Global Flash Droughts Characteristics: Onset, Duration and Extent at Watershed Scales

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Key Points:

- The onset and duration of flash droughts at the watershed scale are influenced by climate variables, but not by the length of wet and dry spell.
- Flash droughts extents are affected by intraannual precipitation variability, but not by intraannual air temperature variability.
- Watersheds in tropical, temperate climates, and with savanna and grassland land cover are more susceptible to flash droughts.

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Abstract

Addressing impacts of flash droughts (FDs) on the water-food nexus requires a understanding of FD mechanisms and drivers at the watershed level. Examining climatic drivers, dry and wet spell lengths from 1980 to 2019 using long term MERRA-2 reanalysis data, we analyzed FD spatial and temporal characteristics, emphasizing areal extent, onset time, and duration. Our findings reveal substantial variations in FDs among different watersheds. Notably, watersheds in the Southern Hemisphere are witnessing expanding, faster-developing, and longer-lasting FDs, aligning with climate variations in precipitation and temperature. Additionally, at the watershed scale, the onset and duration of FDs are significantly more influenced by the intensity of climatic drivers than the duration of wet and dry periods. FD-extents, however, correlate with both climatic conditions and wet and dry periods, underscoring watershed connectivity. Ultimately, our results underscore the necessity for research to comprehend the interplay between FDs and watershed characteristics and how it manifests in overall water resource management.

Plain Language Summary

Flash droughts (FDs), which are sudden and severe dry periods, are causing problems for our water and food systems and making it harder to prepare for disasters. To address these challenges effectively, it is crucial to gain a thorough understanding of the underlying mechanisms and factors driving FDs at the watershed level. In this study, we looked at climatic patterns alongside the lengths of dry and wet periods spanning from 1980 to 2019. Our primary focus was on three key aspects: the extent of FDs, when they begin, and how long they persist. Our research findings demonstrate considerable variations in FDs occurrences across different regions. Notably, in the Southern Hemisphere, FDs are expanding rapidly, developing more swiftly, and enduring for extended periods, closely mirroring shifts in precipitation and temperature patterns. Interestingly, the onset and duration of FDs seem to depend more on the intensity of climatic

factors than on how long it's been dry or wet. The expansion of FDs in a region is linked to both the climatic and dry/wet periods, emphasizing the geophysical connectivity within a watershed.

1. Introduction

Droughts are often described as "creeping hazards" due to their indefinite start and end times, encompassing wide spatial ranges (from a few kilometers to regional scales) and temporal footprints (spanning from weeks and months to even years) (Svoboda et al., 2002). Among these, flash droughts (FDs) stand out as a distinct category, marked by their rapid onset and intensification often over a matter of days to few weeks (Mo and Lettenmaier, 2016; Tyagi et al., 2022; Christian et al., 2021a; Christian et al., 2021b). This unique characteristic renders them more challenging to anticipate and address compared to traditional droughts. For example, FDs in the Dakotas and Montana in 2017 led to $2.6 billion in agricultural losses in the U.S. alone (Basara et al., 2023). Recent years have witnessed a surge in research dedicated to understanding FDs, given the escalating challenges they pose. However, consensus remains elusive within the scientific community regarding a singular, universally accepted definition for this complex phenomena (Mo and Lettenmaier, 2015; Mo and Lettenmaier, 2016; Ford and Labosier, 2017; Chen et al., 2019; Koster et al., 2019; Pendergrass et al., 2020; Christian et al., 2021a; Christian et al., 2021b). Moreover, there is a range of indices available to identify FDs, including the Evaporative Demand Drought Index (EDDI) (Hobbins at al., 2016), the Evaporative Stress Index (ESI) (Otkin et al., 2014), the Standard Evaporative Stress Ratio (SESR) (Christian et al., 2019), and combinations of climate variables such as precipitation, air temperature, soil moisture, root-zone soil moisture, vapor pressure deficit, evapotranspiration and vegetation greenness. However, root zone soil moisture is key variable to several of these FD definitions, due to its relevance to vegetation and low noise relative to soil moisture, precipitation and temperature (Osman et al., 2021). Within the various definitions proposed, Christian et al., 2019 uses the ratio between evapotranspiration and potential evapotranspiration, while Otkin et al., 2018 uses intensification of an index (like evapotranspiration) accompanied by declining soil moisture. Conversely, Ford and Labosier, 2017 and Koster et al., 2019b, define it as a drop in root zone soil moisture from the 40^{th} to below the 20^{th} percentile over a 20-day span. This delineates the upper threshold as indicative of non-drought soil moisture conditions, while the lower threshold corresponds to the definition of moderate drought as per the U.S. Drought Monitor (USDM; Svoboda et al., 2002). Chen et al., 2019, base their definition on the USDM and its association with cold ENSO events. Similarly, Pendergrass et al., 2020 define FDs through rapid shifts in USDM categories, while Mo and Lettenmaier (2015, 2016) categorize them based on triggering

factors: heatwaves and precipitation deficits. However, in aiding the identification and conceptualization of FDs, studies have postulated three overarching principles:

