

# MASTER THESIS

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## Global drought impacts on hydrosphere and biosphere

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## **Abstract**

Changes in hydrosphere and biosphere during the strongest soil moisture drought between January 2001 and December 2015 are analysed at a global scale. The aim of this study is to understand the partitioning of evapotranspiration and runoff based on soil moisture droughts. Observational-based machine learning data as well as model-based data are used. The ecosystem limitation index (ELI) is used to distinguish energy and water limited regions, and drought development and recovery periods are separated in this study. Evapotranspiration declines in water limited regions due to missing soil moisture during the drought development period, whereas it increases in energy limited regions benefitted from radiation surplus. Runoff has overall negative changes during the drought development period, intensifying from water to energy limited regions. This is due to the strong coupling of runoff and precipitation during the drought development. Overall, energy limited regions suffer from runoff decrease, whereby water limited regions mainly suffer from decreased evapotranspiration. During the drought recovery period, evapotranspiration is recovering faster than runoff, as runoff and soil moisture are coupled. Generally, changes in evapotranspiration and runoff under drought are explained by hydro-meteorological conditions based on radiation, precipitation, soil moisture and vapour pressure deficit (VPD) and their interactions. Vegetation, represented by total vegetation fraction and leaf area index (LAI) also has an essential impact on evapotranspiration but not on runoff. Both independent measures, total vegetation fraction and LAI, show an interlinkage of increased evapotranspiration and decreased runoff. Lastly, model-based analysis work well for drought detection, but not for distinguishing water- and energy-limited regimes. Based on this, a solid drought impact of evapotranspiration and runoff is not feasible.

## **Zusammenfassung**

Die Veränderungen in der Hydrosphäre und Biosphäre während der stärksten Bodenfeuchtetrockenheit zwischen Januar 2001 und Dezember 2015 werden auf globaler Ebene analysiert. Ziel dieser Studie ist es, die Aufteilung der Evapotranspiration und des Abflusses auf der Grundlage von Bodenfeuchtigkeitsdürren zu verstehen. Es werden sowohl beobachtungs-basierte Daten maschinellen Lernens als auch modellbasierte Daten verwendet. Der Ökosystem-Limitierungsindex (ELI) wird verwendet, um zwischen energie- und wasserbegrenzten Regionen zu unterscheiden und Dürreentwicklungs- und -regenerationsperioden zu trennen. Die Evapotranspiration nimmt in wasserbegrenzten Regionen aufgrund der fehlenden Bodenfeuchte während der Dürreentwicklung ab, während sie in

energiebegrenzten Regionen, die von einem Strahlungsüberschuss profitieren, zunimmt. Der Abfluss weist insgesamt negative Veränderungen während der Dürreentwicklung auf, die sich von wasser- zu energiebegrenzten Regionen verstärken. Dies ist auf die starke Kopplung von Abfluss und Niederschlag während der Dürreentwicklung zurückzuführen. Insgesamt leiden energiebegrenzte Regionen unter einem Rückgang des Abflusses, während wasserbegrenzte Regionen hauptsächlich unter einer geringeren Evapotranspiration leiden. In der Regenerationsphase der Dürre regeneriert die Evapotranspiration schneller als der Abfluss, da Abfluss und Bodenfeuchtigkeit gekoppelt sind. Im Allgemeinen werden die Veränderungen der Evapotranspiration und des Abflusses bei Dürre durch die hydrometeorologischen Bedingungen erklärt, die auf Strahlung, Niederschlag, Bodenfeuchte und Dampfdruckdefizit (VPD) und deren Wechselwirkungen beruhen. Die Vegetation, dargestellt durch den Gesamtvegetationsanteil und den Blattflächenindex (LAI), hat ebenfalls einen wesentlichen Einfluss auf die Evapotranspiration, nicht aber auf den Abfluss. Beide unabhängigen Messgrößen, Gesamtvegetationsanteil und LAI, zeigen einen Zusammenhang zwischen erhöhter Evapotranspiration und verringertem Abfluss. Abschließend eignen sich modellgestützte Analysen gut für die Erkennung von Dürren, aber nicht für die Unterscheidung zwischen wasser- und energiebegrenzten Regionen. Auf dieser Grundlage ist es nicht möglich die Auswirkungen einer Dürre auf Evapotranspiration und Abfluss eindeutig zu bestimmen.

## 1 Introduction

Human-induced climate change has dramatically strengthened in the past decades and lead to extreme events such as droughts (IPCC 2021). Drought is one of the most destructive, costly and also deadly natural hazard and has a wide range of far-reaching negative impacts on the human health and vegetation productivity at a global scale (Lloyd-Hughes 2013, Tian et al. 2018). There are numerous cases in the recent climate history such as 2003, 2007, 2011, 2012, 2015, whereby the drought of 2003 is the most popular one in Europe (Tian et al. 2018, Markonis et al. 2021). Environmental changes as well as vegetation activities and productivity are being altered under severe drought, which can lead among other things to a widespread plant-mortality (Martin-StPaul et al. 2017, Markonis et al. 2021). A decrease of crop productivity and water supply results in a decline in food security which affects many people (Zargar et al. 2011, Koster et al. 2017, Markonis et al. 2021). These aggravated socioeconomic losses and environmental impacts can further enhance the interdependence of people and water (Van Loon et al. 2016, Markonis et al. 2021). Societal impacts due to water security, food security, infrastructure, and forestry differ according to the region under consideration (Van Loon et al. 2016, Orth and Destouni 2018). Depending on the strength of the drought and its impact, there can arise political instabilities such as farmers profits, water rights and disturbed water access, which can lead to commodity prices (Van Loon et al. 2016). Long-lasting drought impacts on environment, economy and society can also be linked to the collapse of known ancient societies as the Mayan or Mesopotamia's Akkadian Empire (Koster et al. 2017). Since the 2000s, the society began to adapt to hydrological vulnerability by implementing water-saving measures such as building reservoirs or by changing regulations and policy (Van Loon et al. 2016, Koster et al. 2017). An important way to deal with droughts are predictions for better preparations of the society (Koster et al. 2017). Further problems are increasing populations accompanied by reductions in water quality due to climate change (Koster et al. 2017, Tollefson 2021). Overall ecosystem services are affected which has direct impact on human living (Martin-StPaul et al. 2017).

Drought is in general defined by a shortage of precipitation and can be divided into meteorological, agricultural and hydrological droughts (Zargar et al. 2011). The complex feedback related to how natural and anthropogenic processes interact contributes to a hydrological imbalance between demand and supply (Seneviratne et al. 2010, Lloyd-Hughes 2013, Van Loon et al. 2016). Droughts can be naturally induced and influenced by Anthropocene when the water shortage is caused or modified by human management such as changes of the earth's surface (Van Loon et al. 2016).

There are 23 unsolved problems formulated by the hydrology community, which underline the importance of understanding interactions of soil moisture with evapotranspiration and runoff (Blöschl et al. 2019, Ghajarnia et al. 2020). As soil moisture is a key variable of the climate system, it is used to define the drought in this study (Seneviratne et al. 2010). Its availability is also important in amplifying droughts or hot extremes (Wehrli et al. 2019). Soil moisture droughts are also known as agricultural droughts, as they reduce crop production, among other things (Van Loon et al. 2016). It controls the land-atmosphere coupling regimes (Orth 2021) and is an important variable for hydrological interactions (Ghajarnia et al. 2020). Soil moisture is also the driver of dryness stress and consequently controls ecosystem production and vegetation growth (Liu et al. 2020). Its deficit is leading to changes in evapotranspiration and runoff fluxes, which affects ecosystem functioning and provided ecosystem services (Orth and Destouni 2018, IPCC 2021), so that soil moisture is irreplaceable for studying droughts. Changes in evapotranspiration have effects on forestry, agriculture and terrestrial vegetation and will lead to changes in food security and crop security (Liu et al. 2020, Ghajarnia et al. 2020, 2021). Changes in runoff have effect on water security such as freshwater availability and potential flood risks (Ghajarnia et al. 2020). Depending on what soil moisture droughts influence more, food security or water security will be a bigger problem for humankind and ecosystems (Padrón et al. 2020). Moreover, to ensure societies' sustainable use of water, it is crucial to understand impacts of droughts on important variables, such as evapotranspiration and runoff (Koster et al. 2017). This further implies that it is important to understand the relationships of soil moisture, as it controls the carbon sink of land ecosystems (Green et al. 2019) and therefore the ongoing climate change (Liu et al. 2020). A depletion of soil moisture is known to have a negative impact on vegetation and further on biogeochemical cycles (Seneviratne et al. 2010). Droughts are leading to a lesser productive vegetation, which can absorb less CO<sub>2</sub> (Seneviratne et al. 2010). The well-known drought of 2003 in Europe was even measurable in Mauna Loa by a rise in CO<sub>2</sub> (Seneviratne et al. 2010). Droughts often result in an enhanced plant mortality, which has been observed in several droughts (Konings and Gentile 2017). The impact of droughts on vegetation is thereby dependent on the vegetation type, as they have different responses and strategies when facing such a water stress period (Ghajarnia et al. 2020).

Specifically, this study is an extension of a Europe based study of Orth and Destouni (2018), which analysed the impacts of soil moisture drought on hydrosphere and biosphere by investigating the unknown resulting evapotranspiration and runoff in Europe. But the importance of a global perspective is growing to get a full spatial and temporal

coverage and to analyse the hydrological pattern at a large scale (Koster et al. 2017, Ghajarnia et al. 2021). Therefore, a revisitation and extension of a complete analysis is necessary, for understanding drought impacts on blue- and green-water fluxes. As drought will contribute to societal and environmental risk, it is important to further investigate knowledge about this topic to contribute to risk management and early warning systems (Orth and Destouni 2018, Liu et al. 2020, IPCC 2021). This study analyses how soil moisture droughts propagate to evapotranspiration and runoff to better understand future changes in hydro-meteorological conditions and soil moisture droughts into potential impacts. This further helps to identify important climate impacts related to droughts and reduce uncertainties in predictions and how to mitigate the impacts (Seneviratne et al. 2010). This is reinforced by the fact of increased frequency and intensity of agricultural droughts due to global warming (IPCC 2021).

In this study, observation-based data as well as model-based data are being analysed globally, whereby the main variables of observations, soil moisture, evapotranspiration and runoff originate from machine learning data. During January 2001 and December 2015 is a soil moisture drought for each grid cell investigated. The methodological importance of anomalies and ELI is carried out. In the following points, the results are presented first and secondly interpreted in the discussion. During the soil moisture drought period, the hydro-meteorological conditions will be investigated based on radiation, precipitation, soil moisture and VPD to understand drought characteristics. Further on, the propagation of evapotranspiration and runoff will be explained through these hydro-meteorological conditions. This is carried out for each variable individually and then compared, to get information about the different impact of droughts on evapotranspiration and runoff. Afterwards, analysis based on tree-grass ratio and LAI are carried out in this study to provide information about ecosystem responses to soil moisture droughts. At the end, observation-based data will be compared to model-based data. A conclusion will complete this study.

## **2 Data and Methods**

To achieve the previously mentioned aims, the used datasets and methods are explained. This study covers monthly data from January 2001 until December 2015. Investigation period is limited due to availability of data. All used variables are derived with a globally spatial resolution of  $0.5^\circ \times 0.5^\circ$ . Python is used for analysis.



## 2.1 Observation-based Data

The main part of the study is based on observation-based data (Table 1). The fundamental variable of this study is soil moisture, as it defines the drought in this study. Soil moisture is derived using machine learning algorithms from O and Orth (2021) and is then averaged from layer 1, layer 2 and layer 3 calculated according to their depth.

Meteorological conditions during the drought are being analysed from radiation, temperature, precipitation, and VPD. All these variables are provided by ERA5-land (Muñoz-Sabater et al. 2021). Radiation is used as surface solar radiation downwards and is transferred from  $\text{J/m}^2$  into  $\text{W/m}^2$ . Temperature data corresponds to a measured temperature two metres above the ground. The dataset of precipitation is converted from metre to millimetre.

