



## Accelerated Hydrological Wet-to-Dry Transitions and Their Driving Mechanisms over Africa

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**Abstract.** Abrupt wet-to-dry (W2D) events represent a damaging natural disaster, exerting more far-reaching impacts on the environment and society than single extreme events. While sub-seasonal and interannual precipitation whiplash have recently been analysed, hydrological W2D transitions, especially at smaller time scales such as sub-monthly, have yet to be examined. In this study, we quantify changes in the characteristics of hydrological W2D transitions based on soil moisture in Africa and identify the drivers behind these changes. The results show that the total W2D transition has accelerated markedly: transition speed increased by 19% and duration shortened by 10% from 1981 to 2024. The area averaged proportion of rapid W2D events to total W2D events has increased from 52% during 1981-2000 to 58% during 2001-2024. The spatial extent of rapid W2D transitions has increased significantly. On average, 13% of the continent has experienced rapid W2D transition in the 1980s, increasing to 17% after 2010. These findings suggest a general shift from slow to rapid hydrological W2D transitions on a sub-monthly timescale. We further find that the speeding up of W2D transition onset is driven by greater precipitation deficits, higher temperature, and higher evaporative demand during the transition onset period. Overall, the shift from slow to rapid W2D transitions reduces the predictability of hydrological volatility regimes, which has adverse impacts on agriculture, ecological stability, and water resources management.

**Key words:** Soil Moisture, Occurrence Frequency, Transition Duration, Rapid W2D Transitions, Onset Speed



## 30 1. Introduction

Climate change accelerates hydroclimate swings between two opposing extreme weather conditions (Francis et al., 2023). A rapid change from drought to floods or from extreme heatwave to abundant wetness and flood is described as weather whiplash (Alotaibi, 2023; Chen et al., 2022; Mishra et al., 2021). The water cycle is becoming increasingly imbalanced given that hydro-climate whiplash occurs  
35 more frequently and more severely (Tabari, 2020; Ficklin et al., 2022). Anthropogenic activities have naturally complicated the hydrological cycle and consequent precipitation variability (Afuecheta and Omar, 2021; Marra et al., 2025). The hydrological cycle response to global warming has accelerated extreme events' volatility (Touma et al., 2021; Ullah et al., 2024). The growing threat of hydroclimate whiplash is increasing globally (Chen et al., 2022), and it has considerable impacts on society, water  
40 resources development, agriculture, and infrastructure systems (Madakumbura et al., 2019; Na and Najafi, 2024). These rapid transitions have been intensifying under a changing climate, negatively impacting ecosystem services (Johnston et al., 2021; Wang et al., 2023; Weiskopf et al., 2020).

Precipitation whiplash, described as abrupt shifts from intense and frequent wet-to-dry (W2D) events and vice versa, has been analyzed at a global level (Tan et al., 2023). Conversely, seasonal abrupt  
45 atmospheric volatility shifts in unusual hydroclimate extreme events have been studied in North America and Europe on a regional basis (Francis et al., 2023; Loecke et al., 2017). Diverse investigators set different definitions to characterize the W2D transitions globally (Casson et al., 2019; De Luca et al., 2020; Fu et al., 2025). The long-term precipitation anomalies of the 90th and 10th percentiles, representing precipitation event threshold values for extreme wet and dry conditions, respectively, were  
50 used to define W2D or D2W transitions (Tan et al., 2023). A transition from the occurrence of the wet ( $\geq 80^{\text{th}}$ ) to the dry ( $\leq 20^{\text{th}}$ ) threshold percentile values of the events or vice versa was used to define W2D or D2W transitions (Chen et al., 2022; Swain et al., 2018). Conversely, numerous scholars have used drought indices like the standardized precipitation index (SPI) (Ford et al., 2021; Na and Najafi, 2024), the standardized precipitation evapotranspiration index (SPEI) (Ansari and Grossi, 2022; Swain et al.,  
55 2025), and the monthly self-calibrated Palmer Drought Severity Index (De Luca et al., 2020) to characterize hydroclimate whiplashes at seasonal and sub-seasonal time scales. However, hydrological W2D transitions, especially at smaller timescales such as sub-monthly periods, have yet to be thoroughly



studied. Most studies conducted in Africa on extreme hydroclimate events have focused on single extreme events (Ayugi et al., 2022; Gebrechorkos et al., 2023; Mahlalela et al., 2020), overlooking the rapid swings from wet-to-dry transitions and their characteristics. Extreme rainfall is intensifying in Africa (Kendon et al., 2019), especially in regions like East Africa and the Sahel (Dosio et al., 2021; Han et al., 2019), while drought extremes are further projected to develop more frequent and lengthy in western, eastern, and southern Africa on account of changing climate (Teshome et al., 2022).

Understanding the mechanisms of hydrological wet-to-dry (W2D) transitions is essential, as these rapid swings surpass hydroclimatic anomalies and impact economies, ecosystems, and human welfare across generations (Cheng et al., 2023; Swain et al., 2025). Numerous mechanisms may facilitate the occurrence of hydrological W2D transitions, including increased precipitation deficits, evaporative demand, and land–atmosphere feedbacks via soil moisture and vegetation (Chen et al., 2022; Chen et al., 2020a). However, the mechanisms that intensify the occurrence of rapid hydrological W2D transitions remain poorly understood. This knowledge gap restricts our ability to predict when and where rapid hydrological W2D transitions will occur and to detect the vulnerable regions. The environmental effects of W2D transitions relates to terrestrial hydrological processes in addition to precipitation (Madrigal et al., 2024; Götte and Brunner, 2024). Therefore, a reliable and comprehensive study of the hydrological W2D transition that considers both precipitation and terrestrial hydrological indices is crucial.

The key objective of this study is to quantify changes in the spatiotemporal characteristics of hydrological wet-to-dry (W2D) transitions using root-zone soil moisture data up to one meter (1 m) at both grid and continental levels. This study employed soil moisture to identify transition events and categorized them as rapid or slow based on the onset speed of the transition (Yuan et al., 2023). In addition to investigating the spatiotemporal dynamics of hydrological W2D transitions, this study also intends to identify the drivers behind these changes in Africa.

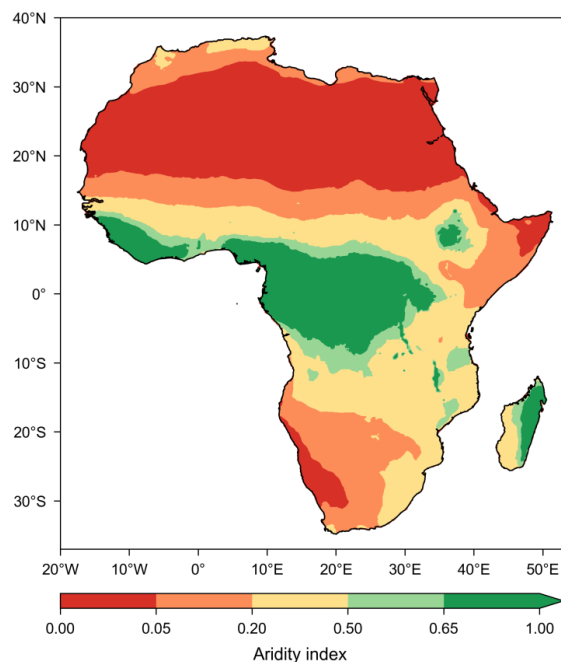
## 2. Data and Methods

### 2.1. Description of Study Area

With an overall area coverage of around 30.2 million km<sup>2</sup>, Africa is the second-largest continent in the world (Kaba, 2024). It comprises a varied range of climates, including deserts like the Sahara; tropical



85 rainforests; highlands like the Ethiopian Highlands; and major river basins such as the Niger, Congo,  
Nile, and others. Africa shows significant variations in precipitation patterns (Wmo, 2024): North Africa  
experiences a hot, extended dry period with little or no precipitation (Fig. 1), whereas the transitional  
zone Sahel region receives precipitation ranging from 100 mm in its northern part to 700 mm in its  
southern part each year (Adigun et al., 2024). Heavy precipitation is typically observed in West and  
90 Central Africa (Komelo et al., 2024), while in East Africa, rainfall patterns are seasonal; El Niño-related  
rainfall creates flooding and landslides (Demissie et al., 2025; Li et al., 2025; Mologni et al., 2024).  
Periodic convective summer storms and tropical cyclones dominate the rainfall season in Southern Africa.  
Less than 10% of cultivated land is under irrigation, and rain feeds 90–95% of agricultural output.



