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Future changes in runoff over western and central Europe: disentangling the hydrological behavior of CMIP6 models

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S1. Choice of eight clusters

The number of clusters has been chosen empirically to provide a good compromise between ensuring a diversity of hydrological behaviors and avoiding clusters consisting of only one model or clusters with similar characteristics.

The use of a limited number of clusters (4 in Fig. S1 and 6 in Fig. S2) in the classification facilitates the identification of predominant behaviours (Fig. S5 and S6). The two types of annual behavior highlighted in the main manuscript are evident: half of the clusters show a decrease in runoff and the other half show an increase. The clusters with a decrease in runoff either project an increase in precipitation and an even greater increase in evapotranspiration or a decrease in precipitation and small changes in evapotranspiration. The outlier behavior of the CCCma models is seen in Fig S1 and Fig S2. The clustering could have been stopped at six clusters but there are still clusters with high intra-cluster variance (C2 and C3 in Fig. S2). Two additional clusters were added without lowering the dissimilarity threshold to prevent TaiESM1 from forming a single-model cluster.

With ten clusters, the C5 and C6 clusters are split (Fig. 1) to give the new C5, C9, C6 and C10 clusters (Fig. S3) with C10 being a single model cluster. In this classification, C5 and C9 have very similar behaviors (their seasonal changes in R, P and E are close) except in summer. C6 and C10 also have similar behaviors except for runoff in DJF and MAM, with C10 showing a stronger than usual increase (Fig. S6).

Note that it is harder to identify the mechanisms that might be responsible for a particular behavior with a single model cluster (especially as there are not enough models available in the MIPs analyzed in the main manuscript to have at least one model per cluster). The issues are the same with 10 clusters or more.

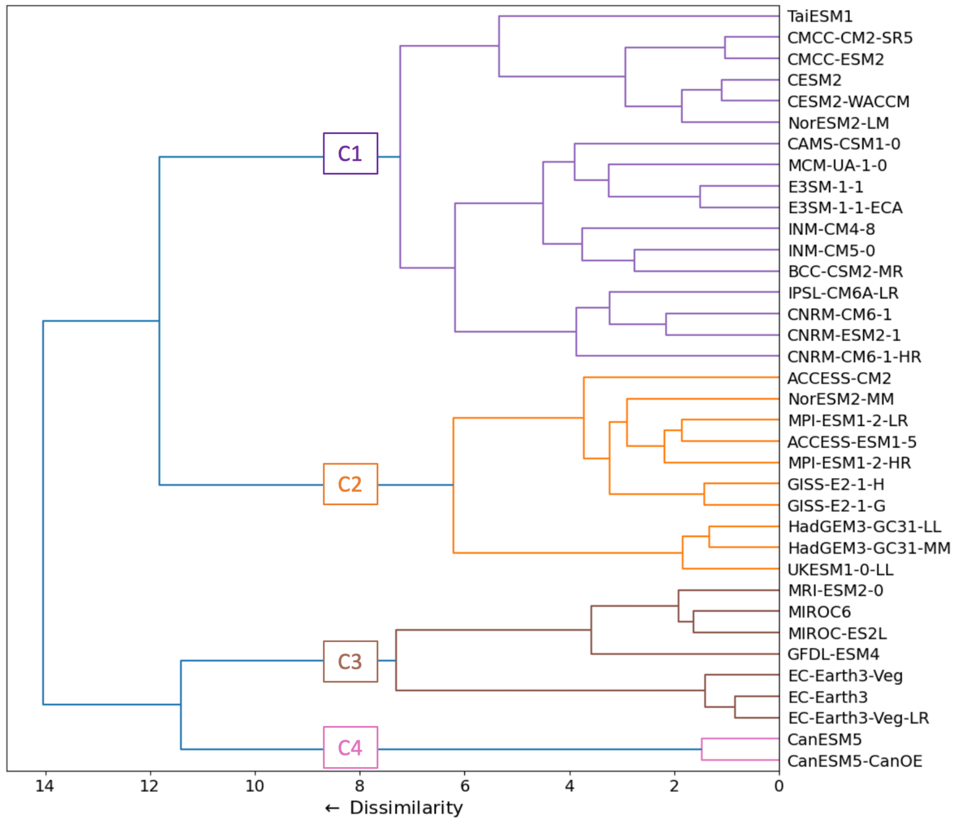

Figure S1: Same as Fig. 1 in the main manuscript but with four clusters.