The key variables for the analysis are evapotranspiration and runoff. Both variables are based on machine learning data. The dataset of evapotranspiration is FLUXCOM, which merges eddy covariance measurements with meteorological data and remote sensing (Jung et al. 2019).

To detect a fraction of short vegetation and tree cover as an indicator for hydro-meteorological changes during droughts, a vegetation cover and LAI are used. The total vegetation fractional is used as vegetation cover with an average from 2007 to 2016 (Song et al. 2018). LAI is based on Myneni et al. (2015) and used as average from 2000 to 2020.

Another vegetation dataset is used to compute a vegetation mask. For this purpose, the tree cover fraction is used, which represents the tree fraction divided by the total vegetation fraction averaged from 2007 to 2016 (Song et al. 2018).

*Table 1: Data sets of observations*

Variable	Data set (Version)	Remarks	Reference
Soil Moisture [ $\text{m}^3/\text{m}^3$ ]	SoMo.ml	Mean of layer 1 (0-10 cm), layer 2 (10-30 cm) and layer 3 (30-50 cm) weighted by soil depths	O and Orth (2021)
Radiation [ $\text{J/m}^2 \rightarrow \text{W/m}^2$ ]	ERA5-land (e1)	ssrd (surface solar radiation downwards)	Muñoz-Sabater et al. (2021)
Temperature [K]	ERA5-land (e1)	t2m (2 metre temperature);	Muñoz-Sabater et al. (2021)

		used for <i>Temperature mask</i>	
Precipitation [m → mm]	ERA5-land (e1)		Muñoz-Sabater et al. (2021)
VPD [kPa]	ERA5-land (e1)		Muñoz-Sabater et al. (2021)
Evapotranspiration [mm/d]	FLUXCOM		Jung et al. (2019)
Runoff [mm/d]	G-RUN ENSEMBLE MMM (G-RUN ENSEMBLE 1.0)		Ghiggi et al. (2021)
Total vegetation fraction	VCF5KYR v001	Vegetation cover; Averaged from 2007 to 2016; Sum of short and tall vegetation fraction	Song et al. (2018)
Tree cover fraction	VCF5KYR v001	Used for <i>Vegetation mask</i> ; Averaged from 2007 to 2016; Tree fraction divided by total vegetation fraction	Song et al. (2018)
LAI	MOD15A2H v006	Averaged from 2000 to 2020	Myneni et al. (2015)

## 2.2 Model-based data

A comparison to observation-based data is computed by model-based data. For this analysis, three land surface models of the ensemble of Trendy were used (Sitch et al. 2015, Le Quéré et al. 2018). Model VISIT and LPJ-GUESS are used in their version 8, and LPX-Bern and CRU-JRA in version 7. The models include CO<sub>2</sub>, climate, and land use changes. The used variables for each model are soil moisture, evapotranspiration, runoff, while total soil moisture is used in the model analysis to fully consider hydrological processes in the models. Soil moisture (mrso) is given as kg/m<sup>-2</sup> and is not being changed.

Evapotranspiration (evapotrans) and runoff (mrro) are being derived in  $\text{kg/m}^2\text{s}^{-1}$  and transformed into mm/d. The dataset of temperature is provided by the model CRU-JRA v2.0 and kept in the original unit  $^{\circ}\text{C}$ .

## 2.3 Methods

In the following subsections, the methodologies are introduced for (i) defining soil moisture droughts, (ii) computing anomalies and (iii) calculate the ecosystem water and energy limitation. These procedures are applied in the same way for observation-based and model-based data to enable the comparison of the results, even though some analyses are performed for observation-based data only.

### 2.3.1 Soil Moisture-Droughts

Soil moisture is used to define the period of droughts, whereby the absolute minimum for each grid cell was used (Figure 1). To get real life conditions, the original dataset was used, which indicates the lowest water availability for agricultural productivity. As the agricultural productivity can only be measured during the growing season, a temperature mask was implemented. The growing season was selected according to grid cells with a temperature higher than 5

$^{\circ}\text{C}$ , in order to analyse only soil moisture droughts influencing vegetation functioning when plants can be actively growing. The soil water deficit during growing-season periods also does not depend on frozen water in winter. To further exclude deserts, a vegetation cover mask, based on the tree cover fraction dataset, at 5% was implemented. At last, grid-cells are only considered if they have more than 60 months of data. This represents one third of the whole period and is set to prevent incorrect detection of soil moisture droughts due to insufficient data. The same observation-based datasets were used as masks for the models. But to detect the soil moisture drought based on model data, soil moisture was used as original dataset for each model.

The soil moisture drought period is further on divided into drought development and drought recovery. Three months before the drought peak, including the drought month, are defined as drought development. Three months after the drought peak are defined as

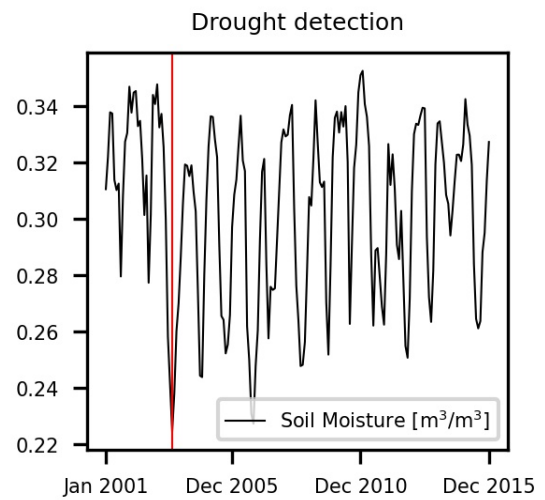


Figure 1: Detection of soil moisture drought month for one grid cell close to Jena.

drought recovery. Therefore, the drought period equals to 7 months in total. According to Orth and Destouni (2018), the following analysis are based on “soil-moisture drought periods”.

### 2.3.2 Anomalies

After detecting the soil moisture drought, all variables are used as anomalies for both observations and models. To convert the variables into monthly anomalies, the mean seasonal cycles are computed and removed. Furthermore, long-term trends for each grid cell were excluded, using a locally weighted smoothing (Cleveland 1979). Hereby, 40% of the data is used to compute each smoothing value. This is done to get clear information about the deviation from normal conditions and to avoid variations from seasonal cycles, long-term trends and potential decadal variations which could be influenced from some large-scale drivers such as atmospheric and ocean circulations and global warming. Anomalies appear as positive and negative signs. Positive anomalies indicate a surplus of a specific variable during a drought compared to normal conditions. Negative anomalies accordingly indicate a deficit. The variables used as anomalies are evapotranspiration, runoff, precipitation, radiation, soil moisture and VPD (Table 1).

Furthermore, a normalisation of anomalies for evapotranspiration and runoff is calculated by  $\frac{anomaly}{mean\ absolute\ values}$ . These normalised anomalies explains whether the drought induced change in evapotranspiration and runoff is strong or weak compared to ecosystem-specific long-term mean conditions.

### 2.3.3 Ecosystem Limitation Index

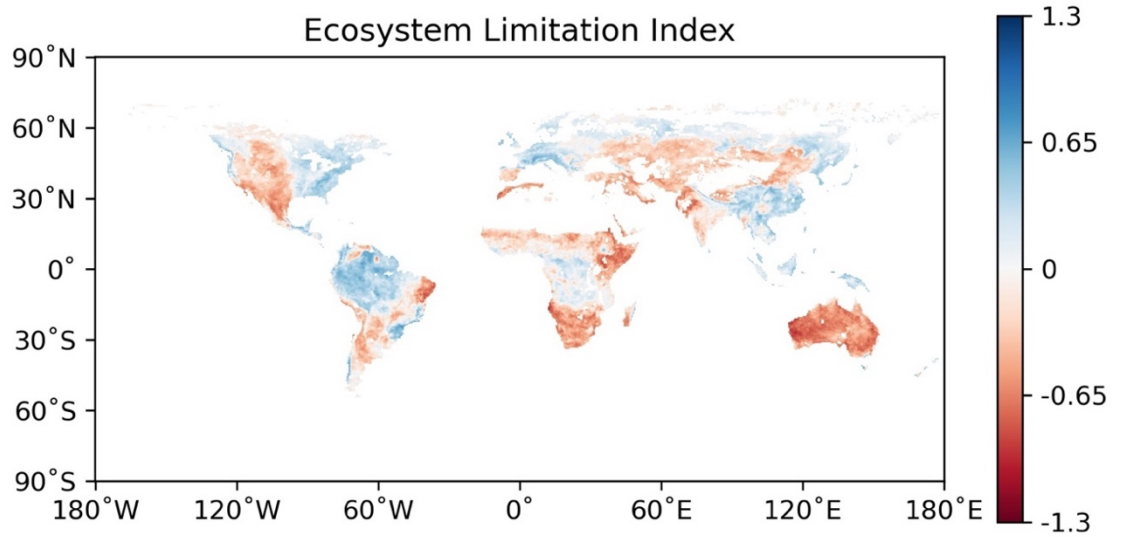
The ELI is an index to combine global grid cells with the same ecological characteristics in bins. The general classification in water and energy limited regions is provided. This index is used after Denissen et al. (2020). The goal of the ELI is to determine if vegetation is mainly controlled by water or energy supply. For this purpose, it considers the difference between the correlations of evapotranspiration with soil moisture and with temperature. Whereby evapotranspiration (ET) represents the vegetation functioning, soil moisture (SM) represents the water variable and temperature (T) represents the energy variable.

This results in the following equation:

$$\Delta corr = corr(A_T, A_{ET}) - corr(A_{SM}, A_{ET}) \quad (1)$$

Negative values represent water limited regions (Figure 2). Regions close to zero are in a transitional zone. And positive values indicate energy limited regions. ELI will be subdivided into strongly water limited, weakly water limited, weakly energy limited and strongly energy limited regions to jointly analyse grid cells with similar ecosystem conditions.

The same analyse is carried out for model-based data. Here, model-based data of soil moisture, evapotranspiration, and temperature are used.



*Figure 2: Global distribution of Ecosystem Limitation Index.*

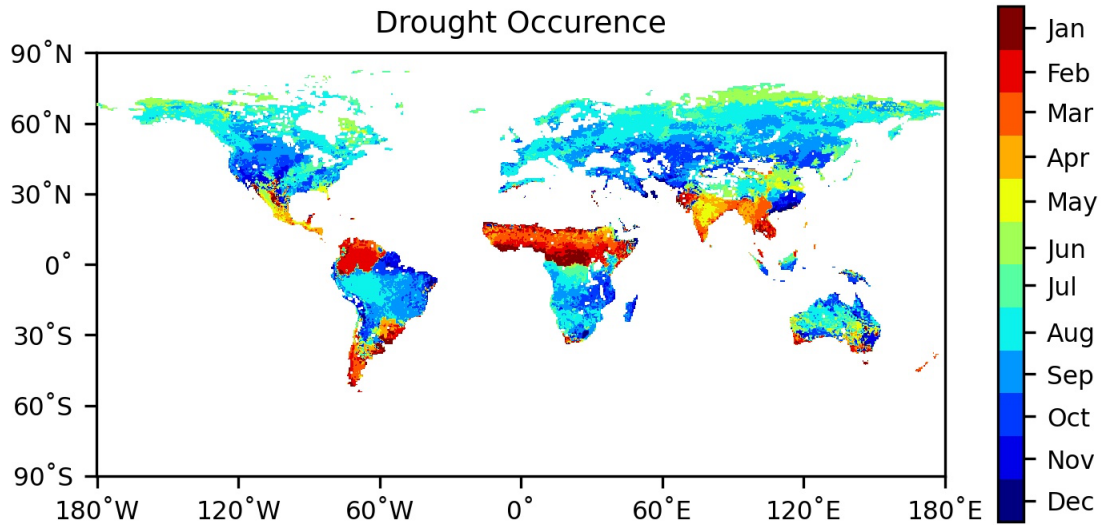
### 3 Results

In the following section, all results of this study are being presented. First the month-of-year of soil moisture drought occurrence is shown, then the second part illustrates the hydro-meteorological conditions associated with soil moisture droughts. The third part analyses water deficit in the soil propagation into evapotranspiration and runoff, followed by the relevance of vegetation on the variables during the drought peak. Finally, the observation-based results are compared with that of offline land surface models.

