological variables is similar for the different irrigation scenarios (Figure 1). Drought indices which correlate best in scenarios with irrigation (PIRR, FUTIRR) correlate similarly well in the scenario without irrigation (NOIRR).

Drought indices correlate slightly better with discharge in the scenario without irrigation compared to scenarios that include irrigation (average difference in correlation: 0.04 in present climate, 0.03 in future climate). This result is nevertheless consistent for all indices in present and future climates. This can easily be explained as the drought indices consider only precipitation as water input, whereas discharge is of course affected by irrigation water.

For water deficit, no consistent differences in the correlation coefficient between the two irrigation scenarios are observed in the present climate (Figure 1, panel c). In future climate, the correlation between drought indices and water deficit is slightly larger in the scenario without irrigation (Figure 1, panel d). The difference is small (on average: 0.08), but consistent for all indices. As stated above, irrigation is an additional source of water not accounted for in the drought indices. Irrigation influences actual evapotranspiration and its influence increases in future climate because of the warmer conditions. Hence, the drought indices correlate less with water deficit when irrigation is present and the decrease in correlation is more pronounced in the future.

For hydraulic heads, the influence of the irrigation scenarios depends on the location of the wells. Observation wells situated at higher surface elevation (e.g., PO8) do not show large differences in the correlation coefficient between the irrigated and non-irrigated scenarios (average difference: 0.04 in present climate). However, hydraulic heads in the wells in the lowest part of the catchment (e.g., PO10) show larger differences in the correlation coefficient (average difference: 0.12). As the majority of cultivated fields are situated in the lower parts of the catchment, most of the irrigation is applied in this area, resulting in a larger impact of irrigation on the hydraulic heads in this zone. PO8 correlates better with the drought indices when irrigation is present (Figure 1, panels e and f). PO10 shows the opposite behavior (Figure 1, panels g and h). Indeed, irrigation has different impacts on the correlation coefficients for hydraulic heads: Firstly, as in the discharge case, correlation coefficients between hydraulic head and drought indices are smaller when irrigation is present because irrigation is an additional water source which is not directly considered. Secondly, irrigation raises the water table, resulting in an increased impact of climate on hydraulic heads (von Gunten et al., 2015) and so in a larger correlation with drought indices. The relative importance of these effects depends on the position and depth of the observation well.

References

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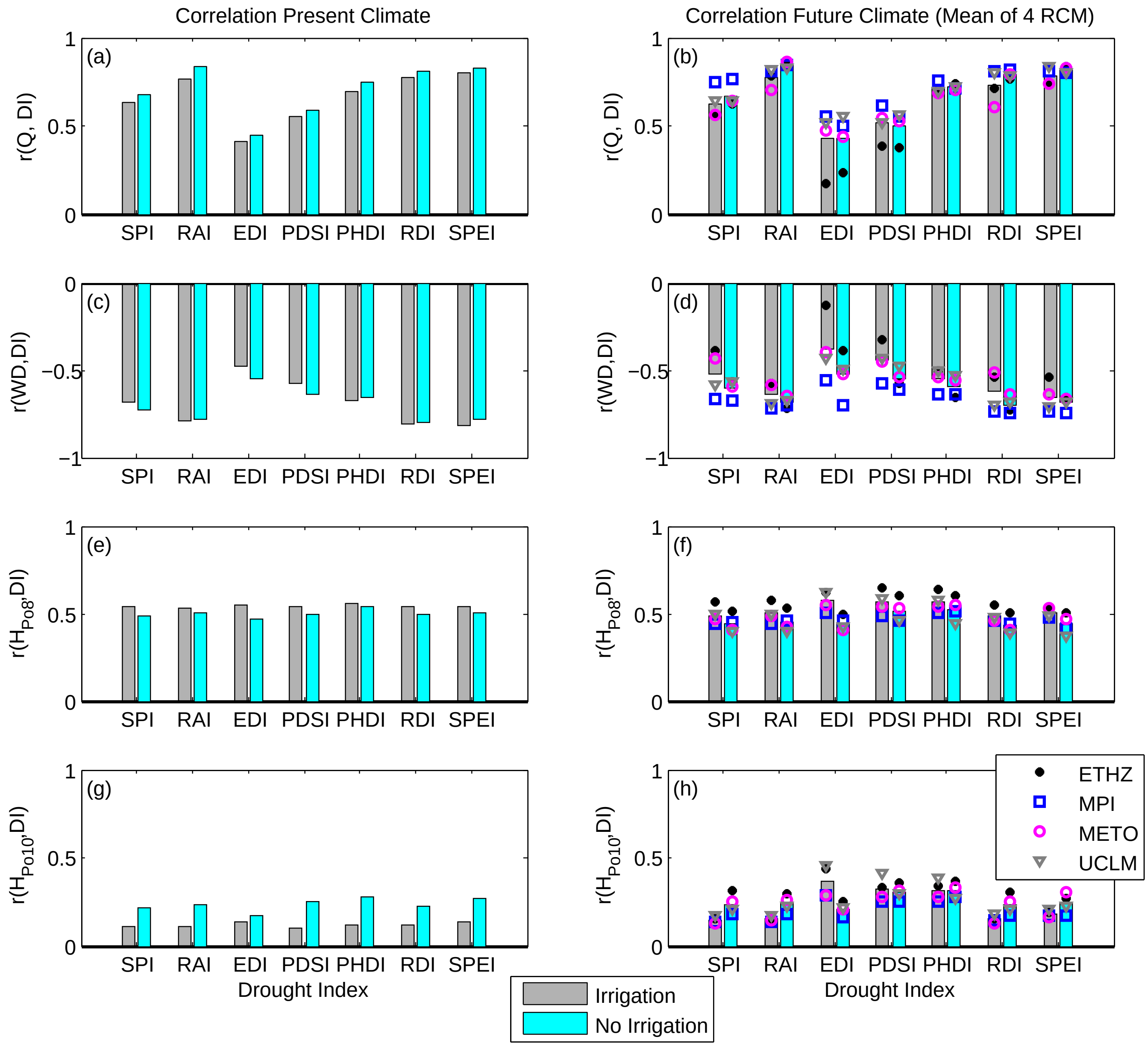

Figure 1: Correlation coefficients *r* between the drought indices (DI) and the hydrological variables (discharge, water deficit, and hydraulic heads). In future climate (right column), the plotted bars are the average of the outputs of the four regional climate models. See Table 2 of the publication for information about the climate models.