95 **Figure 1. The spatial distribution of the aridity index (AI) across Africa. AI is computed as the fraction of average annual precipitation to the average annual potential evapotranspiration.**



## 2.2. Data Sources

Daily historical data, including top-1 m soil moisture, temperature, and potential evapotranspiration aggregated from ERA5-Land hourly data, were used to quantify wet-to-dry (W2D) transition characteristics. For comparison purposes, daily soil moisture data from the ERA5 reanalysis were also used. ERA5-land and ERA5 are the fifth-generation global land and atmospheric reanalyses, respectively produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020; Muñoz-Sabater et al., 2021). The ERA5-land and ERA5 reanalysis data can serve as reliable alternatives to ground-based observations in Africa, specifically in areas like Africa where there is a limitation of observational data (Bodjrenou et al., 2024; Gbode et al., 2023). In addition, precipitation data from the CHIRPS v.2 dataset, which well represents precipitation patterns in Africa (Mekonnen et al., 2023), was used to identify the drivers that contribute to change in W2D transitions. The data were regridded to a  $0.1^\circ$  spatial resolution employing bilinear interpolation. Lastly, the study period from 1981 to 2024 was selected based on the availability of the CHIRPS dataset, which begins in 1981.

## 2.3. Methods

### 2.3.1. Identification of Wet to Dry Transitions

In this study, soil moisture, which is the most commonly used indicator of agricultural drought, was used to identify and analyze the spatiotemporal characteristics of W2D transitions at the sub-monthly timescale. It allows for utilization of many climate variables impacts to characterize the events transitions in relations of space and time, serving as a useful metric to identify rapid W2D transitions in terms of hydrological and agricultural viewpoints. Generally, flash drought's definition was initially designed based on soil moisture to describe the development of flash and slow droughts (Yuan et al., 2023).

We averaged daily soil moisture data of both reanalyses to create pentad means (five-day averages) and changed them into percentiles per grid based on the climate for each calendar pentad from 1981 to 2024. The transition of W2D was then identified and characterized based on the framework designed by Yuan et al. (2023), which was established for the identification of flash and slow droughts. The below listed are the criteria for identifying and characterizing a wet-to-dry transition event:

1. The soil moisture content depletion in percentile decreases from above the 75th percentile (wet)



- to below the 25th percentile (dry).
- 125      2. To ensure that the dry event is persistent and not just random variation, we consider a minimum length of 4 pentads (20 days) after the dry period starts (when soil moisture is depleted below the 25th percentile).

All criteria are adopted from Yuan et al. (2023), which was designed for the identification of flash and slow drought events, except the first criterion used to characterize the transitions starting with wet  
130 conditions. All percentiles were obtained from the time-series of soil moisture data at the grid level. Employing these criteria, only impactful and persistent events are identified as hydrological W2D transition events. These criteria make it possible to identify sub-monthly timescale transitions, which differ from hydroclimate indices like precipitation percentiles (Chen et al., 2022; Swain et al., 2018) and drought indices (SPI, SPEI, etc.) (Chen and Wang, 2022; Chen et al., 2020b; Li et al., 2024).

### 135      2.3.2. Characteristics of W2D Transitions Events

The key characteristics and metrics of a W2D transition event are listed and described in Table 1. The historical spatiotemporal characteristic indicators were computed for the 1981–2024 period. Occurrence frequency is the number of W2D shifts that happened within the specified timeframe. Transition duration is the period of time span, in days, between the termination of wet events and the start of individual dry-  
140 spell pentads. Transition onset speed is described as the difference in percentiles between the values recorded on the extreme wet-end pentad and the first dry-start pentad per the total number of pentads during a transition. Additionally, spatial transition metrics, such as spatial fraction, were calculated to assess variations in transition area coverage over time (Table 1). Finally, trends were calculated employing Sen’s slope estimator, and the Mann–Kendall non-parametric test was utilized to evaluate  
145 statistical significance, with p-values derived using Kendall’s  $\tau$ , as in SciPy.

Table 1. Spatiotemporal characteristics of W2D transitions

Characteristics	Description	Unit/range
Occurrence frequency	Number of transitions in a given period (W2D events).	Times yr <sup>-1</sup>



Transition duration	The time (in days) between the last pentad of wet and the first pentad of dry start.	Days
Transition onset speed	The rate of soil moisture percentile difference between the wet ends and the dry start pentad per unit pentad (% change per pentad during a transition event).	%/pentad
Rapid W2D ratio	This is the ratio of a rapid W2D transition frequency to the total W2D transition frequency.	%
Slow W2D ratio	This is the ratio of a slow W2D transition frequency to the total W2D transition frequency.	%
Spatial fraction (area coverage)	The ratio of the total number of grids exposed to the transition of W2D events divided by the total number of grids in the study area.	0 - 1

### 2.3.3. Rapid and Slow W2D Transition Events

After identifying W2D transition events employing the set key criterion, each event was categorized as a rapid or slow W2D event based on the onset speed of the transition. A rapid W2D transition is a rapid onset (i.e., steeper decline in soil moisture) with an average soil moisture depletion rate of at least 5% per pentad from the wet-end pentad to the dry-start pentad. For instance, the occurrence of rapid and slow W2D transitions in 1983 and 2015 are displayed in Figs. A1a and b, respectively. Slow W2D transitions have a gradual onset (slower decline), with the speed of onset less than 5% per pentad. Regions with an aridity index of less than 0.05 were excluded from the W2D identification analysis because the soil moisture is extremely low and varies minimally. Additionally, the W2D events have minimal agricultural and ecological implications in these regions (Fig. 1).

### 2.3.4. Sensitivity Test

The chosen criteria (75<sup>th</sup>, 25<sup>th</sup>, and 5%/pentad) are arbitrary; they show one way to define wet, dry, and rapid onset speed. Different values may change the number and type of W2D events detected. To determine the trends dependent on the thresholds, we apply the sensitivity analysis approach by running the framework with different combinations of thresholds: Wet thresholds: 80<sup>th</sup>, 85<sup>th</sup>, and 90<sup>th</sup> percentiles;



dry thresholds: 20<sup>th</sup> and 25<sup>th</sup> percentiles; and onset speed: 5, 8, and 10 percentile points/pentad. Finally, we compare the trends of the rapid ratio and onset speed of W2D transitions.

### 2.3.5. Physical Mechanisms for Changes in W2D Transitions

165 To identify the drivers that contribute to change in W2D transitions, we calculate an event's average anomalies of precipitation (P), potential evapotranspiration (PET), and temperature over its specific duration (from the wet end to the dry start) onset stage (Eq. 1).

$$A_i = X_i - X_{\text{mean}}, \quad \text{Eq. (1)}$$

170 Where;  $A_i$  is the pentad anomaly value,  $X_i$  is the pentad mean value, and  $X_{\text{mean}}$  is the pentad climatological mean for that location.

Then, average anomalies over all rapid and slow W2D events were computed to obtain composite P, PET, and temperature anomalies at each grid level. Finally, the composite P, PET, and temperature anomalies difference was computed for the onset stages between rapid and slow W2D transitions separately at the grid level.