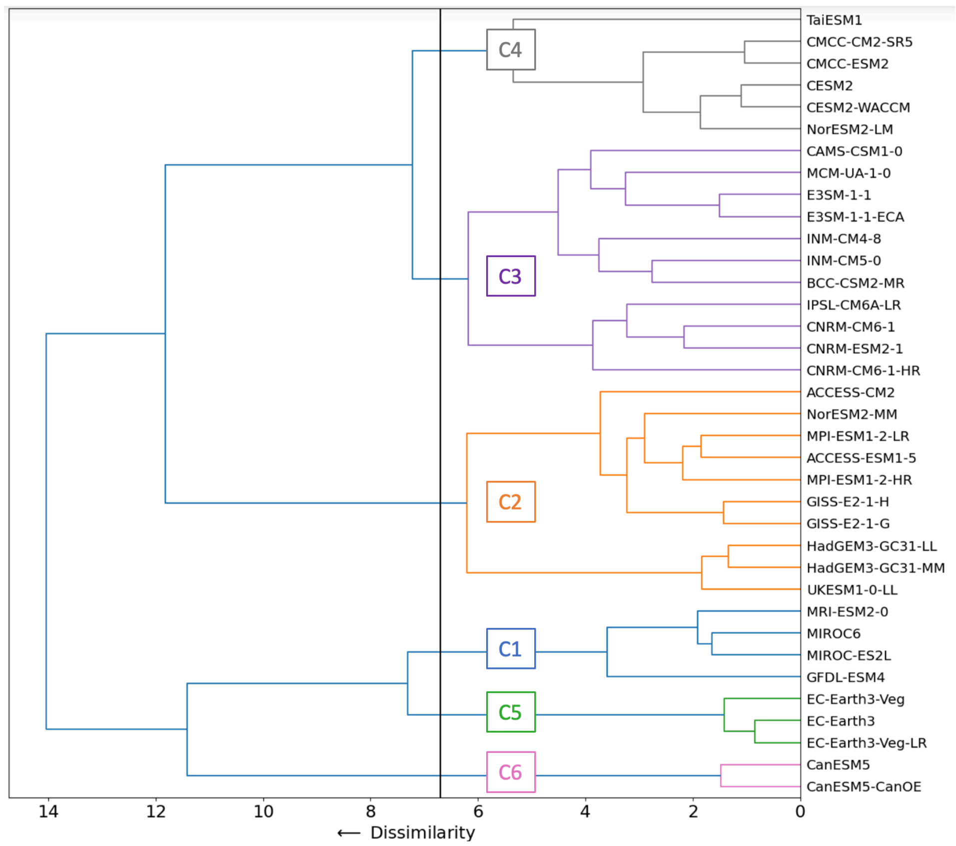

Figure S2: Same as Fig. 1 in the main manuscript but with six clusters.