#### 3.1 Soil Moisture Drought

The occurrence of drought months for each grid cell is investigated (Figure 3) and further described according to hemisphere specific meteorological seasons. Droughts in the Northern Hemisphere occur predominantly in its summer and autumn months, with a distinguishable development from north to south. At 30° N, droughts occur more often during spring months. The months of January and February become more relevant towards the equator. The equator further represents a separation between north and south, whereby southern occur in the months of July and August. The Southern Hemisphere is dominated

by droughts in the spring months and, below 30° S, by droughts occurring in the summer months.



*Figure 3: Global distribution of month-of-year of drought occurrence derived from observation-based data.*

### **3.2 Hydro-meteorological Conditions during soil moisture droughts**

Precipitation, radiation, soil moisture and VPD are used as anomalies and show the hydro-meteorological conditions during the drought period (Figure 4). Based on these results, it is easier to explain changes of evapotranspiration and runoff. To view the variable conditions, an analysing diagram is used. The diagram contains bins filled with grid cells according to specific drought periods, climate conditions or vegetation characteristics, and represent the median results of the variability of the objective with colours within the certain numbers of grid cells. Negative anomalies indicate a depletion of the variable, whereas positive anomalies indicate an increase. The y-axis sorts the information according to the previous mentioned period, and the x-axis is based on the previous mentioned ELI. This form of presentation is used to aggregate data from similar conditions. This prevents local-scale effects and noise and enables to discover more general relationships. The first variable considered is precipitation (Figure 4a). Precipitation has intensifying negative anomalies during the drought development, up to -1.26 mm. The intensification in energy limited regions is much stronger than in water limited regions. During the drought recovery, there are almost no precipitation anomalies.

The next variable is radiation, which has a similar pattern to precipitation (Figure 4b). Only the anomalies are positive instead of negative. The drought recovery generally shows weak signals for these climate anomalies, indicating that water and energy related climate variables return to equilibrium states after remoistening from droughts.

The third considered variable is soil moisture (Figure 4c). Even though this variable is used to define the drought, here it serves to question the results found and to investigate the influence of soil moisture during drought development and recovery. The negative anomalies of soil moisture are intensifying during the drought development. For strongly water limited regions is a slow development of intensifying negative anomalies recognisable. A slow recovery with depleting negative anomalies is equal for all ecosystem regions.

The final variable is VPD, which has a similar pattern to soil moisture during the drought development (Figure 4d). The colour bar is swapped, as positive VPD anomalies indicate the same effect as negative soil moisture anomalies. In contrast, the drought recovery is rather comparable with precipitation and radiation than with soil moisture.

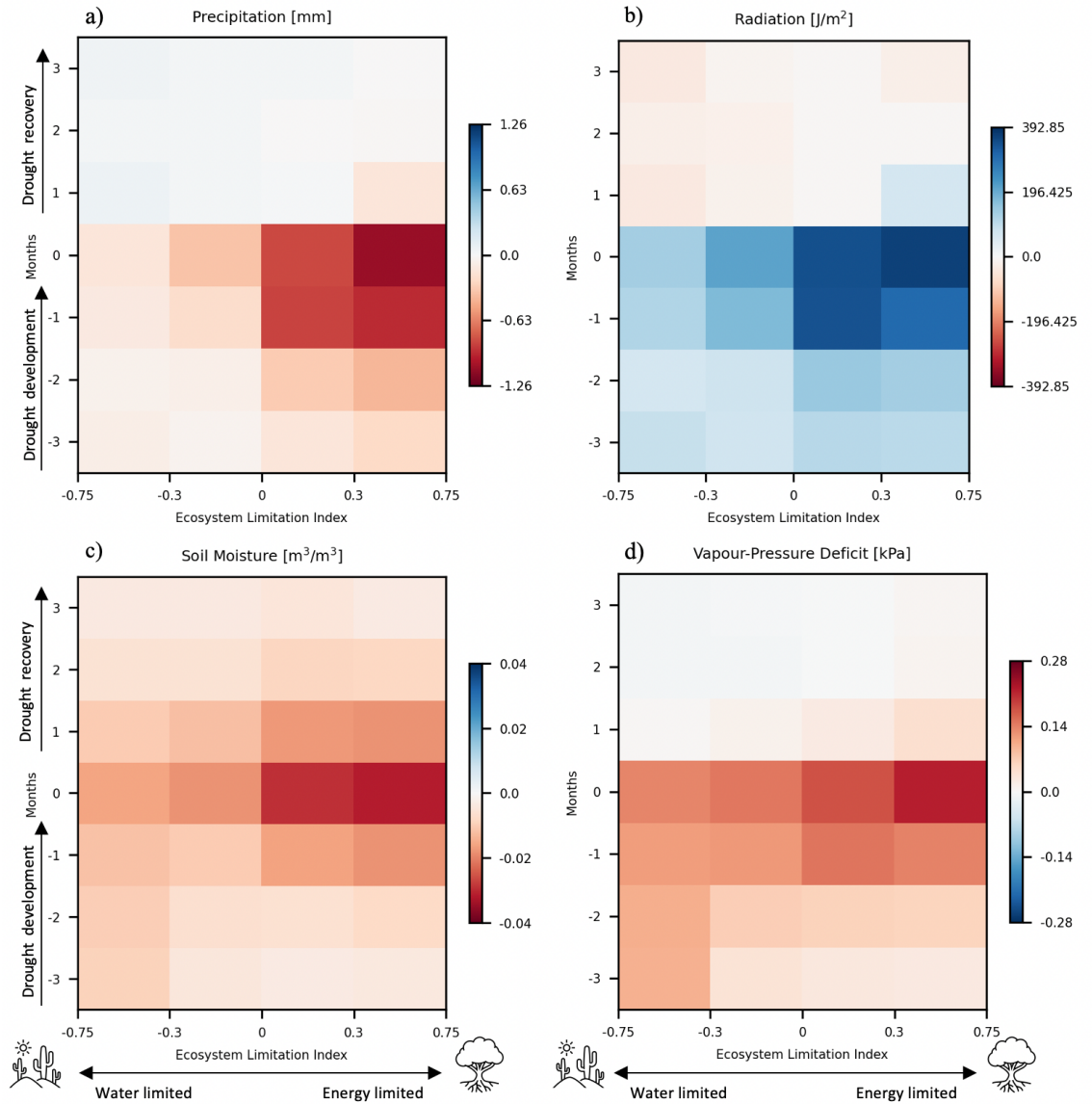


Figure 4: Anomalies of (a) precipitation, (b) radiation, (c) soil moisture and (d) VPD during detected drought period, grouped by hydro-climate regimes.

### 3.3. Impact on evapotranspiration and runoff

The impact of soil moisture drought on evapotranspiration is shown as anomalies (Figure 5a). Evapotranspiration anomaly can be broken down into three main signs, namely a separation between drought development and drought recovery. The drought development has higher anomalies than the drought recovery and another separation within drought development itself. In this case, differences between water limited and energy limited regions is apparent. Strongly water limited regions have negative evapotranspiration anomalies and the maximum is therefore during the drought month. In energy limited regions, positive anomalies are contrastingly striking, with a maximum one month before the drought peak.

The impact of soil moisture drought on runoff shown is based on the anomalies (Figure 5b). The runoff anomalies have a clear separation between water and energy limited regions. Water limited regions have very weak or no anomalies, whereas energy limited regions have strong anomalies. The intensity of runoff anomalies is increasing from very water limited to very energy limited regions. Overall, the negative anomalies are intensifying during the drought development and decrease during drought recovery.

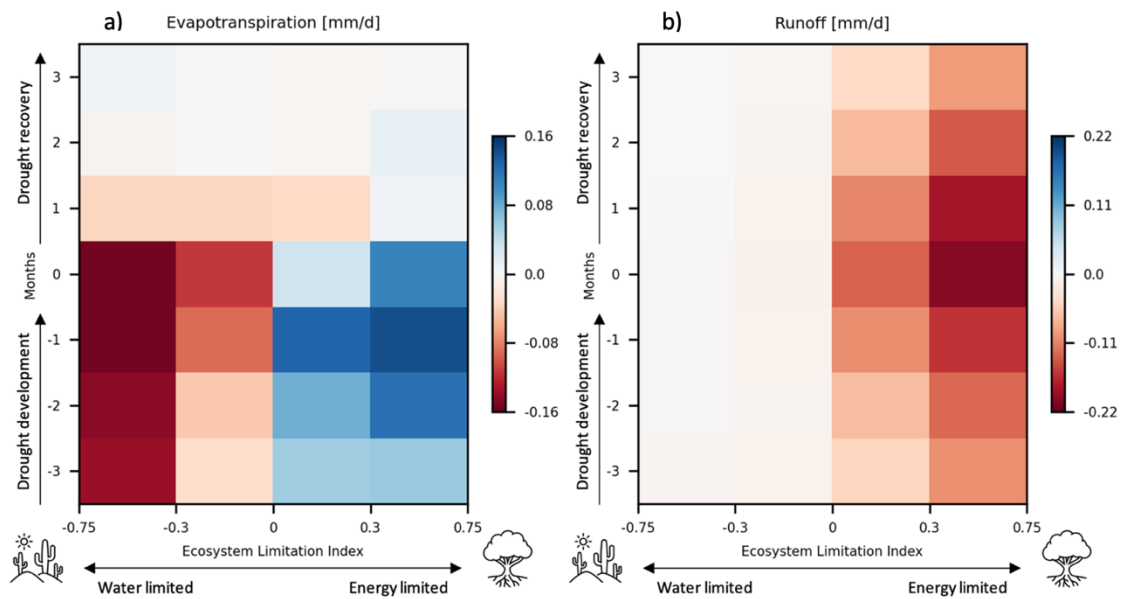
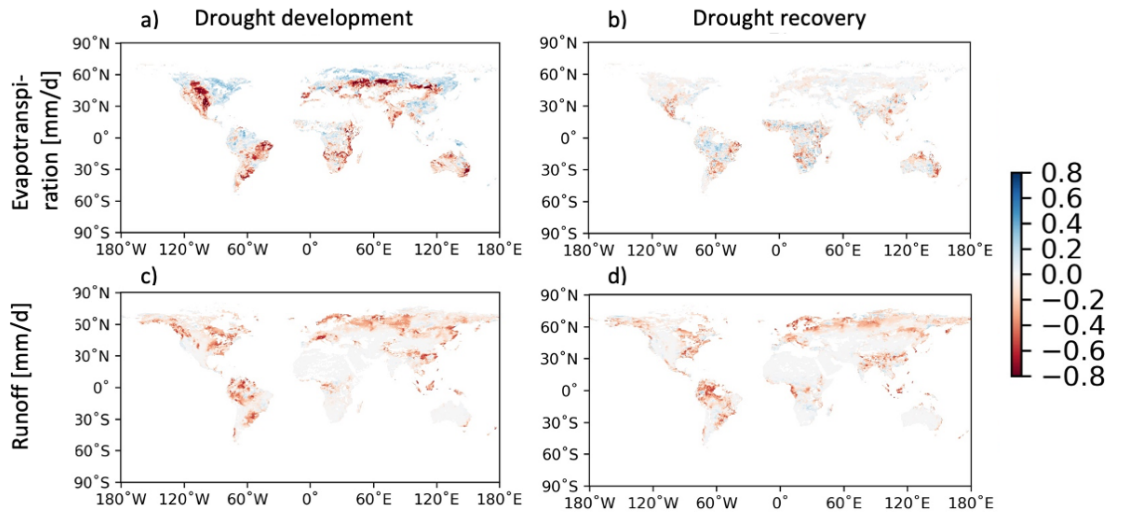


Figure 5: Anomalies of (a) evapotranspiration and (b) runoff during soil moisture drought development and recovery, grouped by hydro-climate regimes.