## 175 3. Results

### 3.1. Change in W2D Transitions Characteristics

180 The ERA5-Land and ERA5 datasets showed a similar spatial distribution of W2D transition frequency (times yr<sup>-1</sup>) with mean frequencies of 0.32 and 0.36 times yr<sup>-1</sup>, respectively. For Africa, ERA5-Land shows similar interannual variability ( $\pm 0.06$  times yr<sup>-1</sup>) compared to ERA5 ( $\pm 0.05$  times yr<sup>-1</sup>). Both datasets indicated a similar area with high W2D frequency. The coefficient of variation (CV) of the two reanalyses is low over most semi-humid and humid regions but high over semi-arid and arid regions, with an area average of 27.2% for the occurrence frequency of W2D, so there is strong agreement between datasets except in the Sahel regions and some parts of South Africa (Fig. B1). Because the difference between the ERA5-Land and ERA5 datasets is minimal, only the results using the ERA5-Land dataset are shown hereafter.



The spatiotemporal patterns of the changes in the onset speed and transition duration of total W2D transitions showed increasing and decreasing trends, respectively, from 1981 to 2024 (Fig. 2). Based on the results of Sen's slope estimator and the Mann–Kendall test, spatially, the onset speed of W2D events exhibited an increasing trend across large parts of Africa over the period 1981–2024 (Fig. 2a), with increases of up to 1.3%/pentad per year. In contrast, the transition duration of total W2D events showed a decreasing trend during the same period (Fig. 2b), with reductions of up to 14 days per year.

Temporally, the speed of total and rapid transition onset from wet to dry increased significantly ( $p < 0.01$ ) by 19% and 22% from 1981 to 2024, respectively (Fig. 2c). The mean annual duration of both total and rapid W2D transition events showed statistically significant decreasing trends from 1981 to 2024, with a reduction of 10% and 21%, respectively averaged across the continent (Fig. 2c). Moreover, in the most recent period (2020–2024), the average rapid transition duration decreased by 12% compared with the mean for 1981–2019. Rapid W2D transitions revealed significant increasing trends in area coverage from 1981 to 2024. On average, 13% of the continent experienced a rapid W2D transition in the 1980s, rising to 17% after 2010 over Africa (Fig. 2c). The areas affected by rapid W2D transitions increased to an average of 22% of the continent in the recent five years (2020–2024) (Fig. 2c).

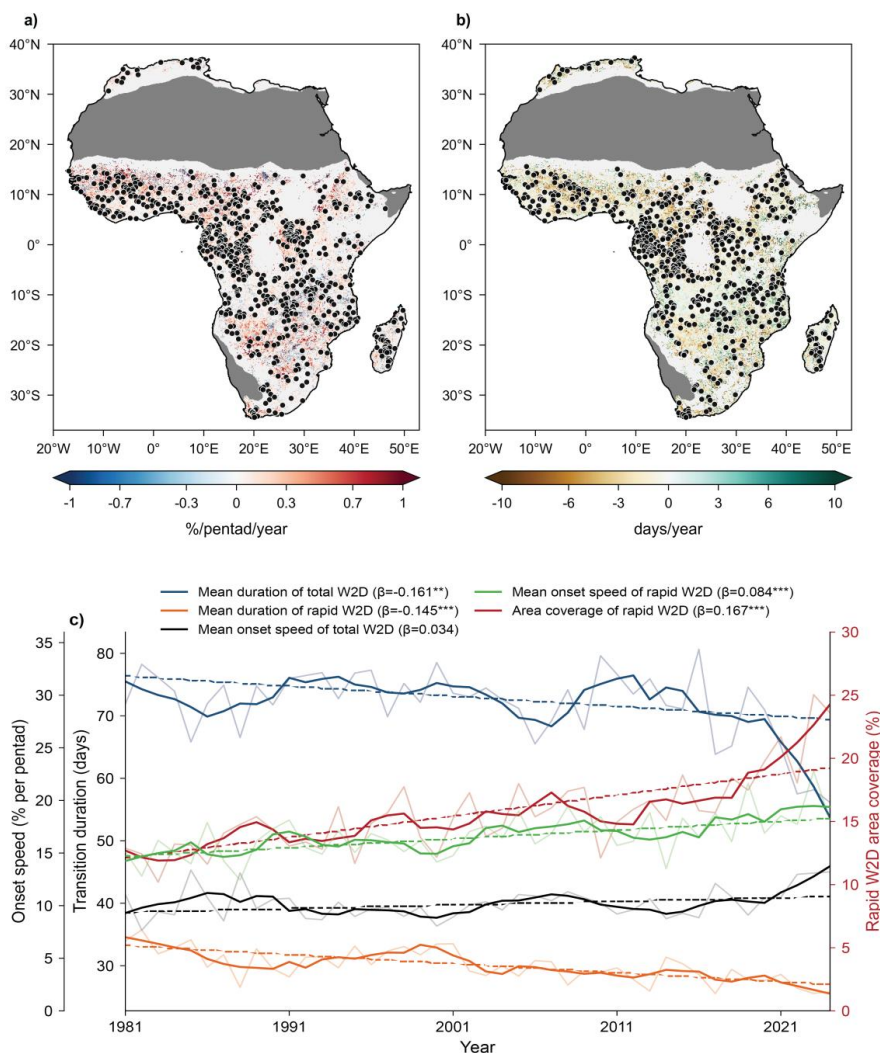


Figure 2. Spatial and temporal distribution of the trends in onset speed, transition duration, and area coverage from 1981 to 2024 using the ERA5-land dataset: a) trend magnitude of onset speed of the total W2D transitions (%/pentad/year); b) trend magnitude of transition duration of the total W2D transitions (days/year); and c) temporal time series of W2D transition metrics with Sen slope analyses and smoothed trends of yearly mean durations of total and rapid W2D transitions, mean onset speed of total and rapid W2D transition events, and yearly spatial area coverage of rapid W2D transition events from 1981 to 2024 over Africa. Significant trends ( $P < 0.1$ ) are marked with solid black circles. The grey shaded area is masked out based on the aridity index being less than 0.05, and Sen slope estimates derived from the Mann-Kendall trend

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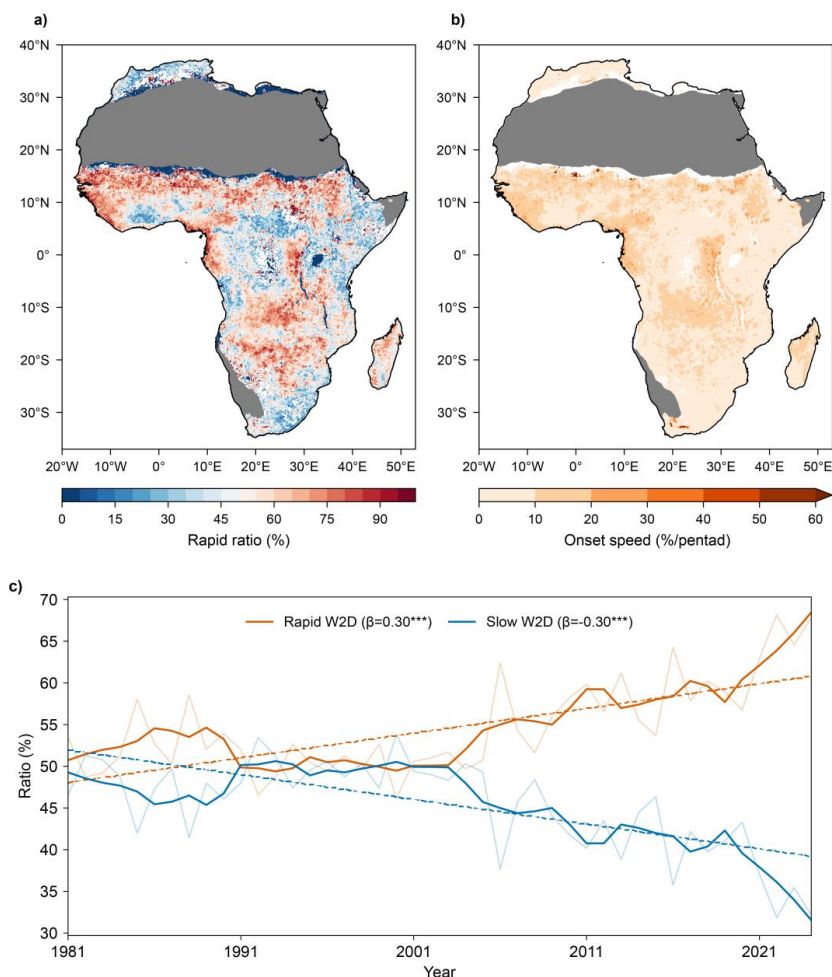