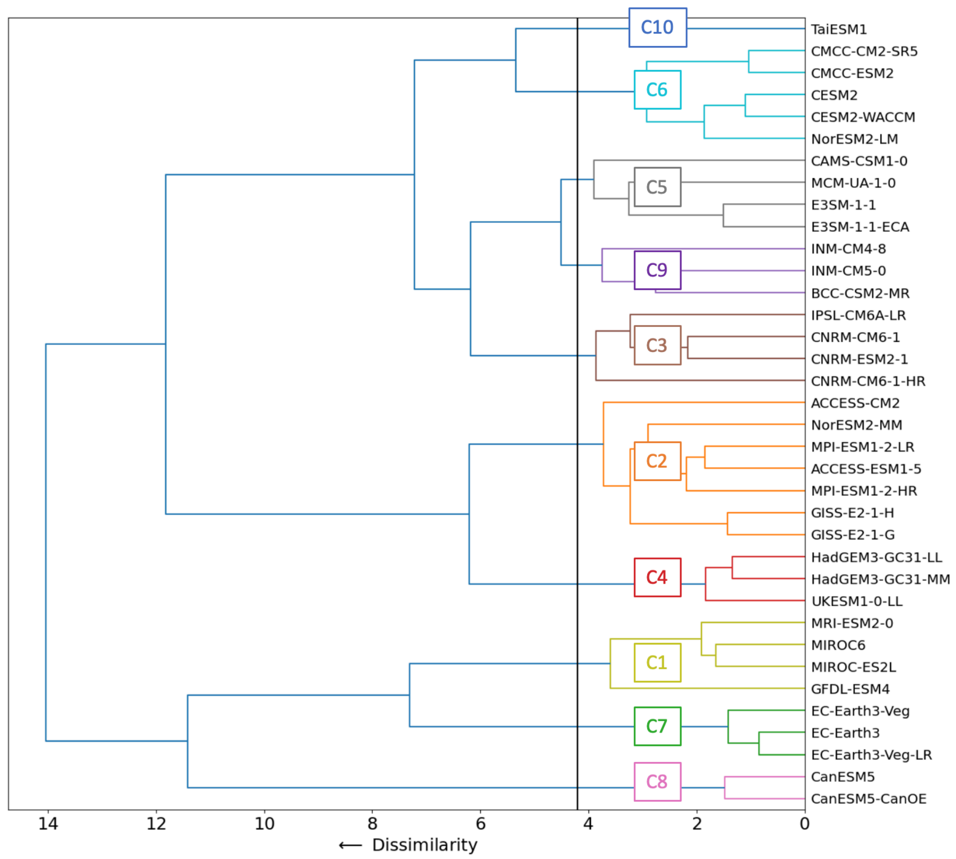

Figure S3: Same as Fig. 1 in the main manuscript but with ten clusters

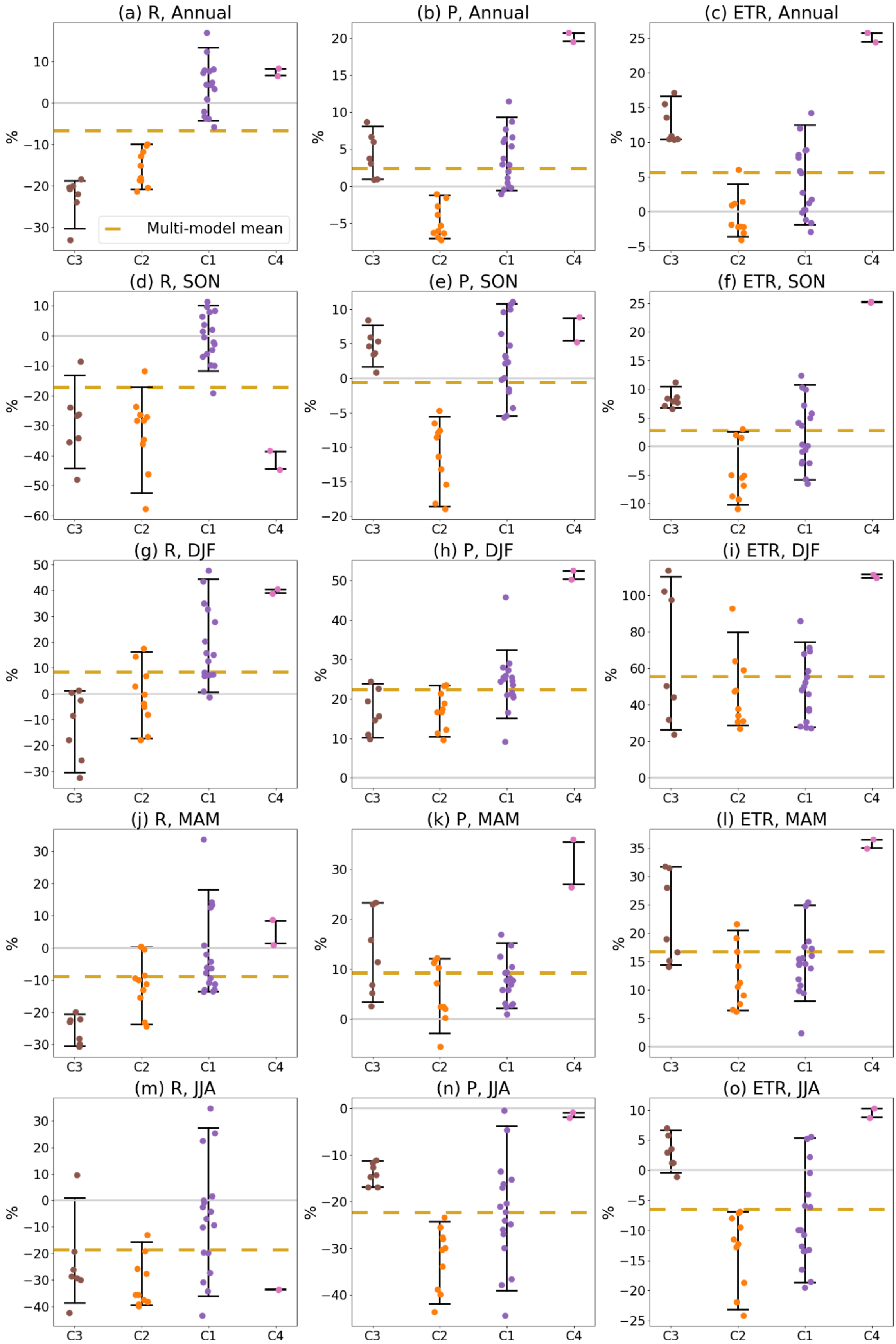

Figure S4: Same as Fig. 4 in the main manuscript but with four clusters. The associated dendrogram is shown in Fig. S1.

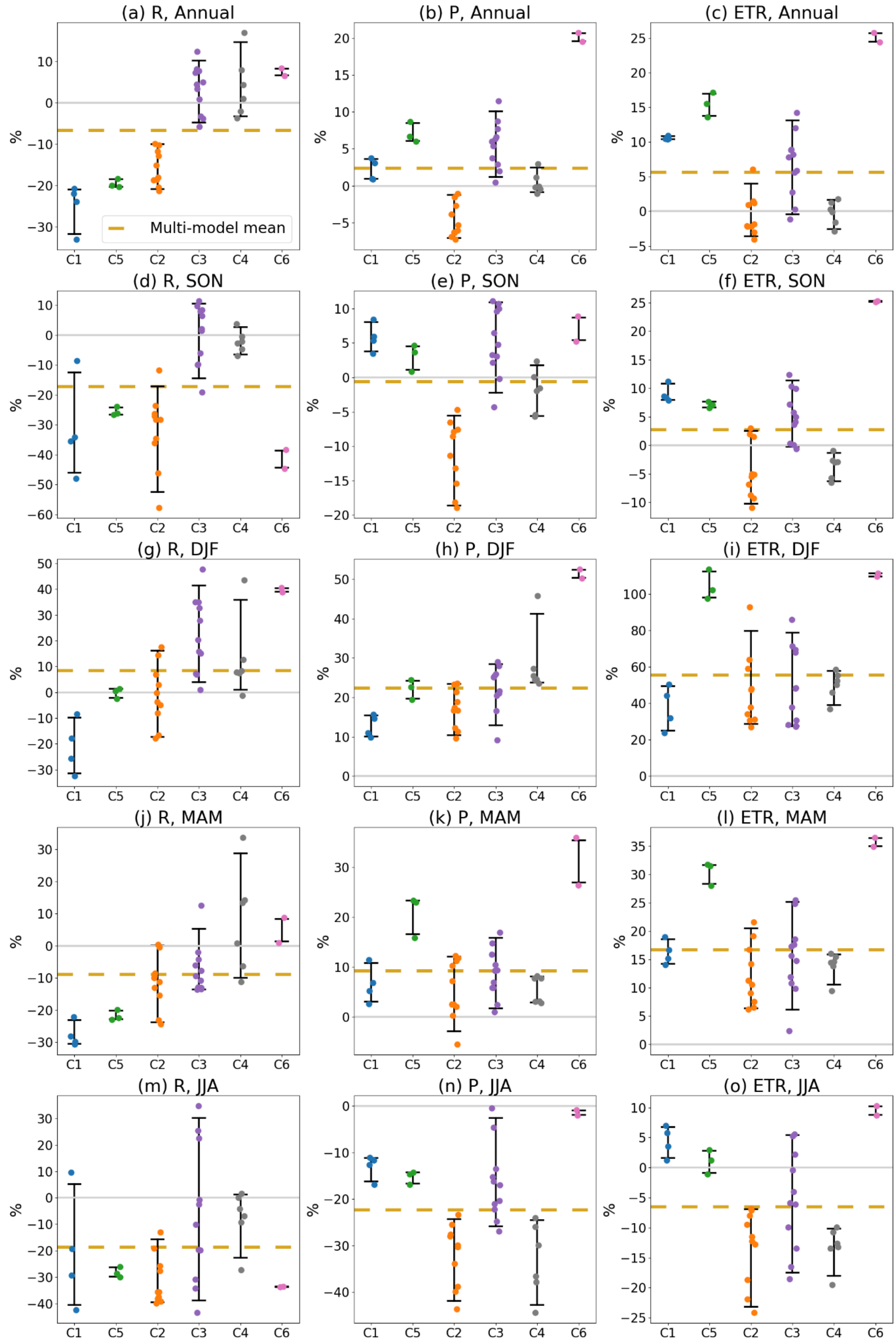

Figure S5: Same as Fig. 4 in the main manuscript but with six clusters. The associated dendrogram of the clustering is shown in Fig. S2.