The global distribution of evapotranspiration and runoff according to the defined drought periods is shown (Figure 6). Evapotranspiration anomaly has positive and negative values up to -0.8 mm/d while, during the same period, runoff has only negative values. Those occur mainly in regions with positive evapotranspiration anomalies. Eurasia is divided by



positive evapotranspiration anomalies in the north and negative anomalies in the south. North America has an east-west separation, with positive values in the eastern part and negative anomalies in the western part. During the drought recovery, evapotranspiration anomalies are weaker, especially in regions north of  $30^{\circ}$  N, such as Eurasia and North America, and south of  $30^{\circ}$  S. In contrast, runoff anomalies are showing a similar pattern with similar anomaly intensity during drought development and recovery. The negative runoff anomalies occur particularly in northern part of Eurasia, eastern North America and northwest of South America.



*Figure 6: Global distribution of evapotranspiration anomalies during (a) drought development and (b) drought recovery and similarly for (c, d) runoff anomalies.*

As explained in method section 2.3.2, a normalised anomaly of evapotranspiration and runoff underlines the strength of long-term mean conditions compared to drought induced changes (Figure 7). The normalised drought impacts on two water fluxes can reveal the impact-relevant aspect for local ecosystems, as it indicates relative changes rather than the absolute changes of evapotranspiration and runoff. The normalised evapotranspiration anomalies have the similar pattern as evapotranspiration anomaly (cf. Figure 5a). During drought development, it can be seen that evapotranspiration has negative anomalies in water limited regions and positive anomalies in energy limited regions. During the drought recovery period, the evapotranspiration anomalies recover fast. However, the pattern of runoff differs from runoff anomaly (cf. Figure 5b). The strongest differences of runoff anomalies are in medium energy limited regions during the drought peak. Normalised runoff anomalies are higher in water limited regions than anomalies of runoff.

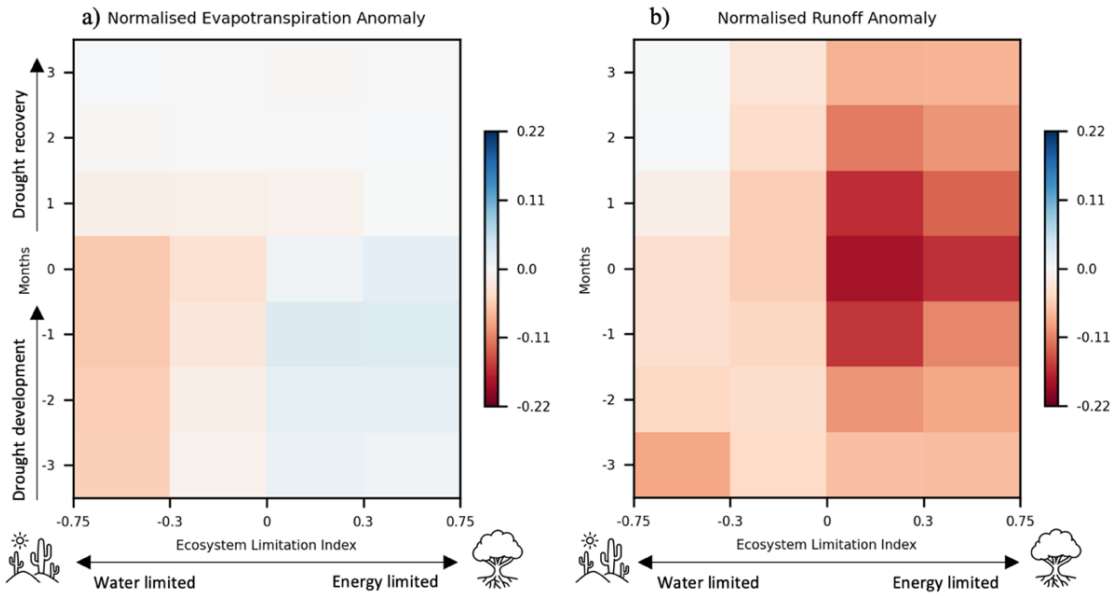


Figure 7: Normalised (a) evapotranspiration and (b) runoff anomalies during soil moisture drought development and recovery, grouped by hydro-climate regimes.

### 3.4 Relevance of Vegetation

The influence of tree-grass ratio on evapotranspiration and runoff during the drought peak is shown in Figure 8. The tree-grass-ratio ranges from 0 to 1, with 0-5 considered as short vegetation such as grass and shrubs, and 0.5-1 standing for tall vegetation such as trees. The impact of vegetation on evapotranspiration can be divided by their height (Figure 8a). Tall vegetation has an overall positive effect on evapotranspiration, where stronger positive results exist in strongly energy limited regions. Whereas strongly water limited regions have no evapotranspiration change due to tall vegetation. Short vegetation shows a subdivision along the ELI. Water limited regions as well as weakly energy limited regions result in negative evapotranspiration anomalies. Strongly energy limited regions have overall positive anomalies.

Runoff anomalies are always negative regardless of the vegetation type (Figure 8b). There is an intensifying negative runoff anomaly recognizable from water to energy limited regions. The same pattern is identifiable from short vegetation to tall vegetation, except for strongly energy limited regions.

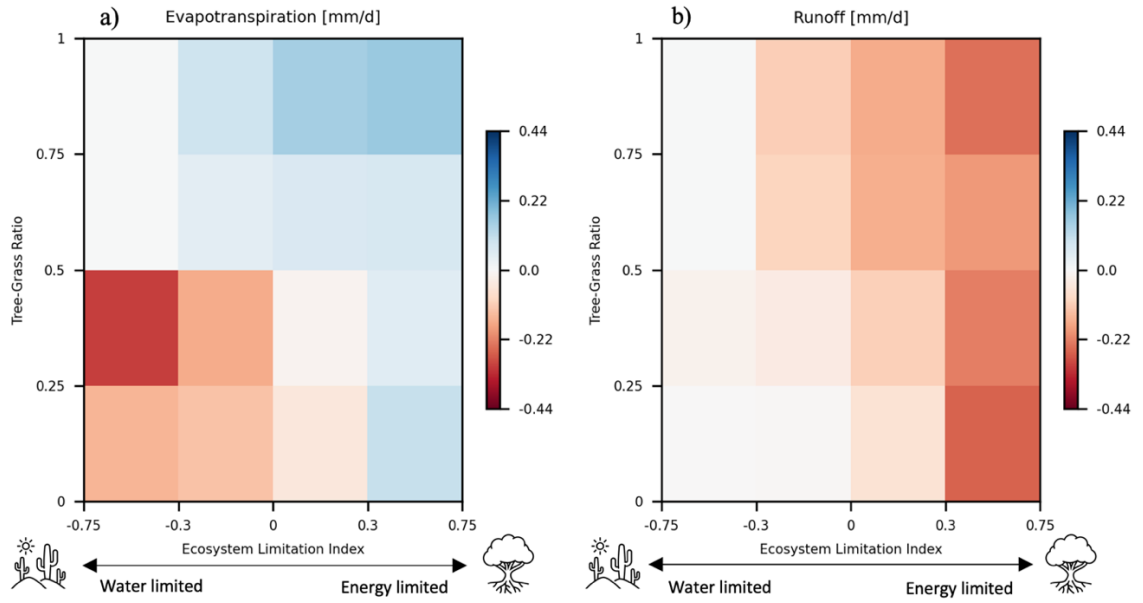


Figure 8: Anomalies of (a) evapotranspiration and (b) runoff across vegetation types, derived from tree-grass ratio during the drought peak, grouped by hydro-climate regimes.

Next, LAI is used as an alternative measure of vegetation amount in addition to tree-grass ratio, and it is directly related to biophysical processes such as the energy portioning via evapotranspiration (Figure 9a). LAI has a range from 0 to 6 and is subdivided in low, medium, high, and very high LAI. The pattern of LAI is comparable to tree-grass ratio, except for a few bins. In weakly energy limited regions with medium LAI, evapotranspiration has positive anomalies instead of no change based on the tree-grass ratio. And weakly energy limited regions with low LAI have negative evapotranspiration anomalies instead of slightly positive based on the tree-grass ratio. The highest evapotranspiration anomaly is in strongly water limited regions with medium LAI. The impact on evapotranspiration is divided by LAI and accompanied by ELI.

Runoff anomalies have the strongest negative flux in energy-limited regions with the highest LAI which is different from the case of using tree-grass ratio (Figure 9b). Another difference is that the minimum value is larger in the case of LAI than the case of tree-grass ratio. Other than these differences, the intensification of anomalies from water to energy limited regions is also noticeable.

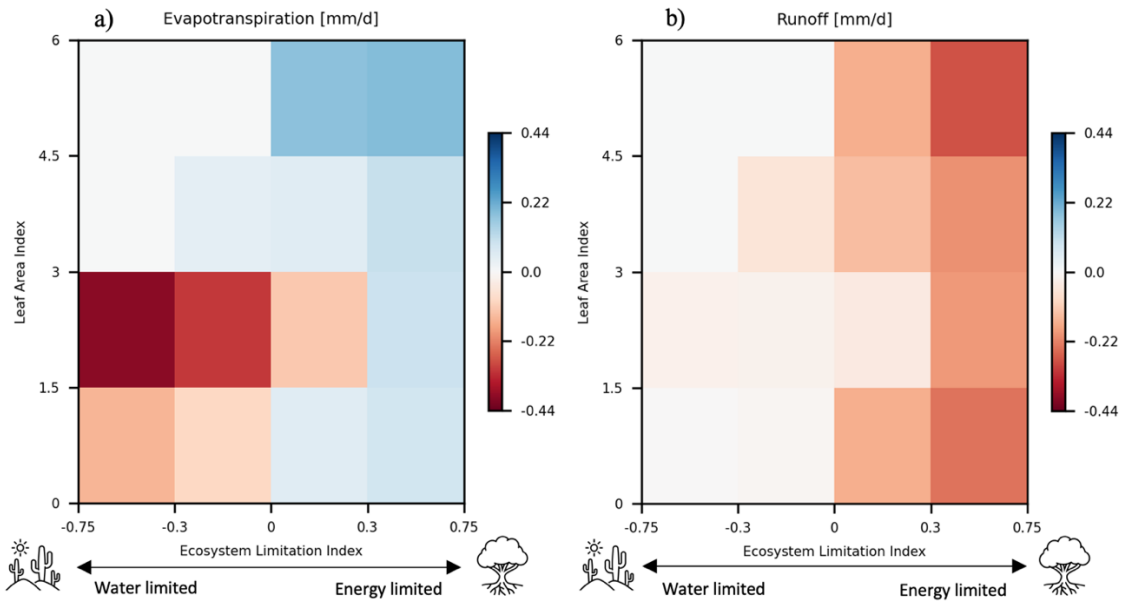


Figure 9: Anomalies of (a) evapotranspiration and (b) runoff across vegetation types, derived from Leaf Area Index during the drought peak, grouped by hydro-climate regimes.

### 3.5 Models

In the following, a comparison of observation-based data and model-based data for detecting drought occurrence are shown (Figure 10). The drought occurrence based on observation-based data was already shown in Figure 3.

The drought occurrence in observations and models is similar regarding the seasons but not always with the months. Droughts occur mainly in summer in the Northern Hemisphere, but autumn droughts become more frequent towards the south. The biggest difference between observations and models is in Sub-Saharan regions and Southern Asia. Australia also shows great differences with winter months in observations and summer months in the models. VISIT contains more detailed with more small-scale variability and LPJ-GUESS has the most deviations compared to observations.