210 test are represented by dashed lines with significance in panel c. "\*\*\*\*" shows a p-value < 0.001, and "\*\*\*"  
shows a p-value < 0.01.

### 3.2. Changes in Rapid and Slow W2D Transitions

The occurrence frequency of rapid W2D transition events shows spatial variability across Africa, ranging  
from 0 to 1.31 times per year, while the slow W2D transition frequency varies from 0 to 0.73 times per  
215 year (Figs. C1a and b). The transition duration of a rapid W2D event typically ranges from 5 to 63 days,  
with an area-averaged mean of 32.2 days (Fig. C2a). Generally, rapid W2D events occur in a shorter  
duration, whereas total W2D events show a wider spread covering a lengthy duration (Fig. C2c). Rapid  
W2D events tend to occur more frequently than slow W2D events across much of the continent (Fig. 3).  
Conversely, the slow W2D ratio shows higher spatial variability, with low percentages across most grid  
220 cells.

The rapid W2D transition ratio occurs at a higher rate than slow transitions across many grids in the  
eastern, western, and southern parts of Africa (Fig. 3a). Regionally, the Sahel regions, a semi-arid zone,  
exhibit a high rapid W2D transition ratio (Fig. 3a), reflecting the existence of tough climate variability.  
In comparison, western Africa is exposed to a high frequency of rapid W2D transitions associated with  
225 high climate variability. Generally, the sharpest W2D transitions occur in semi-arid transitional zones  
like the Sahel region (Fig. 3b), where rainfall is brief and intense, and soil moisture depletes quickly.  
North Africa has uniformly low frequencies as a result of its extensive desert environment and very low  
rainfall intensity. Overall, desert regions are mostly excluded (Fig. 2), as W2D transitions are rare due to  
limited soil moisture and precipitation. In general, the observed rapid W2D transition metrics exhibit  
230 spatially diverse characteristics across Africa (Fig. 3).



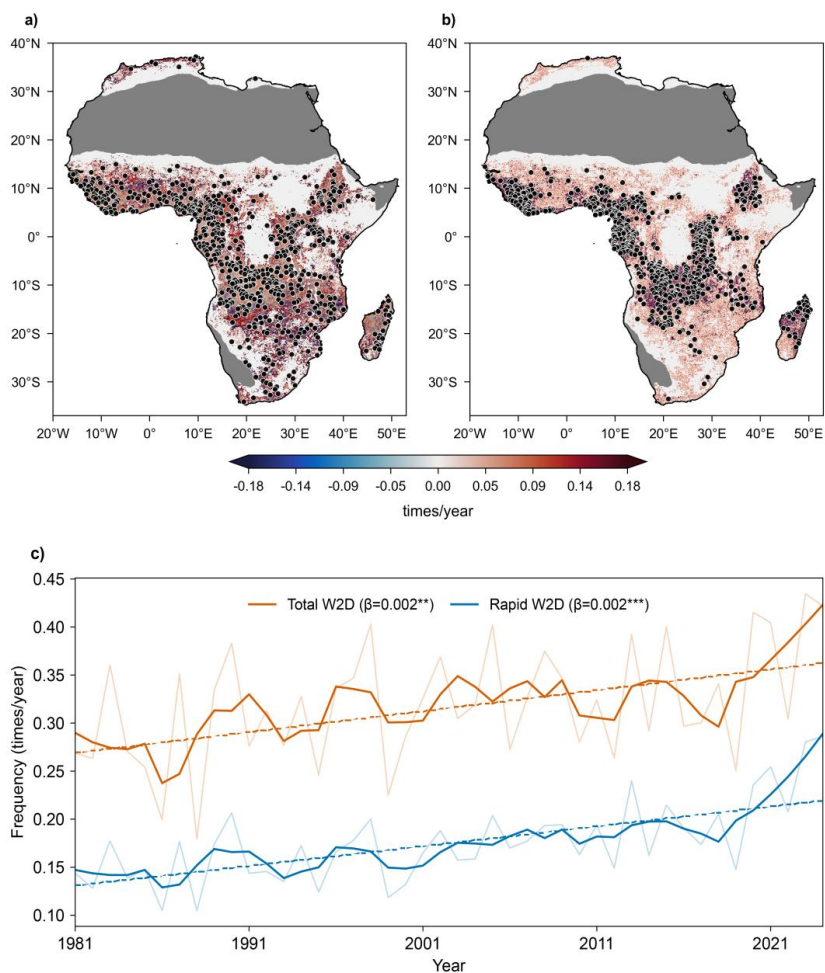
235 **Figure 3.** Spatial and temporal distribution of the rapid W2D ratio and onset speed characteristics from 1981 to 2024 using the ERA5-land dataset: a) rapid W2D ratio, b) onset speed of the total W2D transitions (%/pentad), and c) the annual mean of the rapid and slow W2D transition events smoothed trends ratio in percentage in relation to the total detected number of observed W2D events. The grey shaded area is masked out based on the aridity index being less than 0.05, and Sen slope estimates derived from the Mann–Kendall trend test are represented by dashed lines, with significance in panel c. \*\*\* indicates a p-value < 0.001.

To determine whether the continent-level trends are sensitive to the definition of wet-to-dry transitions, we varied the thresholds for soil moisture percentiles for wet-ending and dry-starting points, as well as



240 the rate at which transitions occur (onset speed, %/pentad). We observed that the area-averaged  
increasing trends of the rapid ratio and onset speed remain significant ( $P < 0.05$ ) (Fig. C3). The area-  
averaged frequency of rapid W2D ratio events, expressed as a percentage, showed a statistically  
significant increase at the continent level and covers, on average, 55% of total events per year (Fig. 3c).  
The area averaged proportion of rapid to total W2D events has increased from 52% during 1981-2000 to  
245 58% during 2001-2024. Generally, the rapid-event ratio has increased by 12.9 percentage points from  
1981 to 2024; conversely, the slow-event ratio has decreased by 12.9 percentage points, corresponding  
to trends of  $\pm 3.0$  % per decade (Figure. 3c). Overall, the findings indicate that onset speed increases  
alongside a higher rapid ratio, confirming a stable trend in the shift from slow to rapid W2D transitions  
(Fig. 3c).

