Supplementary Information: Assessment of future changes in water availability and aridity

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A Sensitivity of the results on the choice of a threshold to divide between arid/humid regions

In this study, arid/humid regions are classified by using $R_n/(\lambda P) = 2$ as a threshold value. Following this approach, regions with $R_n/(\lambda P) < 2$ are classified as humid, whereas regions with $R_n/(\lambda P) > 2$ are classified as arid. This definition is based on common definitions, that are also recommended by the United Nations Environment Programme (UNEP). Following this definition, the domain $1.5 < R_n/(\lambda P) < 2$ is referred to as the 'subhumid' and the domain $2 < R_n/(\lambda P) < 5$ is referred to as 'semi-arid'. However, if we identify that the ensemble of all models at a particular gridpoint is not significantly different from $R_n/(\lambda P) = 2$, the gridpoint is classified as transitional.
Nonetheless, to choice of $R_n/(\lambda P) = 2$ is still somewhat arbitrary. Shown in Fig. A1 and A2 are results obtained for different threshold values of $R_n/(\lambda P) = 1.5$ and $R_n/(\lambda P) = 2.5$. Naturally, the distribution of arid/humid areas changes accordingly, with less humid/more arid areas for a threshold of $R_n/(\lambda P) = 1.5$ (see Fig. A1b) and more humid/less arid areas for a threshold pf $R_n/(\lambda P) = 2.5$ (see Fig. A2b). However, the percentage values of regions confirming the paradigm or not (Fig. A1c,d and Fig. A2c,d) are very similar between both cases, showing that the main results presented in this study are rather insensitive to the choice of a threshold value to divide between arid and humid regions. It is further important to note that for threshold values lower (larger) than 1.5 (2.5) the obtained distributions of arid/humid regions is highly unrealistic (not shown).

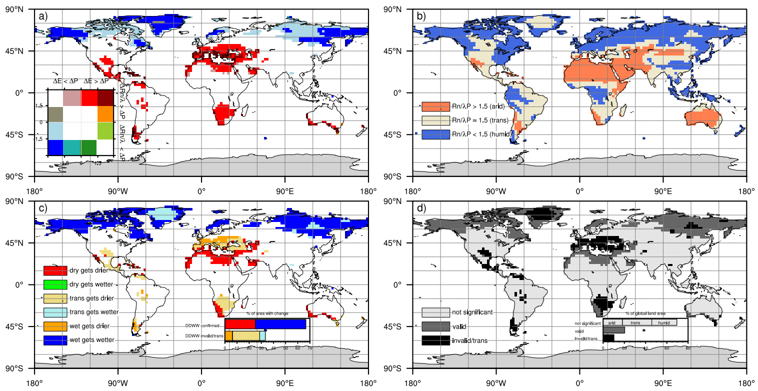

Figure A1: Investigating the DDWW paradigm (similar to Fig. 4 but with $R_n/(\lambda P) = 1.5$ as threshold value). a) Significant drying/wetting trends computed at the grid box level. Dark red (dark blue) denotes a significant change towards drier (wetter) conditions both regarding the land water balance and hydrological regime shifts. Red/orange shows a shift towards more arid conditions. Drying due to changes in the land water balance only is depicted by green/pink color. b) Distribution of arid (orange) to humid (blue) areas within the period from 1980-2000. Beige colors denote transitional areas where no significant attribution is possible. c) Comparing the changes in a) with the hydrological conditions in b) yields an evaluation of the 'dry gets drier, wet gets wetter' paradigm. Red/dark blue colors indicate regions where the paradigm is found to be valid. Humid areas getting drier (orange) are widely found. d) Conceptual evaluation of the DDWW, with areas confirming (dark grey) and invalidating (black) the paradigm compared to areas showing no robust trend. Note that Antarctica is not accounted for in the subplots.