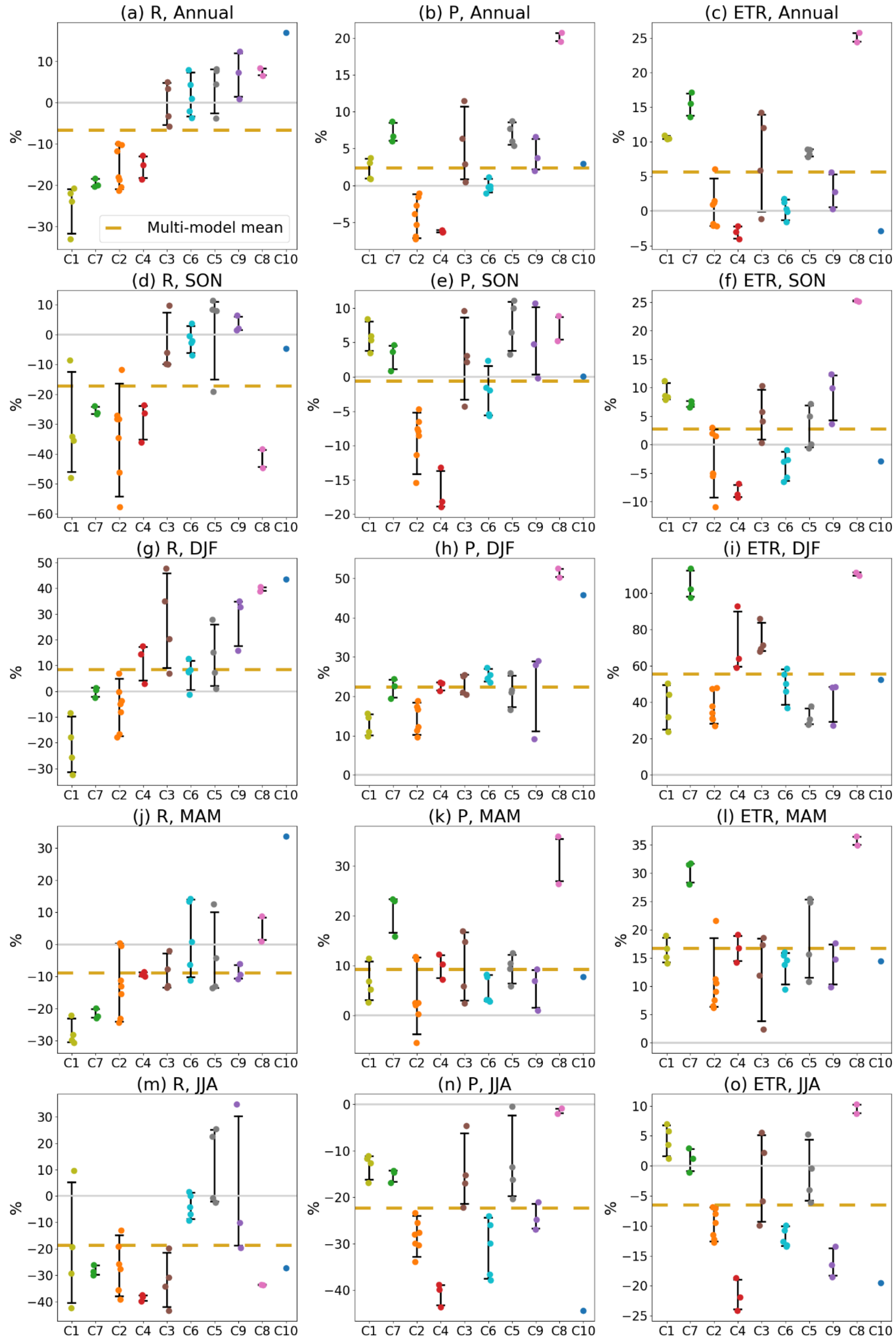

Figure S6: Same as Fig. 4 in the main manuscript but with ten clusters. The associated dendrogram is shown in Fig. S3.

S2. Influence of climate sensitivity on the hydrological behavior of CMIP6 models

The CMIP6 models exhibit a wide range of climate sensitivities and, consequently, project very different levels of warming over Western Central Europe (WCE) by the end of the century under the SSP5-8.5 scenario. Sensitivity analyses have been conducted to investigate how this range of temperature change influences the projected hydrological behaviors across models. Several methods have been used to explore this:

1. The classification is performed as in Fig. 1 in the main manuscript, but the analysis of hydrological behavior is based on hydrological changes normalized by local temperature change.
2. The classification itself is performed on hydrological changes normalized by local temperature change.
3. The classification is performed on hydrological changes normalized by the model's Equilibrium Climate Sensitivity (ECS).

The normalization of hydrological changes by local temperature change after classification (Fig. S7) does not alter the two types of behaviors highlighted in Fig. 4, namely that roughly half the clusters project a decrease in runoff, while the other half project an increase. The main differences lie in the intra-cluster variability, which changes somewhat after normalization by local temperature change. Even after this normalization by local temperature changes, the CCCma models remain outliers but the gap between them and the other models is reduced.

The classification method (2), which uses hydrological changes normalized by local temperature change, shows important similarities with the classification based on raw hydrological changes (Fig. 1 in the main manuscript), though some differences also emerge. For example, the Earth System Model and high resolution climate model of CNRM-Cerfacs switches from cluster C3 in the standard classification to clusters C7 and C8 in this new classification. C2 and C4 from the original classification are now grouped together, suggesting that the difference between their changes in the standard classification must be thermodynamic in origin, or at least correlated with temperature change. The normalization by local temperature changes also highlights the outlier behavior of CAMS-CSM1-0, which shows strong annual hydrological changes despite a small increase in temperature (C4 in Fig. S9 a, b, c). This model presents an unusual increase in runoff during summer, even though precipitation decreases and evapotranspiration increases (Fig. S9 m, n ,o).