250 Africa has experienced statistically significant increases in the frequency of total and rapid W2D  
transitions at the grid level (Fig. 4). Spatially variable significant increasing trends of the total and rapid  
W2D transition frequency were observed in different sub-regions in Africa (Fig. 4). Regionally, the  
increase in W2D transition changes is most prominent over West Africa, the Eastern African Highlands,  
and eastern South Africa (Fig. 4a). The mean annual frequency of both total and rapid W2D transition  
255 events showed statistically significant increasing trends from 1981 to 2024, with an increment of 29%  
and 43%, respectively, averaged across the continent (Fig. 4c). Generally, the growing trends in rapid  
W2D transition frequency, with higher onset speed, are mostly linked to large precipitation variability  
and increases in temperature and evapotranspiration demand (Fig. 5). The seasonal spatial distribution  
of W2D transitions exhibits diversified characteristics, with the highest percentage of occurrences in  
260 spring (Fig. D1a–d). Seasonally, a statistically significant growing trend in the frequency of W2D  
transitions has been detected in spring, summer, and autumn across Africa, but not in winter (Fig. D1e–  
h). These increases may be attributed to the spatial variability of precipitation, evaporative demand, and  
temperature changes patterns over the continent (Fig. 5).



265 **Figure 4.** Historical spatial and temporal trends in the magnitude of occurrence frequency of the total and  
 270 **rapid W2D transition events at the grid level across Africa from 1981 to 2024. a)** Trend in magnitude (times  
 yr<sup>-1</sup>) of the total frequency of W2D events; **b)** trend in magnitude (times yr<sup>-1</sup>) of the rapid frequency of W2D  
 events, mostly sub-monthly W2D transitions; and **c)** temporal time series of total and rapid W2D transition  
 frequency with smoothed trends of yearly mean in times/year across Africa. The trend maps excluded desert  
 areas with an aridity index of less than 0.05, indicated by grey shading, and significant trends ( $P < 0.1$ ) are  
 marked with solid black circles. Dashed lines represent Sen slope estimates derived from the Mann–Kendall  
 trend test with significance in panel c; \*\*\* indicates a p-value  $< 0.001$  and \*\* indicates a p-value  $< 0.01$ .

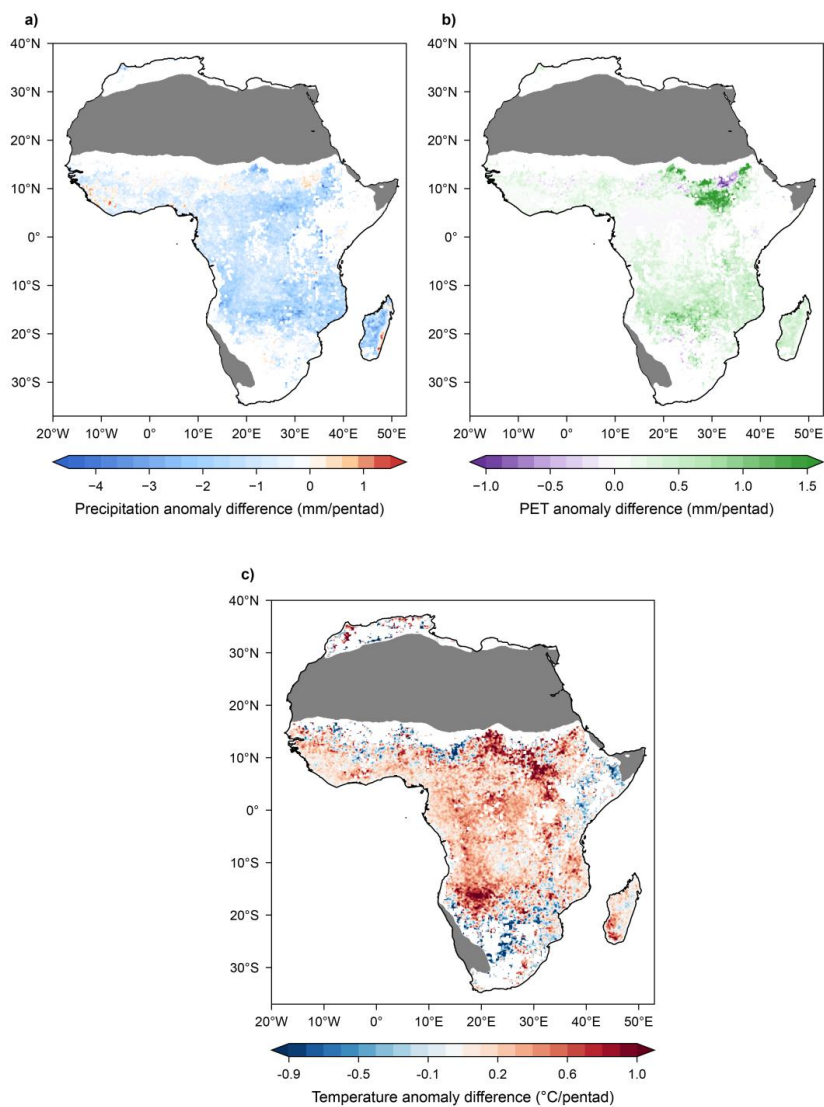


### 3.3. Mechanisms for Changes in W2D Transitions

The average deviations in precipitation, PET, and temperature anomalies from the climatological mean  
275 during the rapid transition of soil moisture from wet to dry, were compared to slow transitions (Fig. 5).

The onset stage of rapid W2D transitions across the continent is characterized by greater precipitation  
deficits than those of slow transitions (Fig. 5a). Apart from the lack of precipitation, the increase in  
potential evapotranspiration and temperature (Fig. 5b, c) accelerates the loss of soil moisture, increasing  
the risk of rapid W2D transitions over humid and semi-humid areas like the west, central, and eastern  
280 African highlands. These regions are characterized by energy-limited evapotranspiration, and the higher  
radiation drives the rise in evapotranspiration and accelerates the rapid dry onset. Over areas, for  
instance, the eastern, northern, and southern regions of Africa, evapotranspiration is water-limited, and  
the decrease in atmospheric evaporative demand during the onset stage suggests that precipitation  
deficit is the main driver of rapid W2D transitions (Fig. 5).

285 The main driver for the occurrence of rapid W2D transition events varies spatially across the continent;  
for example, associated with precipitation deficits, the regions in Africa, such as the highlands of East  
Africa, West Africa, Central Africa, and southeastern parts of the continent, showed a higher rate of  
negative precipitation anomalies. Additionally, most areas of the continent affected by rapid W2D  
transitions are also associated with a higher rate of positive potential evapotranspiration demand and  
290 temperature anomalies in such events than in slow transitions in the onset stages (Fig. 5).



**Figure 5. Spatial distributions of the differences in the composite anomalies of a) precipitation (P), b) potential evapotranspiration (PET), and c) temperature between the onset stages of rapid and slow W2D transitions. The grey shaded areas indicate the masked-out regions where the aridity index is less than 0.05 (hyper arid).**



295 **4. Discussion**

This study shows spatial and temporal characteristics of W2D transition changes from 1981 to 2024 throughout Africa. A main contribution of these findings is the distinction between slow and rapid transitions in accordance with the speed of soil moisture depletion for transition onset. Our outcomes disclose an overall significant increasing trend in the onset speed and frequency of rapid W2D transitions.

300 The findings also reveal that the rapid transitions occur within a short time span, such as sub-monthly periods. Generally, the results show that the occurrence frequency and transition duration from wet to dry transition events have an increasing and a decreasing trend during the study period, respectively. Therefore, climate variability has accelerated the occurrence of rapid hydrological W2D transitions.

The rapid W2D transition frequencies have revealed a significant increase, largely due to hydrological cycle intensification, which contributes to larger hydroclimate volatility (Chen et al., 2025; Van Der Wiel and Bintanja, 2021). These outcomes were consistent with previous studies about hydroclimate whiplash, which show increasing trends in the W2D or D2W event frequency (Tan et al., 2023; Fu et al., 2025; Li et al., 2024). The hydroclimatic swings are evolving into more frequent and intense, along with increasing trends of frequency and the area coverage of W2D or D2W transitions occurring across North America  
310 under global warming (Na and Najafi, 2024). The short-term climate variability are contributes more to the occurrence of intense and frequent hydroclimate swings in a warming climate (Chen and Wang, 2022). In general, the hydroclimate extreme events such as droughts and flooding in Africa have sizable influences on water resources, agriculture, and ecosystems, and they affect millions of people who rely on rainfall-dependent livelihoods (Taguela et al., 2025; Taguela et al., 2022; Tamoffo et al., 2023).