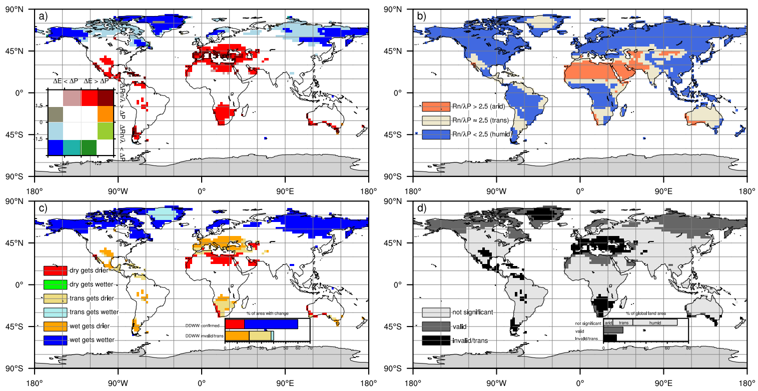

Figure A2: Investigating the DDWW paradigm (similar to Fig. 4 but with $R_n/(\lambda P) = 2.5$ as threshold value). a) Significant drying/wetting trends computed at the grid box level. Dark red (dark blue) denotes a significant change towards drier (wetter) conditions both regarding the land water balance and hydrological regime shifts. Red/orange shows a shift towards more arid conditions. Drying due to changes in the land water balance only is depicted by green/pink color. b) Distribution of arid (orange) to humid (blue) areas within the period from 1980-2000. Beige colors denote transitional areas where no significant attribution is possible. c) Comparing the changes in a) with the hydrological conditions in b) yields an evaluation of the 'dry gets drier, wet gets wetter' paradigm. Red/dark blue colors indicate regions where the paradigm is found to be valid. Humid areas getting drier (orange) are widely found. d) Conceptual evaluation of the DDWW, with areas confirming (dark grey) and invalidating (black) the paradigm compared to areas showing no robust trend. Note that Antarctica is not accounted for in the subplots.

B Seasonal DDWW

The results in this study are based on multi-year averages. Nonetheless, certain seasonal trends in $P - E$ and $P - R_n/\lambda$ might cancel out in this case. Therefore we provide here also seasonal estimates of changes in $P - E$ and $P - R_n/\lambda$ (see Fig. A3). Drying occurs throughout the year e.g. in the Mediterranean region. However, drying conditions that were identified at mean-annual time scales in central/eastern Europe and central Asia are mainly induced by drier condition during boreal summer due to an corresponding changes in $P - R_n/\lambda$. Wetting conditions in the northern high-latitudes are mainly induced trough significant changes in $P - E$ during boreal fall and winter. It is important to note here that, except for some regions in Siberia, no counteractive trends (like e.g. wetting in winter vs. drying in summer) are found.

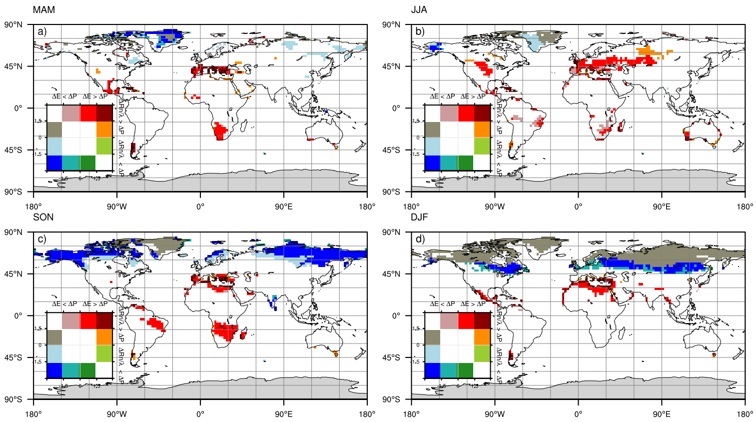

Figure A3: Significant drying/wetting trends computed at the grid box level for a) MAM, b) JJA, c) SON and d) DJF. Dark red (dark blue) denotes a significant change towards drier (wetter) conditions both regarding the land water balance and hydrological regime shifts. Red/orange shows a shift towards more arid conditions. Drying due to changes in the land water balance only is depicted by green/pink color.

C Future hydroclimatological changes based on Priestley-Taylor E_p

In this study, the aridity index was calculated as $R_n/(\lambda P)$. However, the aridity index is usually defined as E_p/P, with E_p being potential evaporation. Here we used R_n instead of E_p for two reasons: (i) E_p is, in contrast to R_n, not a standard output in the CMIP5 archives, and (ii) other approaches to estimate E_p are assumed to be less robust under conditions of significant climate change (see Data and Methods section). However, here we also present results based on the well-established Priestley-Taylor method to estimate E_p.

The obtained results are qualitatively similar to those obtained in the main text. Trends in E_p are showing significant increases for all land area (see Fig. A4). The area of significant aridity change ($\Delta P - E_p$) is, however, larger when using Priestley-Taylor E_p, showing a total of 45.4% of all land area experiencing a significant shift either towards more arid or humid conditions within the 21st century. A shift towards more humid conditions takes place in 7.8% of global land area, entirely located in the northern high latitudes. A significant change towards more arid conditions is instead found for 37.6% of all land area. These changes are generally located in central North America, Middle America, Amazonia, southern and northern Africa, southern Europe, the Middle East, and central Asia, as well as southern Australia.