Finally, method (3) applied to the 30 out of 36 models for which ECS values are available in the literature, show strong similarities to the results of method (2). The key exception is that the CCCma model is less of an outlier because of its very large ECS (Fig. S10 and S11).

In conclusion, normalizing hydrological changes by temperature changes can provide interesting insights, as shown above. However, it is not necessarily more insightful than discussing the raw hydrological changes presented in the main manuscript. Furthermore, normalizing by temperature raises methodological questions: should normalization be performed using ECS, local annual temperature changes, or local seasonal temperature changes? This choice has implications for both the results and their interpretation. Moreover, even if normalizing by temperature sometimes seemingly reduces the differences in hydrological changes between models, it should not automatically be interpreted as evidence that thermodynamic processes, scaling with temperature (e.g., in link with the Clausius-Clapeyron relationship) explain the difference between models, as the relationship between temperature change and hydrological changes may not be causal, or the causality could even be reversed. Indeed, in some cases, the spread in temperature changes may be a consequence of hydrological changes rather than the other way around. For instance, the physiological effect of CO_2 can reduce transpiration and consequently increase temperature.

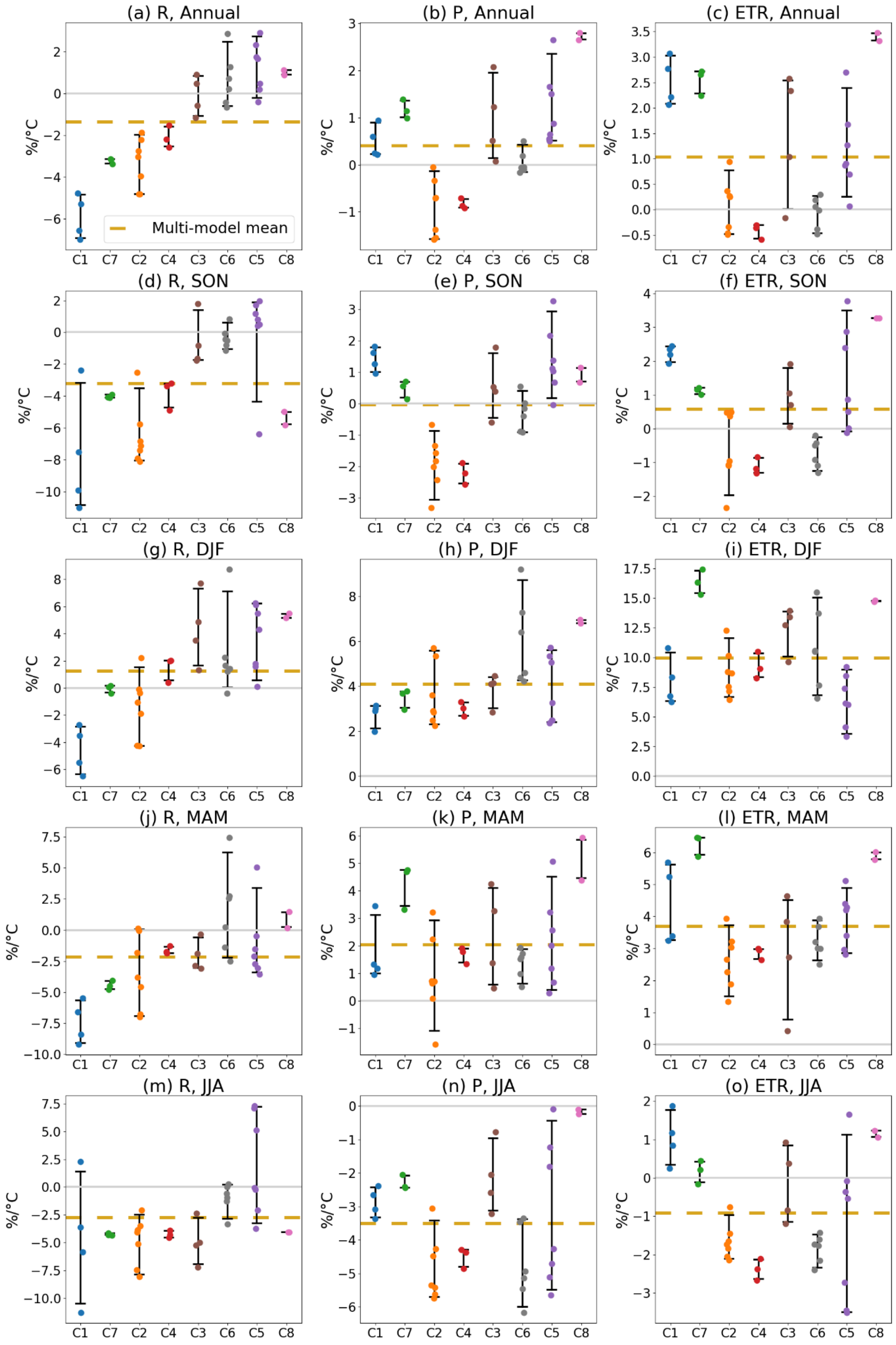

Figure S7: Same as Fig. 4 in the main manuscript but the changes in each season are divided by temperature change in this season. The associated dendrogram is shown in Fig. 4.