315 The continent's dynamics and vulnerabilities to hydroclimatic volatility are exacerbated by its geographical position on both sides of the equator, which is further complicated by varying precipitation patterns, challenging topography, diverse climate zones, and a rapidly growing population (Nash et al., 2016; Nciphya et al., 2024). Moreover, precipitation, PET, and temperature variability also increase the likelihood of a whiplash due to rapidly shifting from wet-to-dry events or vice versa. This variability of climatic factors is not just correlated with hydroclimate whiplash; it is the crucial mechanism that  
320 intensifies and accelerates these volatile swings between wet and dry extreme events (Chen and Wang, 2022). Climate change accelerates the variability of hydrological extreme events and, as a consequence,



increases the frequency of intense and frequent hydroclimate whiplash (Stevenson et al., 2022; Tan et al., 2023).

325 The hydrological extreme abrupt swings from wet to dry events or vice versa are attributable to aggravated climate variability and unpredictability (Qamar et al., 2023; Qiu et al., 2021). The variability of precipitation, which is more intensified by vertical moisture advection resulting from variations in atmospheric circulation and atmospheric moisture, has accelerated the abrupt shifts in the climate system, contributing to the occurrence of intense and frequent extreme events and transition variations (Chen et al., 2025; Zhang, 2021). Unusual dry events could reduce the length of wet periods in such systems by ending wet events more rapidly; in similar ways, shifts in atmospheric evaporative demand could accelerate transitions by causing soil water content variability (Christian et al., 2021).

Precipitation and atmospheric evaporative demand variability increases are linked to greater frequency or abrupt shifts during W2D transition periods in the changing climate context. Additionally, heightened 335 PET demand induces soil water transport from terrestrial regions to the environment, resulting in rapid wet-to-dry transitions (Pendergrass et al., 2017; Qiu et al., 2021). High precipitation volatility enhances the impact of hydrological extremes, particularly floods and droughts, and creates an extremely non-uniform precipitation distribution (Sloat et al., 2018; Zhang, 2021). Therefore, climate volatility is a major driver of extreme hydroclimate whiplash events. Aligned with these findings, the previous findings 340 showed that the increasing trends of precipitation and atmospheric demand variability considerably contributed to decreasing trends in the transition duration from wet to dry or dry to wet events across global regions (Chen and Wang, 2022). These rapid swings can challenge water resource development and management, agriculture, and early warning preparedness, since such rapid transitions reduce the predictability of hydroclimate regimes.

345 The varied spatial distribution of the frequency of W2D transition events, suggesting diversified onset time and variability of lengthy dry seasons, emerges from the broad-scale circulation of the atmosphere (Byrne et al., 2018). Hence, these findings are essential for understanding Africa's hydro-climate variability and have implications for monitoring the development of drought, water resource management, and agricultural planning throughout the continent during extreme event volatility.

350 Generally, the results show that seasonal climate variability contributes to substantial effects on the



increasing trends of occurrence frequency and decreasing trends of rapid transition duration in Africa. Hence, the varied W2D transitions' regional patterns experience considerable challenges in assuring reliable water availability and demanding water management strategies (Madakumbura et al., 2019; Madrigal et al., 2024; Na and Najafi, 2024).

355 The study used root zone soil moisture data from reanalysis datasets to identify and characterize the W2D transition events due to observed data limitations in Africa. The characteristics of W2D transitions may differ depending on the soil moisture dataset used. Additionally, we examined transitions from wet-to-dry events using pentad-based soil moisture percentiles; however, other hydroclimate indices may influence the observed trends, and potentially leading to different conclusions about the frequency and  
360 duration of these swings. Nevertheless, our results were well aligned with numerous findings reporting the increasing and decreasing trends of W2D or D2W occurrence frequency and transition duration, respectively, using precipitation percentiles (Swain et al., 2018; Tan et al., 2023); drought indices, for instance, the standardized precipitation evapotranspiration index (SPEI) (Chen and Wang, 2022; Swain et al., 2025); and the standardized precipitation index (SPI) (Ford et al., 2021).

## 365 5. Conclusions

This study examines the historical spatiotemporal characteristics and patterns in hydrological wet to dry transitions at the continental scale using over four decades of 1 meter root zone soil moisture data from a reanalysis dataset. We also subdivide the transitions into rapid and slow W2D transitions according to the onset depletion speed of soil moisture during W2D transitions and analyze their driving mechanisms.

370 Therefore, this study is vital for improving our understanding of rapid W2D transition trends and mechanisms for formulating strategies for risk mitigation.

W2D transition events in Africa exhibit spatially and temporally diverse patterns. The ratio of rapid W2D events to total W2D events has increased significantly from 1981 to 2024, along with a statistically significant upward trend in the yearly average area coverage across Africa. The duration of rapid W2D  
375 transition revealed significant decreasing trends, with significant increasing trends of onset speed driven by significant precipitation deficits and increases in temperature and evapotranspiration demand. Mostly, precipitation deficits, rising temperatures, and high evaporative demand lead to the speeding up of slow-



to-rapid W2D transitions. These results may enable a more widespread thoughtful of the spatiotemporal features of rapid hydrological W2D transition events, as well as the driving factors behind their intensification. Furthermore, we recommend a comprehensive study of hydroclimate volatility, integrated with action-based solutions to minimize losses intensified by rapid W2D transitions.

### Appendix A: Definition of Rapid and Slow W2D Transition Events

This appendix offers examples of rapid and slow W2D transitions at the grid level (latitude: 0.0°N, longitude: 35.8°E) as shown in Fig. A1. The difference between rapid and slow W2D events is the onset speed, where the rapid W2D transition has an average decline rate of no less than 5% per pentad during the onset stage.