Combining both metrics, $P-E$ and $P-E_p$, results in a total of 51.8% of all land area experiencing a significant hydroclimatological change (see Fig. A5).

Similarly to the analysis based on R_n/λ, the DDWW paradigm is confirmed for humid areas projected to experience a significant increase in water availability in the high latitudes. Further, a significant increase in aridity in many subtropical areas confirms the paradigm for dry desert regions in Africa, eastern Asia, and Australia. However, the DDWW is invalidated for a larger fraction of affected neighboring areas which are currently in a humid or transitional climate regime. These areas include large parts of southern and central Europe, but also region in central Asia, southern Africa and especially also North America. Drying conditions are additionally found in humid tropical Amazonia.

In summary, the DDWW using E_p estimated via the Priestley-Taylor method is confirmed for only ca. 25% of all land area, whereas the DDWW is invalidated for another ca. 25%, and no trend is detectable in the remaining 50% of all land area (see Fig. A5d).

Hence, using Priestley-Taylor estimates of E_p supports the findings presented in Chapter 2. Indeed, the DDWW paradigm is even invalidated for a larger fraction of land area, especially including also regions in North America.

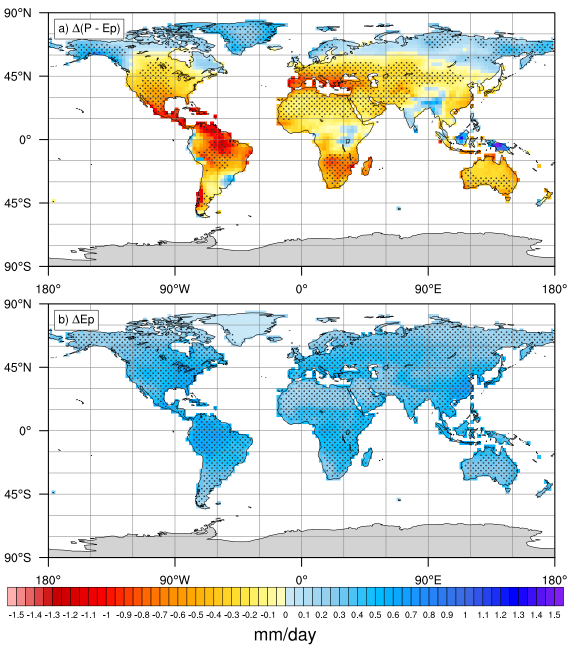

Figure A4: Aridity changes within the 21st century based on the Priestley-Taylor method to estimate E_p. a) Changes in $P - E_p$ comparing present-day (1980-2000) and future climate (2080-2100) following the RCP8.5 pathway and b) changes in Priestley-Taylor E_p. Stippling denotes regions where the change is significant at the 95%-level.

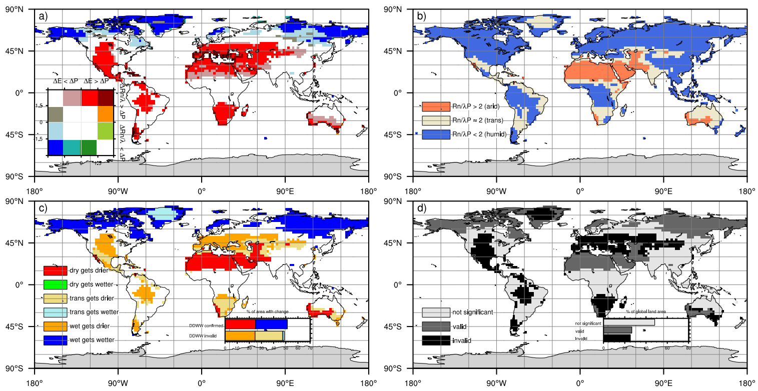

Figure A5: Investigating the DDWW paradigm (similar to Fig. 4 but with E_p estimated via Priestley-Taylor). a) Significant drying/wetting trends computed at the grid box level. Dark red (dark blue) denotes a significant change towards drier (wetter) conditions both regarding the land water balance and hydrological regime shifts. Red/orange shows a shift towards more arid conditions. Drying due to changes in the land water balance only is depicted by green/pink color. b) Distribution of arid (orange) to humid (blue) areas within the period from 1980-2000. Beige colors denote transitional areas where no significant attribution is possible. c) Comparing the changes in a) with the hydrological conditions in b) yields an evaluation of the 'dry gets drier, wet gets wetter' paradigm. Red/dark blue colors indicate regions where the paradigm is found to be valid. Humid areas getting drier (orange) are widely found. d) Conceptual evaluation of the DDWW, with areas confirming (dark grey) and invalidating (black) the paradigm compared to areas showing no robust trend. Note that Antarctica is not accounted for in the subplots.