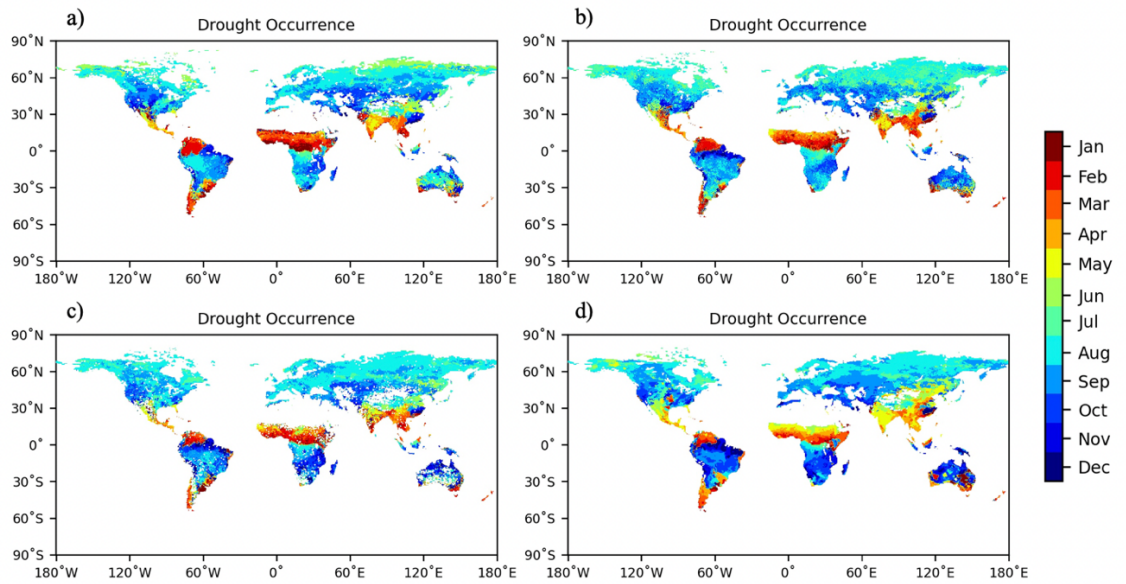
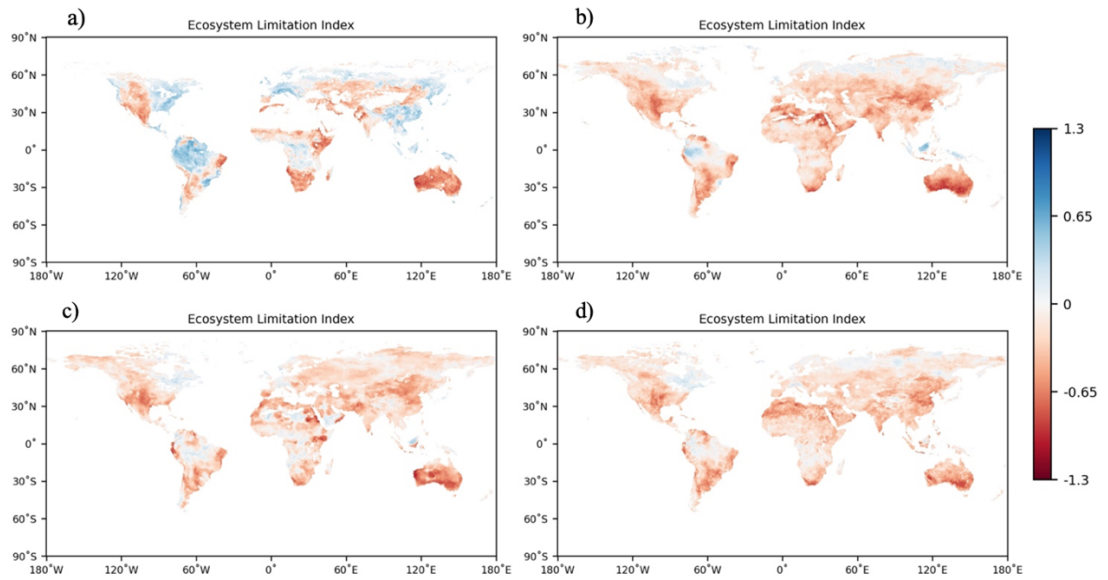


Figure 10: Global distribution of month-of-year of drought occurrence derived from (a) observation-based data and model-based data ((b) LPX-Bern, (c) VISIT, (d) LPJ-GUESS).

Another important evaluation, about whether model can reproduce similar drought impacts on different water fluxes, is the model performance of distinguishing water and energy-limited regimes, since these regimes are identified as one of the most powerful explanatory variables in understanding drought impacts. The global pattern of ELI is shown for observation-based data (cf. Figure 2) and model-based data (Figure 11). A striking difference is the occurrence of positive and negative values in observation-based data and the primary negative values in model data. Positive values occur much weaker in models in northern part of Eurasia, north-eastern part of North America and north-western part of South America. Considering Africa, mainly all regions are misrepresented, either there are no positive values or the regions are too small.



*Figure 11: Global distribution of the Ecosystem Limitation Index derived from (a) observation-based data and model-based data ((b)LPX-Bern, (c) VISIT, (d) LPJ-GUESS).*

To further understand which components of the identified water/energy-limited regimes contribute more to the overall misrepresented patterns, two correlation calculations related to water and energy controls on ecosystem evapotranspiration are presented separately. The first correlation, based on evapotranspiration and temperature, looks more alike between observations and models (Figure 12). The ratio between positive and negative values is similar, but the intensity is stronger in the models, especially in VISIT. Whereas North America has a widespread distribution of positive and negative values in observations, the distribution in models shows more small-scale variability. Southern of this, the differentiated pattern continues for models and observations. Thus, the distribution of the values does not match everywhere.

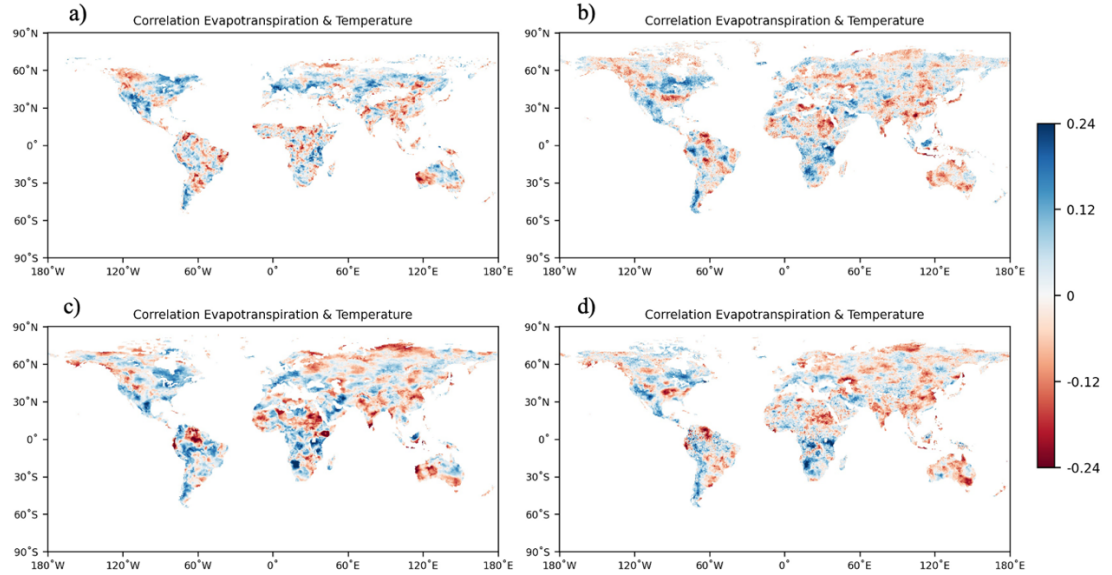


Figure 12: Global distribution of the correlation of evapotranspiration and temperature of the Ecosystem Limitation Index, according to (a) observation-based data and model-based data ((b)LPX-Bern, (c) VISIT, (d) LPJ-GUESS).

The second correlation, based on evapotranspiration and soil moisture, has striking differences between observation-based data and model-based data (Figure 13). Observation-based data has both positive and negative values. Whereas model-based data has a low number of negative values decreasing from VISIT to LPX-Bern and LPJ-GUESS with almost no negative grid cells. The strongest positive values occur in LPX-Bern. The pattern is comparable to the overall ELI pattern, only that the signs are the other way around.

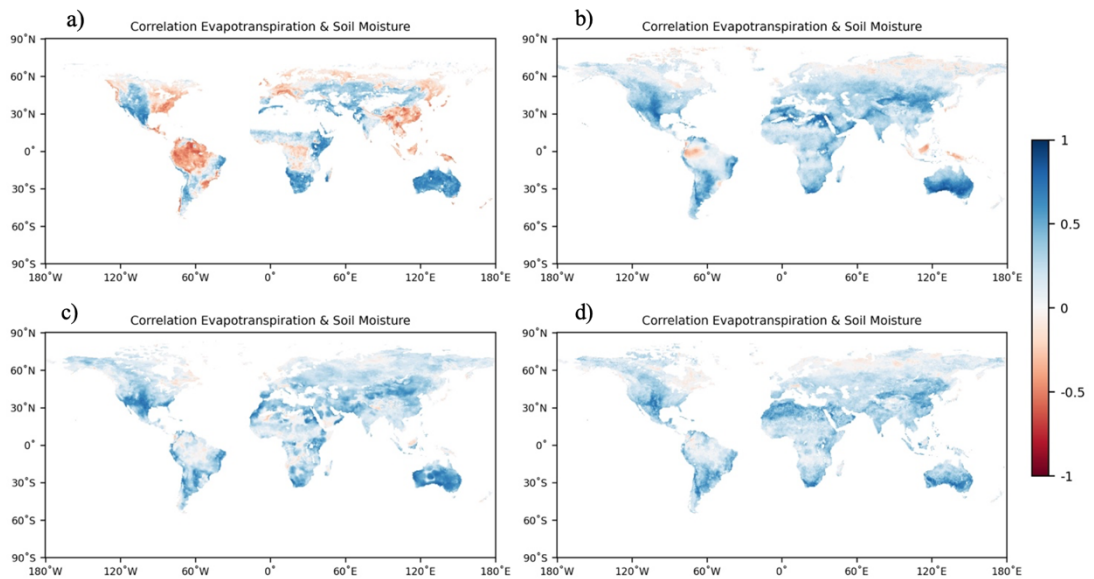


Figure 13: Global distribution of the correlation of evapotranspiration and soil moisture of the Ecosystem Limitation Index, according to observation-based data (a) and model-based data (LPX-Bern (b), VISIT (c), LPJ-GUESS (d)).



## 4 Discussion

The presented results will be discussed according to soil moisture drought aspects, hydro-meteorological conditions, the impact of droughts on evapotranspiration and runoff, the relevance of vegetation on these same variables and lastly the model performance of offline Trendy models.

### 4.1 Soil Moisture Drought

The global distribution of the strongest drought, which is captured within the timescale of January 2001 until December 2015, in each grid cell (Figure 1) is being examined. Based on this timescale, a classical climate period is not covered.

The drought months are based on the absolute minimum of soil moisture which are detected similarly as in Orth and Destouni (2018) which applied the distribution of soil moisture anomalies during the drought. This approach is also applicable, because the strongest soil moisture anomaly is being found in the drought peak (Figure 4c). Droughts which have been captured by soil moisture deficits are known as agricultural droughts (Van Loon et al. 2016). The machine learning dataset used for soil moisture is based on observed data and extrapolated in space and time (O and Orth 2021). An advantage of using machine learning data instead of mere observational data is, that machine learning data is automatically learning all relevant processes between the observational input data. Therefore, no relevant process or interaction can be forgotten. An analysis of only using machine learning data is a new approach and has never been used before. But there are also disadvantages, such as missing data or little data availability of regions or the non-physical impact of humans. Observational-based analyses can be seen as near natural, but this concludes in misinterpretations and data uncertainties of areas with high anthropogenic activity such as cities or regions with high human management like agriculture or dams (Destouni et al. 2012). All these regions are seen as near natural based on machine learning data. Another uncertainty of using observation-based machine learning soil moisture data is that the extrapolation applied in the machine learning likely functions badly if there are relatively few in-situ soil moisture samples available in certain regions or there are only few drought events to detect. Moreover, regions with no available observations cannot be represented. Thus, it is not a direct representation of reality. However, machine learning data constitutes a valuable alternative to model-based data, which will be compared and discussed in a later section.