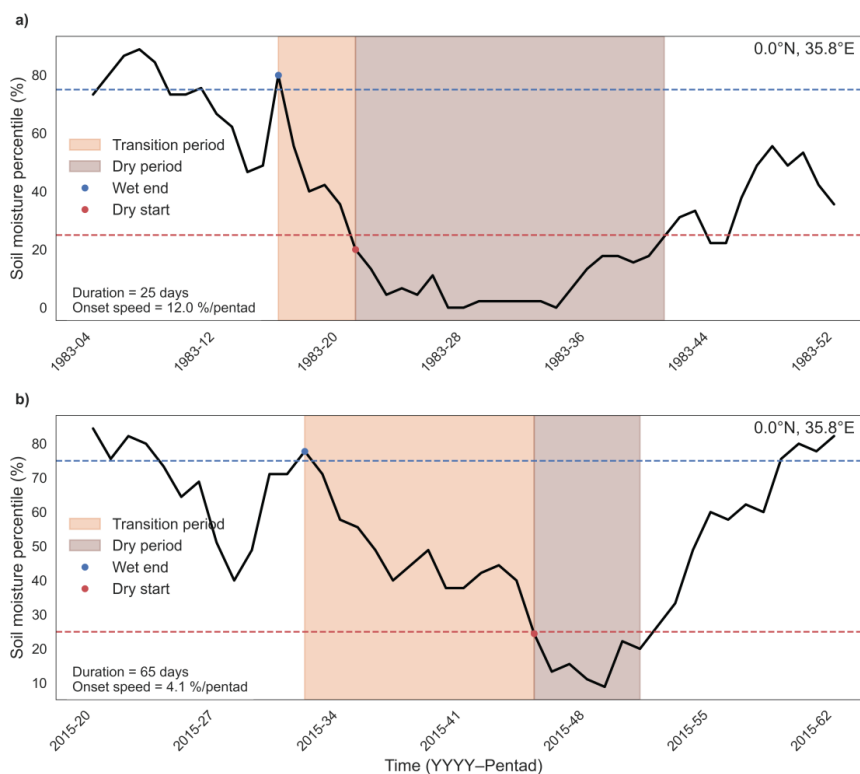


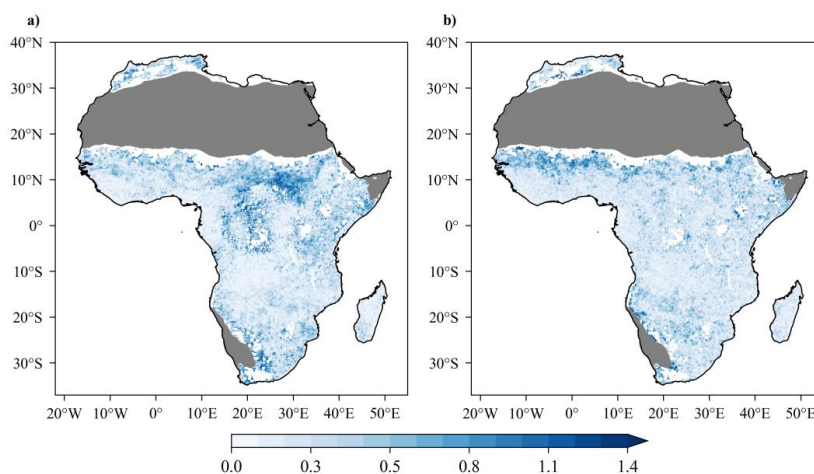
Figure A1. Illustrates the definition of rapid and slow W2D transition events. a) Rapid W2D transition and b) slow W2D transition. The broken blue line indicates the wet threshold, while the broken red line indicates the dry threshold. The blue dot indicates the last wet pentad, the orange color indicates the



transition period, the red dot indicates the first period when dry starts, and the grey color indicates the dry period when soil moisture drops below the dry threshold for at least four pentads.

### Appendix B: Comparison of Gridded Soil Moisture Datasets

The gridded datasets such as ERA5-Land and ERA5 reanalysis products were used in this study, which differ in resolution (9 km in ERA5-Land and 31 km in ERA5) and assimilation (ERA5-Land runs the land surface model separately, while ERA5 employs a fully coupled data assimilation system (satellite and in situ data)) but share atmospheric forcing. This appendix displays the spatial distribution of coefficient of variation (CV) values obtained for both the occurrence frequency and onset speed of W2D events between gridded soil moisture products (i.e., ERA5-Land and ERA5) at each grid level.



400

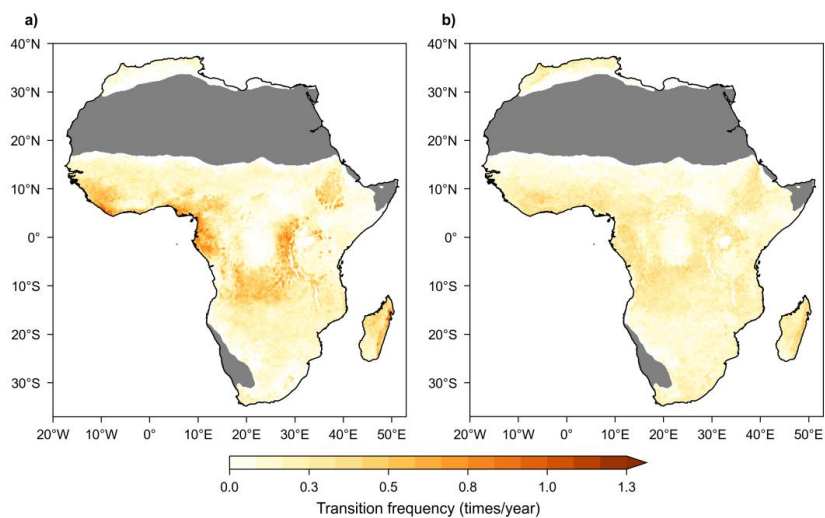
Figure B1. Spatial distribution of coefficient of variations (CV) for both ERA5-land and ERA5 reanalyzes from 1981 to 2024: a) CV of the total W2D frequency and b) CV of the onset speed for total W2D events. The grey shaded area is masked out areas based on an aridity index less than 0.05.

### Appendix C: Characteristics of W2D Transitions Events

This appendix displays the spatial characteristics of W2D transition events, such as occurrence frequency and transition duration for total and rapid events. Additionally, it also addresses the sensitivity of the



trends to the threshold's values of wet and onset speed events. Hereafter, the analysis results presented were obtained using the ERA5-Land gridded soil moisture dataset.



410 Figure C1. The average spatial distribution of occurrence frequency of W2D transition events of a) rapid transition events and b) slow transition events (times  $\text{yr}^{-1}$ ); the grey shaded area is masked out based on the aridity index less than 0.05.