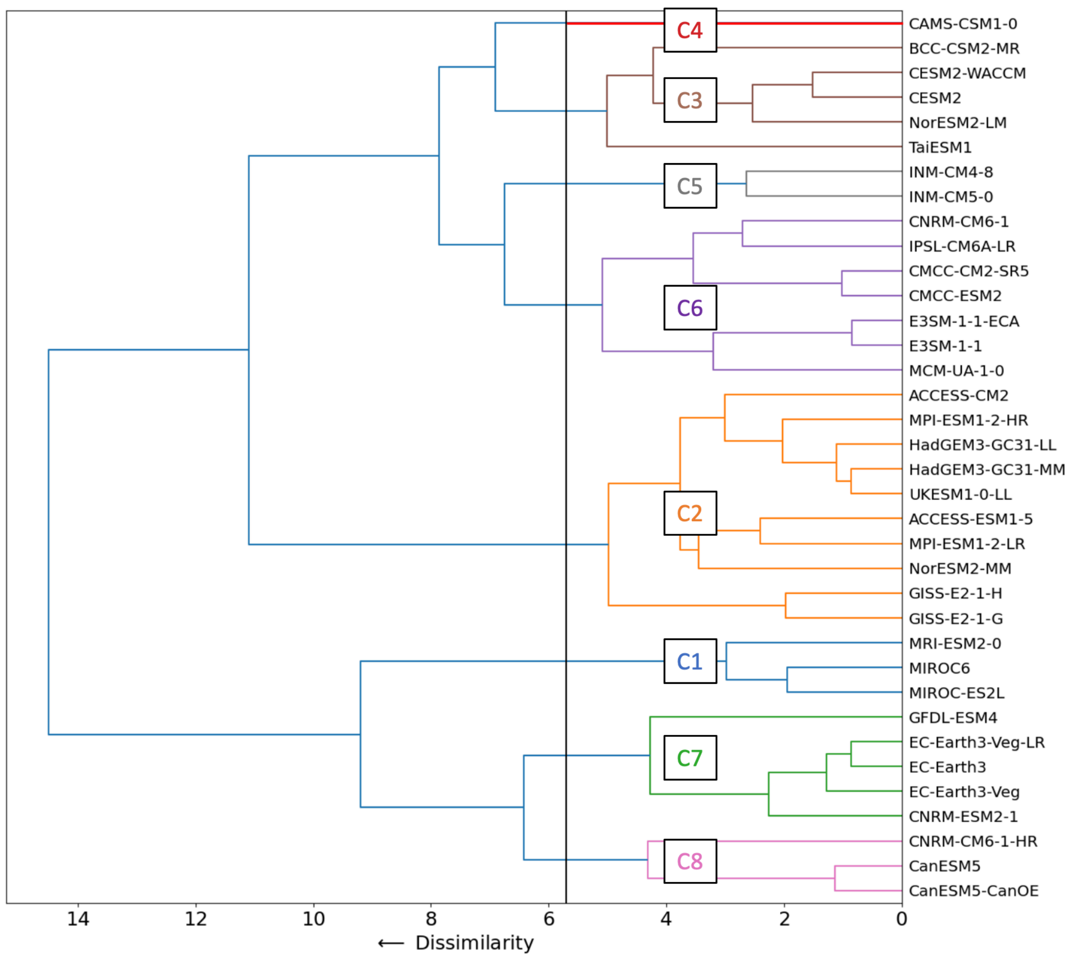

Figure S8: Same as Fig. 1 in the main manuscript but the hydrological changes in each season are normalized by the local temperature changes in each season.