Droughts occur in every season of the year. The Northern Hemisphere is dominated by months in summer and autumn, whereas the Southern Hemisphere is dominated by spring



months. At the equator, there is a shift by half a year. The timing of drought occurrence is not the main focus of this study. However, it is still implemented to give a brief overview of the global distribution.

A specific comparison of drought occurrence in Europe shows slight differences to other papers. Markonis et al. (2021) implemented three drought classes within Europe. They detect and analyse droughts in summer, autumn and winter (Markonis et al. 2021). Winter drought in Europe were also found by Vautard et al. (2007). In this study's findings, there are no winter droughts in Europe. This is because of the implemented temperature mask. The exclusion of cold periods was preferred, as they are not relevant for the vegetation growth and have therefore no effect on water and food security. Nevertheless, there are droughts occurring in winter months, but these are between 30° N and the equator or south of 30° S.

Considering climate change and rising temperature, there will be shifts and changes in drought occurrence, magnitude, and duration (Zargar et al. 2011, Konings and Gentine 2017). Overall, soil moisture might further deplete (Seneviratne et al. 2010). Soil moisture deficits in spring have already increased (Seneviratne et al. 2010), as well as agricultural droughts in general (IPCC 2021). Additionally, summer droughts are temporal increasing while winter droughts are declining (Markonis et al. 2021). This is mainly because of a shift in snow melt or type of precipitation (Markonis et al. 2021). Summer droughts occur due to a lack of precipitation in combination with an increased radiation, whereas in autumn and winter the droughts are computed by precipitation deficit in combination with a shift in type of precipitation (Markonis et al. 2021). A decrease of drought in wetting regions is to be expected, for example in higher latitudes (Markonis et al. 2021). Nevertheless, hydro-meteorological extremes such as soil moisture droughts are defined as hazards. They won't be equally distributed around the globe as the regionally experienced droughts are not defined as a hazard in every region, for example not so much in wet regions.

The ELI considers the balance between the calculation simplicity and the representativeness of ecosystem regimes, although it adds potential biases due to data dependence to understand drought impacts on evapotranspiration when using it as an explanatory variable. An alternative to the used ELI is aridity, which is also known as long-term dryness. This has been successfully used in previous studies, such as Orth and Destouni (2018), Liu et al. (2020) or Ghajarnia et al. (2021). A comparison of ELI and aridity leads to a similar global pattern (Figure 2) (Ghajarnia et al. 2021). The similar pattern of Ghajarnia et al. (2021) and this study further confirms the usage of machine

learning data in comparison to semi-observation-based data. Nevertheless, ELI is used instead of an aridity index because it includes responding of ecosystem qualities, whereas aridity shows only meteorological conditions. This is insufficient for this study, as an insight in changes of food and water security based on evapotranspiration and runoff is not given by aridity. Another way of using ELI is to use radiation as energy controlled variable instead of temperature (Seneviratne et al. 2010).

The results are providing findings only during the soil moisture drought period and long-term consequences or legacy effects are not yet included, which must be kept in mind. To ensure climate relevant findings, the analysed period of drought detection has to be multi-decadal (Seneviratne et al. 2010). This is not the case in this study, wherefore meaningful conclusions about climate change cannot be provided.

## **4.2 Hydro-meteorological Conditions**

After detecting the drought based on soil moisture deficit, a view on hydro-meteorological conditions is presented. This will be carried out in physically sensible order, starting with the impact of changes in precipitation and radiation on soil moisture. During the drought development, a decrease of precipitation is distinguishable. The similar pattern is identifiable for radiation, with the only difference that radiation is increasing due to lower cloud cover (Figure 4). Water limited region have only a small increase in radiation compared to energy limited regions. A decline in precipitation during droughts was also found in a study of Orth and Destouni (2018) and stated as an inducing variable for soil moisture depletion. Soil moisture has a positive feedback on subsequent precipitation (Vogel et al. 2018). When soil moisture depletes, latent heat flux decreases, as well as the cloud cover and precipitation. This ends in a further depleted soil moisture and intensifies the drought. An exacerbation of depleted soil moisture is related to an increase in radiation, which leads to an increase in temperature and latent heat flux, which further depletes soil moisture (Vogel et al. 2018). The combination of high radiation and low precipitation induces water stress and leads to a soil moisture drought (Orth 2021).

Furthermore, precipitation deficits are strongest in energy limited regions one month before and during the drought. A differentiation of Europe has been carried out by Orth and Destouni (2018) which found the strongest anomalies in intermediate climates and lowest in drier and wetter climates. As this trend is not recognisable in this studies results, the trend cannot be transferred globally, or further studies have to break down the ELI into more than four regions. Moreover, the precipitation anomaly deficit increases from water to energy limited regions. From the perspective of Europe, an intensification from humid

to arid is recognisable (Orth and Destouni 2018). As Europe is mainly energy limited, a comparison of the results is not justifiable.

After the drought peak, soil moisture begins to recover due to the rapid increase in precipitation, which also helps the other water and energy-related variables to recover to normal conditions. Higher precipitation theoretically leads to higher soil moisture (Seneviratne et al. 2010). However, this is not the case after the analysed soil moisture drought peak. While precipitation recovered immediately, soil moisture needs several months to recover from its deficit. This is since precipitation is a flux and soil moisture is a state variable. Even though the soil moisture is not at its absolute minimum anymore, it does not recover the soil moisture storage immediately. Contrastingly, Orth and Destouni (2018) found precipitation values that were higher than normal after the drought peak. This is not the case in neither energy nor water limited regions. As mentioned in section 3.2, precipitation increase leads theoretically to a soil moisture increase, but this is not the case in strongly energy limited regions (Seneviratne et al. 2010). There the precipitation results in runoff and not in a soil moisture increase, which is due to a higher precipitation rate compared to the infiltration rate of the soil (Seneviratne et al. 2010). These results are consistent with the findings of this study. Soil moisture recovers faster than runoff, as runoff is responding to soil moisture (Figure 4c, Figure 6) and the intensity of depletion is higher for runoff than for soil moisture.

A depletion in soil moisture generally leads to an increasing atmospheric dryness due to less evaporation, enhancing the water demand in the atmosphere, whereas the increased VPD could also inhibit the vegetation transpiration by stomatal closure and maintain the soil moisture (Seneviratne et al. 2010). As soil moisture is also important for partitioning sensible and latent heat fluxes which further affects temperature and humidity (Seneviratne et al. 2010). Low soil moisture is found to be strongest in energy limited and weakest, but longest in water limited regions. This contradicts findings of Liu et al. (2020) who investigated the largest effects in semi-arid ecosystems.

The last variable to describe the hydro-meteorological conditions during drought is VPD. Soil moisture and VPD have a strong coupling on a yearly scale (Liu et al. 2020). When soil moisture is depleting, VPD is increasing (Liu et al. 2020). This coupling is also supported in the presented results. When soil moisture declines, an increase in temperature and VPD is recognisable. This leads to an intensified soil drying and decline of soil moisture (Vogel et al. 2018).

For all variables, the anomalies are intensifying from water limited regions to energy limited regions following the generally larger meteorological variability in wetter regions,

partly due to their larger magnitudes of long-term mean variations. Projected changes of the mentioned variables are detected by other studies (Seneviratne et al. 2010). These changes may have an influence of drought appearance and impact in the future. But this and the importance of anthropogenic climate change (Koster et al. 2017) are not considered in this study, as well as the impact of CO<sub>2</sub> on water resources, which may further pressurise water limited regions (Ukkola et al. 2015).

The considered variables radiation, precipitation and VPD are based on ERA5-land, which provides a high quality of combined satellite analysis and ground-based observations (Orth 2021). This approach circumvents spatial limitations of mere observation-based data and temporal limitations of remote sensing measurements (Seneviratne et al. 2010). Further on, observation-based data are influenced by regional meteorological forcings (Seneviratne et al. 2010).

### **4.3 Impact on evapotranspiration and runoff**

After discussing potential links between variables, now it is essential to explain the changes of biosphere and hydrosphere with the time shifts from the drought development to the recovery periods provided that evapotranspiration represents the biosphere and runoff represents the hydrosphere.

#### **4.3.1 Evapotranspiration**

During the drought development, evapotranspiration decreases in water limited regions but increases in energy limited regions. This separation of climates is also been found in Europe and confirm the results (Orth and Destouni 2018). A fast change back to the equilibrium state-is detected in all regions. This is explained by various variables. The pattern of evapotranspiration in water limited regions are linked to the distribution of soil moisture (Seneviratne et al. 2010). This only applies to months of drought development. For evapotranspiration recovery, this correlation is not given. It is explained by physical properties. A lack of water supply by depleting soil moisture and precipitation anomalies results in decreasing evapotranspiration in water limited regions (Seneviratne et al. 2010, Orth 2021), whereas soil moisture is the main regulator (Ghajarnia et al. 2021). The similar signal was found in Europe by Ghajarnia et al. (2020). This linkage is broken as soon as precipitation is recovered. Precipitation provides water for the ecosystem to evaporate. But before soil moisture recovers, the water has to fill up the groundwater table and the groundwater runoff (Orth and Destouni 2018, Ghajarnia et al. 2020). Therefore, evapotranspiration is coupled with soil moisture during the development and decoupled during

the recovery. If these analyses are carried out at a more localised scale, a variation of coupling strength may occur (Seneviratne et al. 2010).

In relation to climate change, evapotranspiration variability is expected to strongly increase in water limited regions (Seneviratne et al. 2010). Moreover, a decline in evapotranspiration can lead to enhanced energy surplus such as elevated temperatures and consequent heat waves (Seneviratne et al. 2010). The dependency of soil moisture and further precipitation on evapotranspiration is larger in water limited regions than in energy limited regions, which is supported by Ghajarnia et al. (2021).

Energy limited regions have a different signal during the drought development. Even though the soil moisture deficit is more intense than in water limited regions, the resulting anomaly in evapotranspiration are not negative but positive with a caution of the real value ranges. The positive anomalies in energy limited regions are caused by an interplay of two main reasons. On the one hand, energy limited regions have potentially more accessible water reservoirs such as groundwater and water in the bedrock and are not impacted by root-zone soil moisture changes (Seneviratne et al. 2010). This is used as source for evapotranspiration instead of precipitation. On the other hand, a surplus of radiation and VPD benefits this region. As radiation is strongly increasing in energy limited regions, evapotranspiration anomalies benefit from this surplus of energy (Ghajarnia et al. 2020). The increased radiation offsets the negative counterbalance of the depleted soil moisture anomaly (Orth and Destouni 2018). An increase in this benefit for evapotranspiration is seen until one month before the drought peak. During the drought maximum, the surplus of evapotranspiration anomaly is declining. This is caused by the declination of water reservoirs. Besides the spatial classification of grid cells into water and energy limited regions, a change in time is also possible. During strong drought conditions, energy limited regions can become water limited. Due to the feedback of increasing evapotranspiration on declining soil moisture, an intensification of soil moisture drought can occur (Seneviratne et al. 2010). More specifically, a depletion in soil moisture results in a decrease in evapotranspiration, like mentioned above. Further on, this results in an increase in sensible heat, temperature and evaporative demand (Seneviratne et al. 2010). This positive feedback results in an intensifying depletion of soil moisture and increasing atmospheric dryness (Orth 2021). This leads to the assumption that soil moisture droughts are being intensified in energy limited regions by an increased evapotranspiration due to the surplus of radiation.