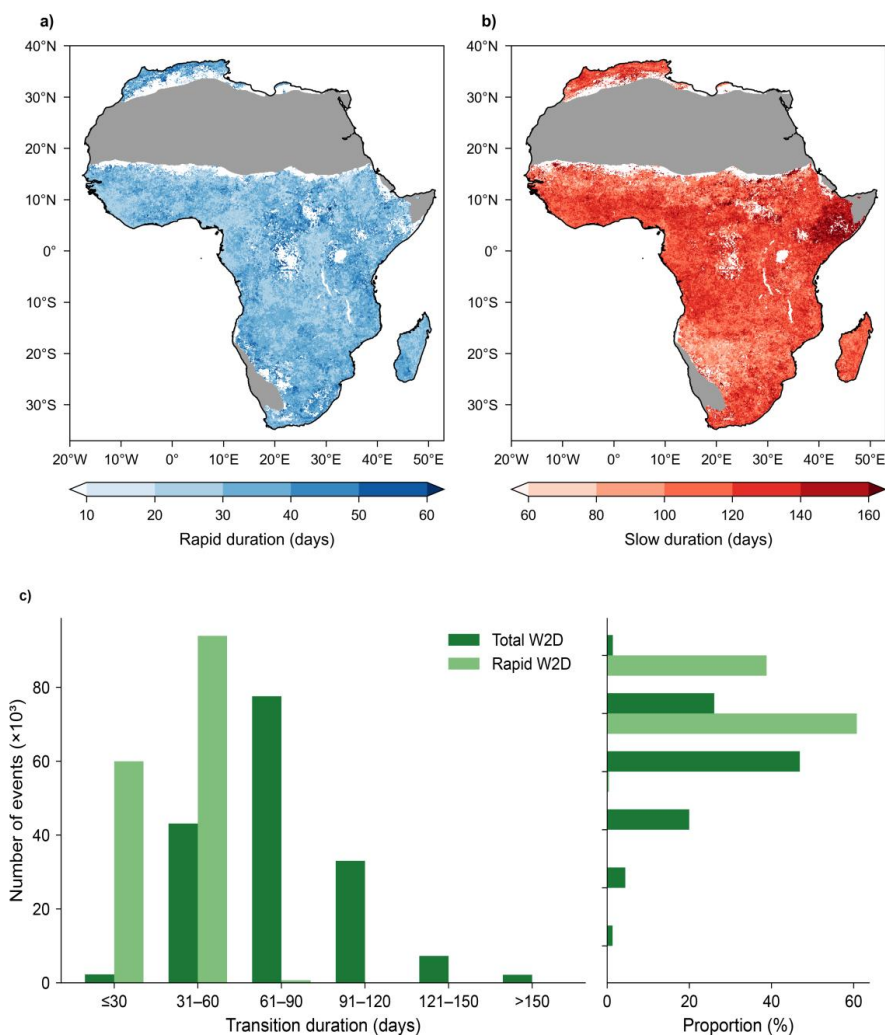
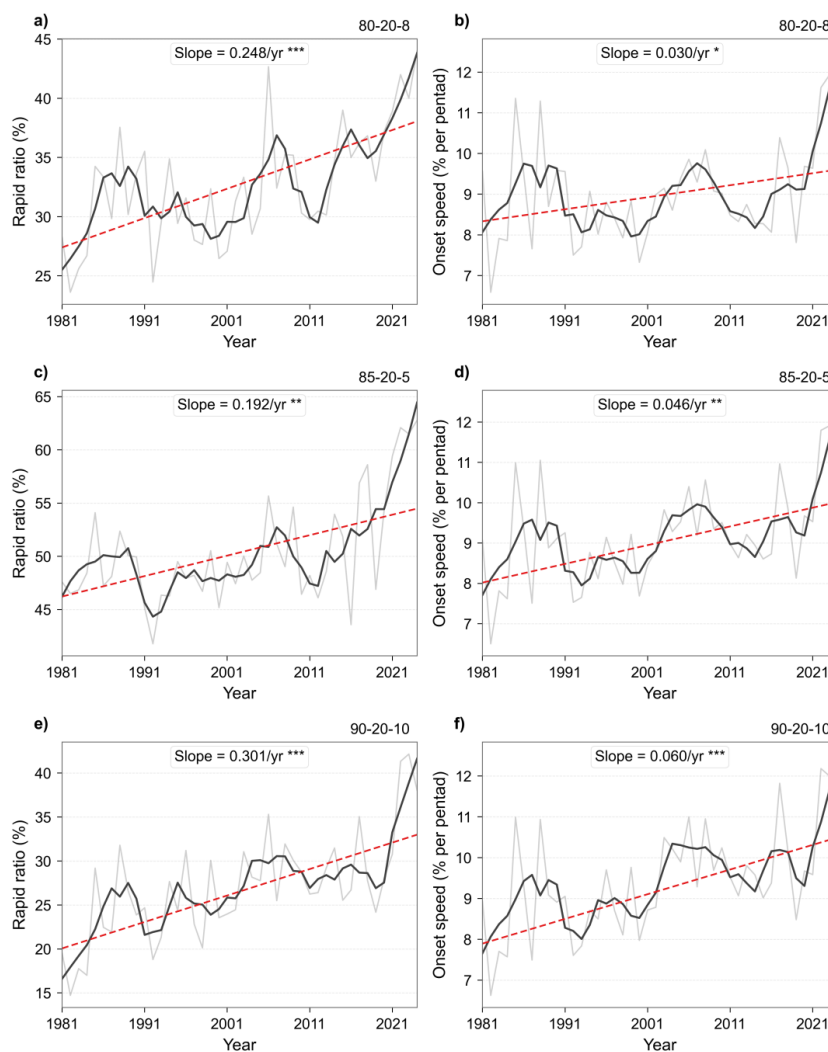


Figure C2. The average means spatial distribution of transition durations for total and rapid W2D events.

415 a) rapid W2D transition duration (days), b) slow W2D transition duration (days), and c) the frequency distribution of the number of events with its corresponding proportions of transition durations across predefined intervals for total and rapid W2D events using ERA5-Land; the grey shaded area is masked out based on the aridity index being less than 0.05.



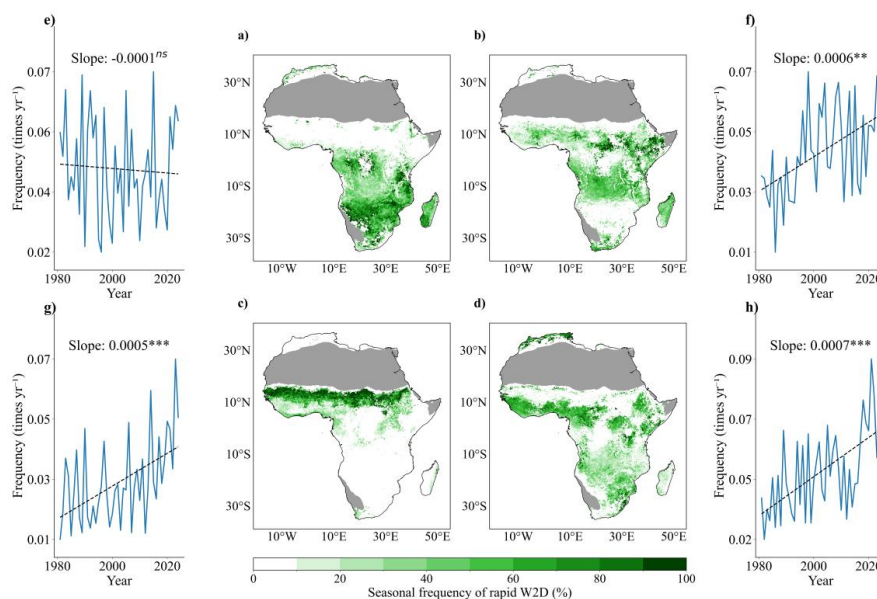
420 Figure C3. Time series of continent level mean rapid W2D ratio and W2D transition's onset speed based  
 425 on different wet and onset speed thresholds. "X-Y-Z" in the upper right corners of each plot represent the  
 wet ending point, dry starting point, and transition onset speed (%/pentad), respectively. The trends  
 (%/year and %/pentad/year for rapid ratio (a, c, e) and onset speed (b, d, f), respectively) during 1981-  
 2024. Trends were calculated employing Sen's slope estimator, and the non-parametric Mann-Kendall  
 test was used to assess statistical significance with p-values derived using Kendall's  $\tau$ , as in SciPy. In all



panels, \*\*\* indicates a p-value < 0.001; \*\* indicates a p-value < 0.01, and \* indicates a p-value < 0.05.

#### Appendix D: Seasonal Variation of W2D Transitions Characteristics

Figure D1 shows the percentage of large spatial heterogeneity in W2D transition frequency that occurred in the four seasons. More W2D transition frequency events occur in spring, but fewer W2D transition events occur in the summer (Fig. D1). The southern regions show a high W2D transition occurrence frequency (> 50%) in the winter season (Fig. D1). On the other hand, some parts of the western and Sahel regions are experiencing a high frequency of W2D transitions in the summer (Fig. D1). Eastern regions showed a high frequency of W2D transitions in spring.



435 Figure D1. Spatial distribution and time series trends of seasonal occurrence frequency of rapid W2D  
 440 transitions during 1981–2024: a. Winter (December, January, and February), b. Spring (March, April,  
 and May), c. Summer (June, July, and August), and d. Autumn (September, October, and November).  
 The rapid W2D transitions are represented by the seasonal time series trends of e) winter, f) spring, g)  
 summer, and h) autumn. Trends were calculated employing Sen's slope estimator and non-parametric  
 Mann–Kendall test was used to assess statistical significance, with p-values derived using Kendall's  $\tau$ ,



as in SciPy. Grey shaded areas indicate the masked-out areas where the aridity index is less than 0.05 (hyper arid). \*\*\* indicates a p-value < 0.001; \*\* indicates a p-value < 0.01, and ns indicates a p-value > 0.05 (non-significant).

#### **Data and code availability**

445 The data that support the findings of this study are openly available. ERA5-Land and ERA5 data were obtained from <https://cds.climate.copernicus.eu/> and CHIRPS dataset: <https://data.chc.ucsb.edu/products/CHIRPS-2.0/>. The code used in the analysis can be provided based upon request.

#### **Author contributions**

450 **MAG:** Conceptualization, Methodology, Visualization, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **GZ:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing. **XL:** Writing – review & editing. **XX:** Writing – review & editing. **PG:** Writing – review & editing. **QT:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

#### **455 Competing interests**

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this article.

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