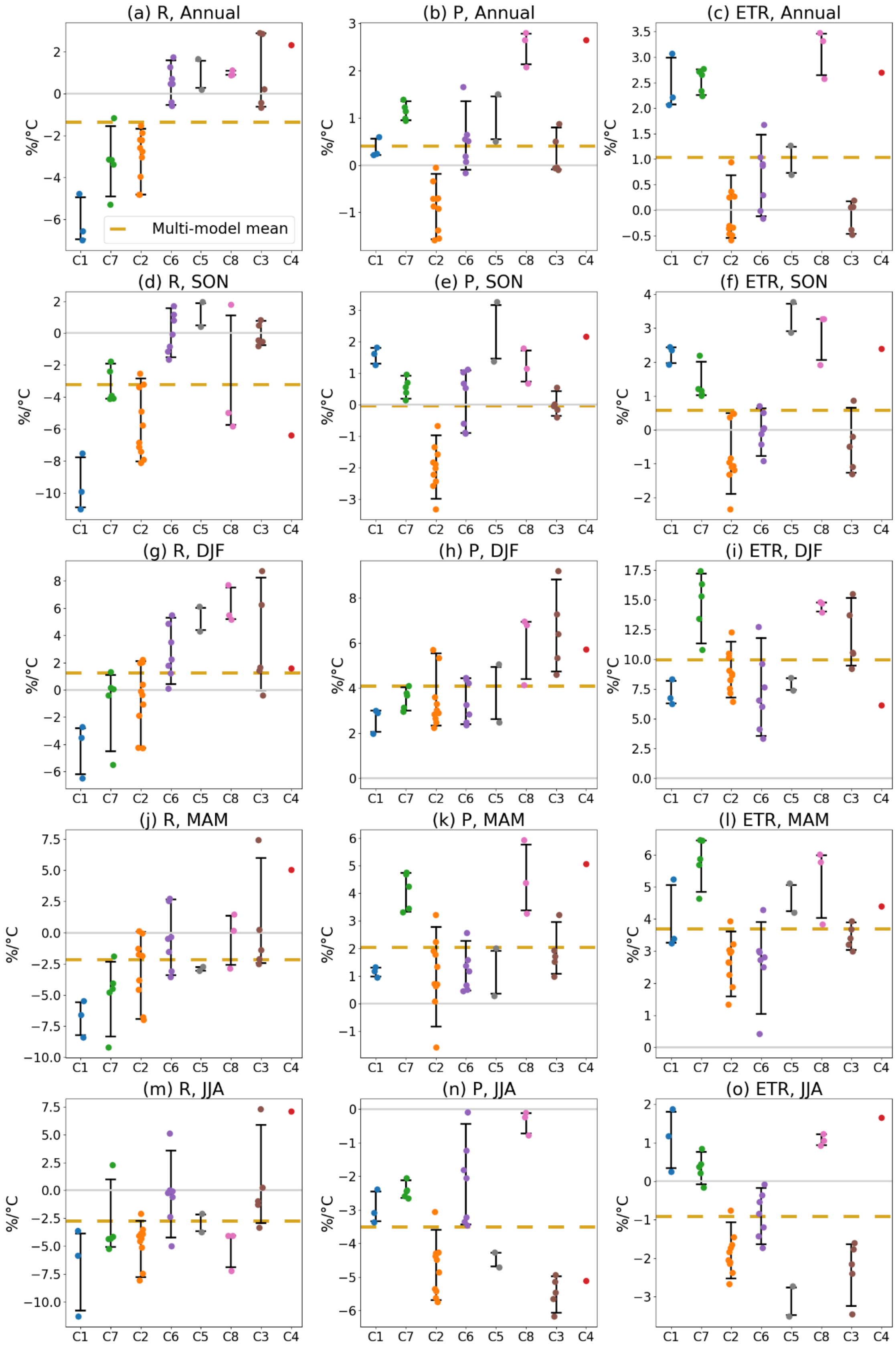

Figure S9: Same as Fig. 4 in the main manuscript but the changes in each season are divided by the local changes of temperature in this season. The associated dendrogram is shown in Fig. S8.

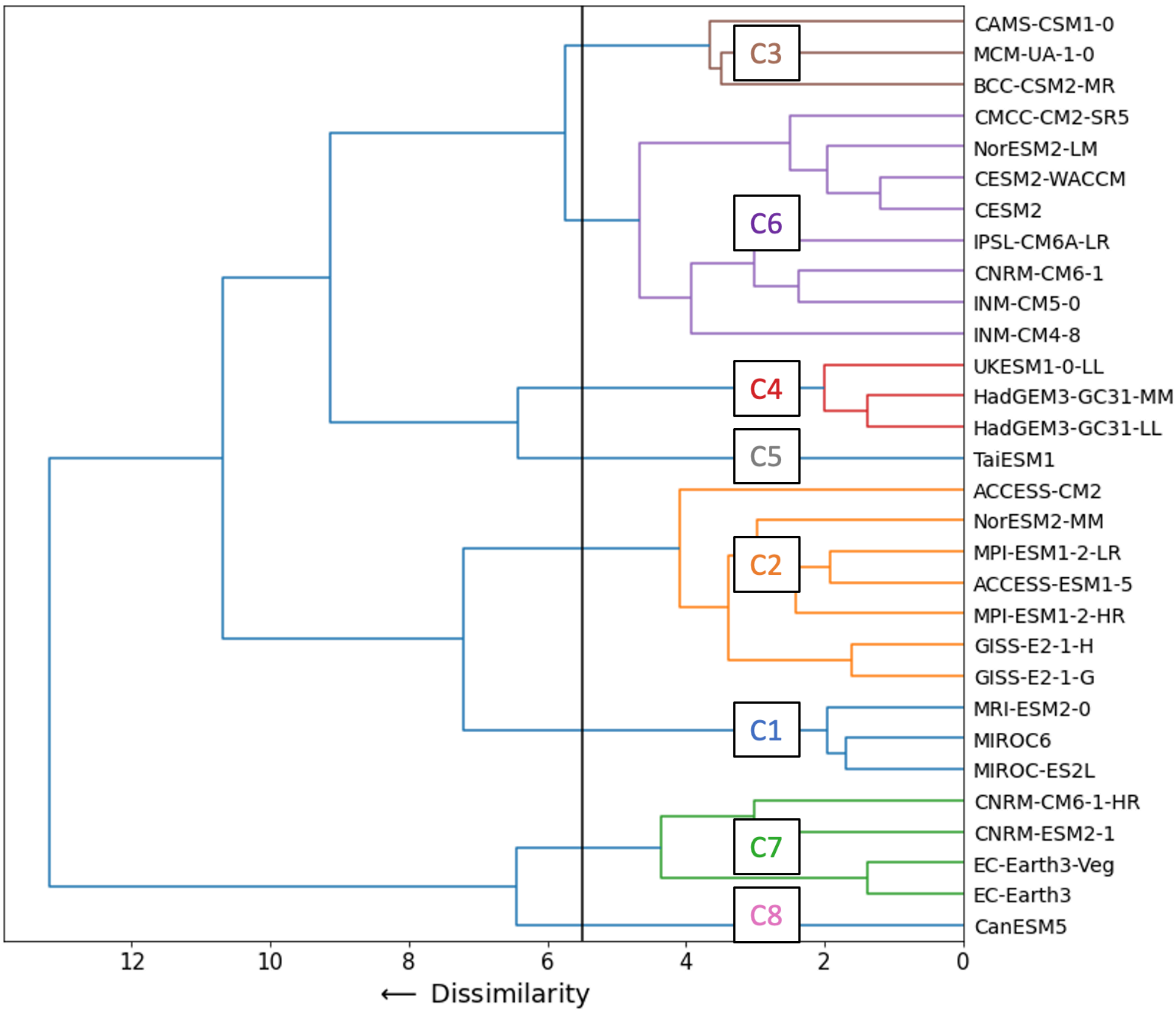

Figure S10: Same as Fig. 1 in the main manuscript but the hydrological changes are normalized by the ECS.