An increase of evapotranspiration in energy limited regions can further favour biospheric activity (Orth and Destouni 2018). It benefits from the short duration of the drought and

the surplus of radiation, as these wet and cloudy regions depend on the availability of atmospheric energy (Orth and Destouni 2018, Orth 2021). An increasing evapotranspiration can furthermore lead to an intensification of dry seasons and increase shorter droughts in Europe (Padrón et al. 2020, Markonis et al. 2021).

During the drought development, the pattern of evapotranspiration, soil moisture and VPD show a classification of long and short droughts. The water deficit in strongly water limited regions is more intense than in weakly water and generally energy limited regions. Long and weak soil moisture droughts occur in strongly water limited regions. The lower water reservoirs and the presence of generally drier conditions, as it takes time to accumulate a precipitation deficit over time in regions where it seldom rains, in strongly water limited regions contribute to the slow development. This is supported by weak anomalies of soil moisture, precipitation and VPD. Short and intense droughts are more common in weakly water limited as well as in mostly energy limited regions. The fast development is caused by stronger meteorological variabilities. That means, if it often rains in a greater amount, it is then easier to have a fast developing strong precipitation deficit even if it does not rain for a short amount of time. This is supported by overall wetter conditions and stronger anomalies of soil moisture, precipitation and VPD.

Evapotranspiration is captured back to normal status quickly for both water and energy limited regions after the drought peak. Evapotranspiration recovers within one month and has no post peak, which is supported by Orth and Destouni (2018). The pattern of more intense evapotranspiration anomalies during drought development than during the recovery is supported by the global pattern (Figure 7). Especially in the northern part of Eurasia and America it is noticeable, that evapotranspiration has a change of up to  $\pm 0.8$  mm/d during the development, whereas during the recovery the anomaly is very low. All evapotranspiration anomalies have a same strong impact compared to normal conditions, as they are shown in Figure 5 and Figure 7.

Changes in evapotranspiration can be explained by precipitation deficits induced by soil moisture (Seneviratne et al. 2010, Orth and Destouni 2018). However, the influence of evapotranspiration on precipitation is marginal and known as precipitation recycling (Seneviratne et al. 2010). Within the water cycle, evapotranspiration also provides a part to local precipitation amount (van der Ent et al. 2010).

#### 4.3.2 Runoff

During the whole drought period, overall negative values for runoff anomaly are detected. This finding is supported by negative runoff anomalies within all climates in Europe (Orth and Destouni 2018). The negative anomalies intensify during the drought development and decrease during recovery. Furthermore, an increase of negative anomalies from water to energy limited regions is recognisable whereas strongly water limited regions have no negative anomaly. This can be explained by missing runoff in normal periods. Strongly water limited regions are very dry and the occurrence of runoff is normally very low or non. Therefore, no depletion can be expected. This is supported by different groundwater storages (Orth and Destouni 2018). Likewise, in water limited regions soil moisture is below saturation and no change in runoff is to be expected.

Compared to this, negative anomalies are intensifying in energy limited regions during drought development. With the strongest runoff anomalies in strongly energy limited regions. This effect is supported by all considered variables, as they have their strongest anomalies in strongly energy limited regions. The similar pattern of high anomalies in energy limited regions and low anomalies in water limited regions is seen in precipitation anomalies and radiation. The stronger decrease in precipitation and lower cloud cover lead to an increase in radiation. These two variables support the separation of runoff anomalies along the ELI, but this pattern of coupled runoff and precipitation only occurs during the drought development. As soil moisture is near to saturation in energy limited regions, a small decrease in precipitation would lead to a large decrease of runoff, as soil moisture is buffering the variability of runoff (Seneviratne et al. 2010).

Runoff needs the similar amount of time to recover as it did to develop the drought in each ecosystem region. Therefore, below-normal runoff anomalies continue to be present after the drought peak. This is in line with findings of Orth and Destouni (2018) for Europe and with the global anomaly distribution. Runoff has the same strength during the entire drought period in, e.g., the north-eastern part of North America and in the north-western part of South America (Figure 6). But the strongest anomalies are not representing the strongest change compared to normal conditions. Weakly energy limited regions do have a stronger change during droughts compared to the ecosystem specific long-term mean conditions. Therefore, the reduction of runoff in weakly energy limited regions is more severe than in strongly energy limited regions, even though the anomalies are higher in strongly energy limited regions.

After the drought peak, precipitation anomaly is at zero and thus, the conditions are back to normal. This increase in precipitation, compared to the decrease during the drought

development, leads theoretically to a higher runoff in strongly energy limited regions as the soil is too dry to infiltrate the water (Seneviratne et al. 2010). If runoff and precipitation are coupled during recovery, through the occurrence of heavy rainfall events, this would result in surface erosion of nutrients, which poses a risk to drinking water quality. However, runoff is not recovering as fast as precipitation is. Here, soil moisture plays an important role. Runoff only recovers if precipitation has a higher rate than infiltration (Seneviratne et al. 2010) and if both the groundwater table and groundwater runoff have recovered (Orth and Destouni 2018). Consequently, precipitation has to refill soil moisture and recover, before runoff increases (Orth and Destouni 2018). Runoff and precipitation are coupled during drought development and decoupled during recovery. The overall pattern in energy limited regions is strongly correlated to soil moisture anomaly pattern. This is to be expected, as soil moisture and runoff co-occur (Ghajarnia et al. 2020). Based on a study of Ghajarnia et al. (2021), runoff and soil moisture have the strongest observation-based co-variations compared to other co-variation patterns of precipitation, runoff, evapotranspiration and soil moisture, whereas runoff and precipitation has the weakest. Therefore, the impact of soil moisture changes on runoff is higher than changes of precipitation, which is also the most misrepresented (Ghajarnia et al. 2020).

#### 4.3.3 Comparison of evapotranspiration and runoff

Differences in evapotranspiration and runoff can be explained by their different limitations. Evapotranspiration is limited by soil moisture anomalies as they are detected to correlate (Orth and Destouni 2018). Additionally, evapotranspiration is regulated by temperature, radiation and the water supply (Ghajarnia et al. 2020). Whereas runoff anomalies correlates and is limited by soil moisture and precipitation anomalies (Orth and Destouni 2018, Ghajarnia et al. 2020). Moreover, a secondary-order mechanism plays a role, according to the interlinkage of evapotranspiration and runoff itself. In Europe soil moisture has a stronger correlation with runoff than with evapotranspiration and extreme values of soil moisture and runoff largely co-occur (Ghajarnia et al. 2020). This can be extended globally, based on this study's findings. Only looking at energy limited regions, evapotranspiration is not directly attached to soil moisture, but runoff is (Seneviratne et al. 2010). As mentioned beforehand, evapotranspiration is mainly dominated by an increase in radiation. The impact of precipitation on both variables also differs. Precipitation deficits lead to a high decrease in runoff and a relatively low decrease of evapotranspiration in energy limited regions such as Europe (Orth and Destouni 2018, Ghajarnia et al. 2021).



During the drought development, a combined deficit of soil moisture and precipitation occurs. Increased evapotranspiration leads to a further depleted soil moisture and therefore water storage but runoff buffers soil moisture content and its water storage. Therefore, in energy limited regions, water storage is depleting by an increased evapotranspiration and buffered by runoff (Orth and Destouni 2018). Other than in water limited regions, where no buffering of runoff is provided. This leads to a directly affected soil moisture by missing precipitation and therefore, no soil moisture is left to evaporate from the soil moisture. The sign of evapotranspiration changes may depend on runoff buffering on soil moisture.

During drought recovery, the main driver is soil moisture as precipitation is back to normal. Runoff, based on soil moisture as a main driver, leads to a slower recovery of several months, because soil moisture has to recover first. This is also related to the fact that runoff consists of two components, surface runoff and sub-surface runoff. However, evapotranspiration recovers within a few months in all regions. This is due to the fast recovery of radiation and water availability. The same results of a stronger and faster runoff reduction compared to evapotranspiration is found in a Europe based study (Orth and Destouni 2018).

Considering the entire drought period, the strongest anomalies are found during the drought peak. This contradicts findings of Orth and Destouni (2018) who found the strongest anomaly before the drought for evapotranspiration and runoff. Even though the impact of soil moisture drought is different within evapotranspiration and runoff, it can be seen that it plays a dominant role in each climate and ecosystem (Orth and Destouni 2018).

According to the normalised anomalies, evapotranspiration changes correspond with the detected anomalies. This leads to the assumption, that the anomalies of evapotranspiration correlate in space and time during the drought in their intensity with long-term ecosystem mean conditions. This is not the case for runoff. For runoff, the strongest anomalies are found in strongly energy limited regions, but the strongest impact compared to long-term mean conditions are to be found in weakly energy limited regions, indicating that the strong runoff reduction could lead to severe negative influence on the associated local services under drought. Therefore, weakly energy limited regions suffer the most from negative anomalies during droughts.

#### 4.4 Relevance of Vegetation

This study further analyses how these responses are modulated by different vegetation types. The influence of LAI on evapotranspiration and runoff during the drought month is comparable to the tree-grass ratio. According to both measurements, evapotranspiration is mainly influenced by vegetation and, to a smaller extent, also by ecosystem regimes. Opposingly, runoff is only divided by ELI and the type of vegetation is not the main impact. The impact of vegetation was only analysed during the drought peak, which represents the absolute soil moisture minimum. As both measurements show similar results of the independent used tree-grass ratio and LAI, this indicates the analysis is robust.

Tree dominated regions have an overall increased evapotranspiration across all ELI regions. This is explained by deep roots of trees, which can still reach groundwater and supply the trees with water (Smith-Martin et al. 2020). Therefore, trees do not suffer during the root -zone soil moisture-induced drought peak and are not reducing evapotranspiration. Besides, a second aspect is important to consider. Trees have a protective characteristic of stomatal regulations. Closed stomata reduce photosynthesis and evapotranspiration to save water and survive better (Konings et al. 2017). Theoretically this would lead to a reduced evapotranspiration, but this is not found in tree dominated regions (Ukkola et al. 2015). This is either because stomatal closure is a second order mechanism and is only regionally relevant, or because the roots still have enough water to avoid having to close the stomata. The latter explains the increase in evapotranspiration the more tree dominant and in the more energy limited the region is.

The same arguments can be applied to grass. Grass-dominant regions are either supporting or preventing evapotranspiration, according to ELI. In water limited regions, grass vegetation reduces evapotranspiration and in energy limited regions it is increasing. In general, grass has no deep roots. It cannot supply from deep groundwater, although there are in-situ experiments indicating root plasticity potential for grasses in some seasonal dry regions (Fan et al. 2017). If the surface dries out, which happens during a soil moisture drought peak, roots have no access to water and they die. Grass cannot benefit from stomatal closure as they do not have this property. Thus, they lose water faster, dry out and die. Nevertheless, a division in increased and decreased evapotranspiration is recognisable. This can be explained by the drought duration. As mentioned earlier, droughts in water limited regions are longer and weaker and, in energy limited regions, shorter but more intense. As the soil moisture drought already lasts longer and evapotranspiration is not limited due to stomatal closure, the most grass has already died. On the other hand, the soil moisture drought in energy limited regions exist only for a shorter time,

evapotranspiration continues and is increased due to the surplus of radiation. As the grass is not dead yet, vegetation regulates the strength of radiation, due to their LAI, and therefore regulates the intensity of evapotranspiration on the surface as well. Increased evapotranspiration of grass in energy limited regions is possible (Ukkola et al. 2015).

LAI has the similar pattern as tree-grass ratio, except for grass dominated and weakly energy limited regions. Strongly grass dominated regions have a slightly increasing evapotranspiration effect on missing water, whereas low LAI has a slight negative effect on evapotranspiration. Weakly grass dominated regions have no impact on evapotranspiration changes and medium LAI has an increasing impact. Regarding evapotranspiration, a division within the regime by both tree-grass ratio and LAI is important. ELI is also not negligible.

In contrast, runoff is decreasing in all conditions based on tree-grass and LAI along the ELI regions. Furthermore, as the pattern is more diverse along the x-axis, runoff is mainly controlled by ELI and not by vegetation. It is also noticeable that negative runoff co-occurs in regions with positive evapotranspiration. This shows the linkage between runoff and evapotranspiration rather than between vegetation and runoff, as vegetation is mostly affecting evapotranspiration and not runoff. A minor effect of vegetation, especially LAI, is the regulation of parting precipitation into either interception or runoff (Ukkola et al. 2015). This effect can be neglected.

Short vegetation is adapting differently to droughts than long vegetation (Seneviratne et al. 2010). Grass dominant regions have a larger respond to soil moisture deficit and drought stress (Liu et al. 2020). This explains the negative evapotranspiration anomalies in water limited regions and the strongest decline of runoff in energy limited and grass dominant regions.

#### **4.5 Model-based analyses**

As seen in section 3.5, the drought occurrence is representable with model-based data. The overall pattern of observations and models is similar. Even though the drought months do not coincide exactly, the season is still the same. Small differences of the drought detection can occur due to potential data noises, as only the strongest soil moisture deficit was used to define droughts. Another possibility is the different soil moisture definition of observations and models. As the models are using the total soil moisture, which includes the deeper layers of soil moisture, they potentially detect less water stress than the observations. This is explained by the decoupling of the root-zone soil moisture with the deeper layers of soil moisture under severe drought. However, the drought

detection is working well with model-based data. Based on this, a direct comparison of drought effects on evapotranspiration and runoff from observation-based and model-based data should be carried out. But based on previous results of model-based ELI, a comparison is not justifiable. Therefore, a comparison of ELI, highlighting problems and questions for further projects are shown.

The ELI for observations has both energy and water limited regions across the world. The same pattern should be represented based on models to ensure the correct rendering of reality. However, model-based ELI is predominantly showing water limited regions and disproportionate energy limited regions. Therefore, the representation of model-based data in ELI is wrong. To detect the main driver of this misrepresentation, both correlations were considered separately. Based on this, models have a more or less good representation of observation in the first correlation, which is based on energy limitations, even though the model values are more intense than the values based on observations. In contrast, models show in the second correlation, based on water limitations, a total misrepresentation to observations. Here, negative values are either very weak or absent, as they are positive, potentially due to the misrepresentation of soil water stress in the models and also the lack of incorporating negative influence of soil moisture on evapotranspiration (Humphrey et al. 2021). This leads to the assumption that the misrepresentation of the evapotranspiration and soil moisture interplay of the second correlation is causing the wrong ELI.

A part of the misrepresentation can be explained by the different definitions from soil moisture. In observations, precisely in SoMo.ml, soil moisture is derived within the first 50 cm of the soil, whereas all models used capture the total soil moisture. Therefore, there are certain differences. Surface soil moisture has a larger sensitivity to precipitation anomalies, while the total soil moisture is associated with groundwater changes (Ghajarnia et al. 2021). This difference was considered but not changed. Each model has different soil moisture layers with different structures and parameters, so that the values given are not comparable to real soil moisture depths. Based on this, it is difficult to re-scale the depth of soil moisture. The benefit of machine learning soil moisture should also be mentioned, as it is based on observation data computed globally. This validates a dataset at global scale, which mere side-scale observations would not provide.

Soil moisture is generally a dynamic variable due to the varying depth-extent of the vadose zone and the groundwater table (Ghajarnia et al. 2020). The variation of soil moisture depth depends on precipitation and evapotranspiration, as discussed in section 4.3.1. Groundwater changes were not considered in observation-based data nor in model-based

data. They are often insufficiently represented in models (Ghajarnia et al. 2020). However, as neither observation nor model analysis are based on this condition, they remain comparable.

For this analysis, offline models were used. This helps to identify if meteorological anomalies lead to the same evapotranspiration and runoff changes during soil moisture droughts as observations. Another possibility would be to use coupled models instead. These include feedbacks between the variables and are likely to better reflecting reality but also potentially have propagated climate data uncertainties when simulating soil moisture, evapotranspiration, and runoff. Nevertheless, if offline models are not capturing the right meteorological conditions, it is very unlikely that the implemented feedbacks can correct it, because of a general wrong presentation of model structure according to biophysical processes, which are not fully understood. Therefore, it can be said that model-based ELI are not representing the comparable results with observation-based data and has thus to be improved. If other models beside TRENDY show better results, they must be analysed in future studies. Future studies can moreover check if models capture evapotranspiration and runoff changes right based on an observational-ELI.

In general, models of a global scale are the key tools of representing hydroclimatic conditions (Koster et al. 2017). To be representative, earth system models have to represent the difference between water and energy limited regions and accurately cover the land-atmosphere coupling, which they don't do until this point (Orth 2021). Further on, the VPD and soil moisture limitations have to be disentangled (Liu et al. 2020).

Even when the attempt of analysing evapotranspiration and runoff changes on droughts based on models fails, a hypothesis according to other studies is still possible. A general poor performance of evapotranspiration and runoff is detected on land (Ghajarnia et al. 2021). Furthermore, a misrepresentation of the soil moisture and runoff relationship is discovered, which is most strongly based on observations but is most weakly based on models (Ghajarnia et al. 2021). Earth system models used by Ghajarnia et al. (2021) show partly inconsistent and misrepresented data in the form of underestimations, overestimations or unrealistic increases. Uncertainties of these models are largest for soil moisture and runoff and lowest for temperature and evapotranspiration (Ghajarnia et al. 2021). Based on relationships between variables, soil moisture-runoff, precipitation-evapotranspiration and precipitation-runoff have the highest errors, whereas soil moisture-evapotranspiration has the lowest (Ghajarnia et al. 2021).

## 5 Conclusion

This study contributes to a better understanding of soil moisture, evapotranspiration and runoff in the terrestrial water balance, as these variables are unclear regarding their responses under drought at a global scale (Seneviratne et al. 2010). Based on soil moisture droughts, evapotranspiration and runoff were used to understand drought propagation, while the meteorological variables are used to understand drought characteristics and reasons for the respective propagation in different directions. A full spatial and temporal coverage of soil moisture droughts are given, as droughts affect biosphere and hydrosphere in different ways and their effects vary in space (Van Loon et al. 2016). A quantification of the beginning of droughts in strongly water limited regions is not possible, as only three months before the drought peak are considered. This is limited by the selected time of three months as drought development.

Soil moisture availability has a direct impact on vegetation productivity, as dryness stress is limiting vegetation growth, and as soil moisture determines the amount of water for plants (Liu et al. 2020). The more developed the drought is, the higher is the time of recovery of hydrosphere water and the higher is the disturbance of vegetation (Orth and Destouni 2018). Soil moisture drought induced plant mortality and the reduction of photosynthetic uptake will have a further feedback on the climate (Ghajarnia et al. 2020). According to the anthropogenic climate change and the proven water stress during soil moisture droughts and their possible legacy effect raises up the question of the sustainability of societies water use (Koster et al. 2017).

This study confirms the usage of machine learning data and further the implementation of ELI, as comparisons with other studies show similar results. Relationships of variables are represented such as the strong coupling of soil moisture and VPD. Soil moisture and precipitation are coupled during the drought development and decoupled during drought recovery. And soil moisture has to recover before runoff is able to. All considered variables are mechanically linked to one another through fundamental water balance (Ghajarnia et al. 2020). The global analysis give insights of first-order mechanisms whereas second-order mechanisms have a regional or specific time related impact (Ghajarnia et al. 2020).

The impact of soil moisture drought on evapotranspiration is separated by the ELI. During the drought development evapotranspiration declines along with soil moisture depletion in water limited regions. The combination of depleting soil moisture and decreasing evapotranspiration rates, as in water limited regions, results in a decrease of vegetation activity (Orth and Destouni 2018). Therefore, vegetation functioning cannot be sustained and

affects agriculture and food security. This is supported by depleting soil moisture and increasing VPD, which leads to a decline of ecosystem gross primary production, as mentioned in the introduction (Liu et al. 2020). The increased radiation is not able to counteract negative evapotranspiration effects in water limited regions (Orth and Destouni 2018), but is possible in energy limited regions. In contrast, energy limited regions have a surplus of evapotranspiration based on radiation and VPD benefits as well as water accessibility. In energy limited regions are droughts intensified by such conditions. Detected changes of higher radiation, higher VPD and lower soil moisture lead individually to a limiting of ecosystem productivity (Liu et al. 2020). Considering food security during soil moisture drought development, a higher impact in water limited regions is recognisable, whereas energy limited regions benefit from the prevailing hydro-meteorological conditions. During the drought recovery, evapotranspiration is not coupled to another variable and recovers immediately.

Runoff has an overall negative anomaly, increasing from energy limited to water limited regions. The greatest water stress can be found in weakly energy limited regions. These regions will need a greater adaptation of water availability than elsewhere. The situation of water availability in water limited regions will not worsen, mainly because they have already no water left to lose. During the development is runoff coupled with precipitation and during the recovery with soil moisture. This indicates that missing precipitation leads to a runoff decline but increase precipitation does not lead to a fast recovery. Here, soil moisture has to recover first, which takes several months. The sensitivity of vegetation production to water availability is an additional effect on agriculture (Padrón et al. 2020). As the water availability is declining everywhere throughout the drought period and is also recovering very slowly, which further challenges humanity.

Runoff has a higher long-term impact in energy limited regions due to the slow recovery than evapotranspiration. Water security will suffer for at least 3 months after the drought peak, a specific time of recovery cannot be determined based on this study. This leads to the conclusion, that water security is more vulnerable than food security. However, food security will also suffer from missing water in a longer term. The imbalance of depleted precipitation and changes in evapotranspiration and runoff will lead to a change in water storage (Orth and Destouni 2018). Due to the slow recovery of runoff, especially energy limited regions need to adapt to the lack of water before or in the beginning of the drought (Orth and Destouni 2018).

As the results of tree-grass ratio and LAI are similar to one another, the impact of vegetation on evapotranspiration and runoff is presented by two independent variables. The

overall pattern of vegetation highlights the results of evapotranspiration and runoff changes during the drought peak. Based on the results, changes in evapotranspiration and runoff can not only be explained by missing water, but also by root depth, incoming radiation and the linkage between evapotranspiration and runoff. Vegetation impacts can be explained by different fractions of trees and grass by a broad definition, which lead to increased or reduced evapotranspiration, although more comprehensive plant functional types could further differentiate the drought impacts. Vegetation is not affecting runoff, but it shows the interlinkage of increased evapotranspiration and decreased runoff. Long-time changes in soil moisture can lead to changes in vegetation and its cover, which further leads to shifts in drought impacts (Seneviratne et al. 2010).

Soil moisture-based droughts are captured similarly to observation-based droughts. The occurrence is globally comparable throughout the different offline models, but a wrong representation of ELI in offline models is detected. Moreover, water limited regions are overestimated. This is supported by consideration of the individual correlations. With a realistic model, changes in the future can be considered. Yet, changes in soil moisture are unpredictable and highly uncertain (Vogel et al. 2018). The improvement of models has been and has to be a high priority research topic, to improve future changes in climate and to give appropriate predictions (Koster et al. 2017).

The attempts to compare evapotranspiration and runoff changes during soil moisture droughts from observations and models account for the complexity between soil-vegetation-atmosphere interactions. This is both more difficult and more challenging than assuming simplistic response patterns but, ultimately, more interesting and closer to the multifarious reality seen in real ecosystems.



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## **Statement of Authorship**

I declare that I have prepared this thesis independently and only using the aids and sources indicated. Direct and indirect quotations are marked as such. The submitted work has not been used elsewhere as an examination paper or published in English or another language as a publication.

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