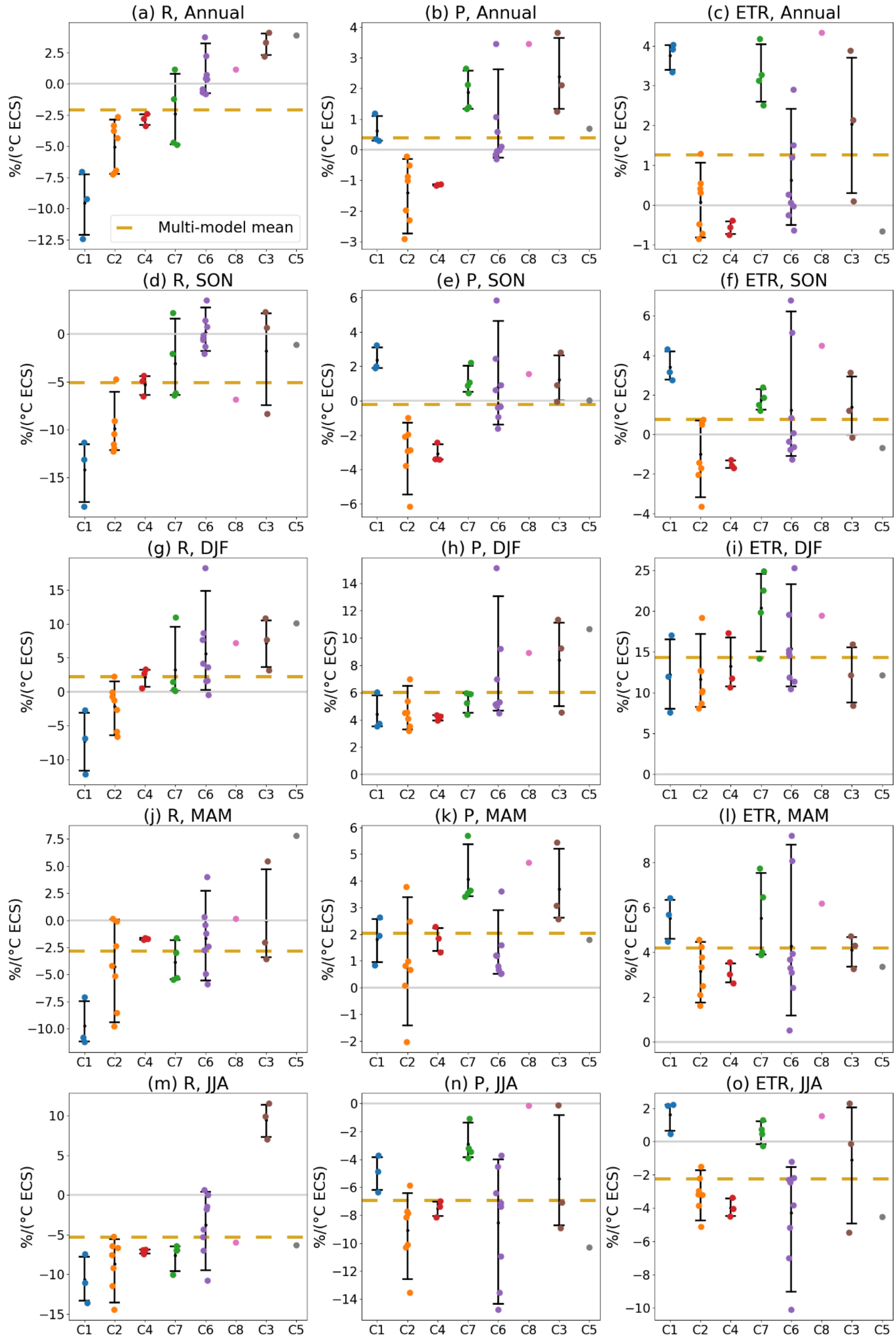

Figure S11: Same as Fig. 4 in the main manuscript but the hydrological changes are divided by the ECS. The associated dendrogram is shown in Fig. S10.

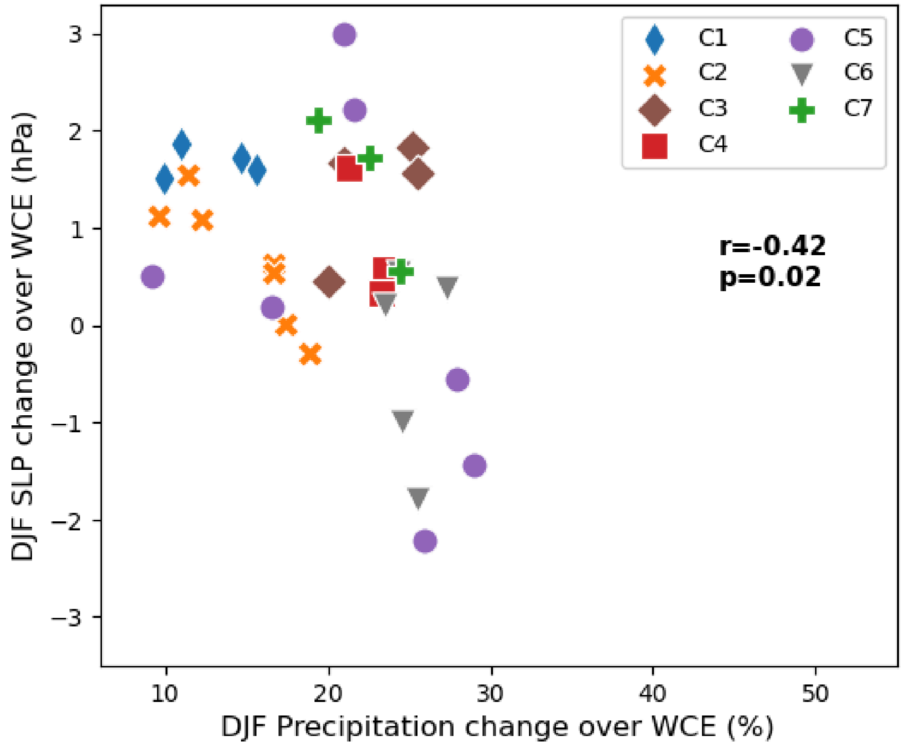

Figure S12: Scatterplot between winter changes in precipitation (%) averaged over WCE (x-axis) and winter changes in sea level pressure (hPa) averaged over WCE (y-axis). All CMIP6 models are used, except the C8 models and TaiESM1. The Pearson correlation coefficient ("r") and the corresponding p-value are given in the figure.