- **Rapid onset:** FDs should initiate within days to a few weeks, distinguishing them from the gradual development of conventional droughts.
- **Intensification:** The severity of the drought should escalate rapidly, allowing for a transition from moderate to severe drought within a short timeframe.
- **Severity of impact:** The ultimate outcome of the event should be sufficiently severe to classify it as a FD.

It's important to note that these principles are not intended as rigid definitions but rather as foundational elements for developing quantitative metrics that facilitate early detection and mitigation of FDs. FDs induced from elevated air temperatures intensifying evapotranspiration and depleting root zone soil moisture. Conversely, FDs stemming from precipitation deficits cause a decline in root zone soil moisture due to insufficient water to wet the rootzone. Thus, FDs are a result of the interplay between factors like precipitation deficits and heightened air temperatures driving increased evapotranspiration (Mo and Lettenmaier, 2015; Mo and Lettenmaier, 2016; Koster 2019; Pendergrass et al., 2020; Christian et al., 2021a; Christian et al., 2021b). Beyond precipitation deficits and elevated evapotranspiration demand, an array of other environmental drivers can either amplify or alleviate the occurrence of FDs. These encompass factors like wet/dry spell, solar radiation, relative humidity, groundwater availability, soil water holding capacity, presence of organic matter, and vegetation cover. Notably, vegetation plays a significant role in modulating the rate of evapotranspiration and can expedite the onset of FDs (Ahmad et al., 2022). In general, vegetation cover influences evaporation and transpiration through precipitation interception, soil shading, and controlled stomatal conductance.

While many studies have explored the impact of climate drivers on FDs at a global scale providing valuable insights into global trends, only a limited number (Van Loon and Laaha, 2015; Konapala and Mishra, 2020) have delved into the specifics of FDs within particular watersheds. Beyond climatic factors, the variability in watershed characteristics plays a substantial role in shaping the spatiotemporal dynamics of FD characteristics, which were overlooked in these studies. The objective of this study is to conduct a quantitative analysis of FD characteristics, climatic drivers, and the durations of wet and dry spells at the watershed level on a global scale, with a particular emphasis on FD spatial expansions. The findings compel the

introduction of a map specifically designed to assess FD vulnerability, which identifies hotspots undergoing one, two or three of these FD characteristics: the rate of change in area coverage, timeframes associated with FD-onset, and duration. The map highlights regions with susceptibility to future droughts, which may be prone to further cascading and compounding disasters.

2. Data and Methodology

2.1. Study Area

The analysis is conducted globally at a watershed scale to gain insights into the dynamics of FD characteristics and the factors driving them. The watershed characteristics, like pooling, attenuation, lag, and lengthening, play a pivotal role in shaping the hydrological responses (Eltahir and Yeh, 1999; Van Lanen et al., 2013). Lag time, for instance, measures the speed of a watershed's response to a runoff-producing rain event. These characteristics significantly impact various aspects of the hydrological cycle, influencing root zone soil moisture, subsurface recharge, and flow patterns. The variability in watershed attributes significantly contributes to the intricate interactions affecting FD propagation, duration, and their implications for the overall water balance (Van Loon and Laaha, 2015; Konapala and Mishra, 2020). It's important to note that while this study doesn't explicitly consider specific watershed characteristics, the analysis of FD at the watershed level inherently encompasses their influence as a significant driving factor in shaping distinct FD attributes.

2.2. Data Description

The focus of this study is on the warm season, which is from mid-April to mid-September in the Northern Hemisphere and from mid-October to mid-March in the Southern Hemisphere. We use Modern-Era Retrospective analysis for Research and Applications Version-2 (MERRA-2) (Gelaro et al., 2017), a state-of-the-art, multiyear atmospheric reanalysis product developed by NASA's Global Modeling and Assimilation Office (GMAO). MERRA-2 blends satellite and more conventional weather observations with model outputs to produce atmospheric and land variables. MERRA-2 fields are gridded hourly at a 0.625° longitude × 0.5° latitude resolution. The advantage of a reanalysis product is that it provides both spatial and temporal coherence for many climate variables, making it highly valuable for studying spatial trends over long periods of time, especially droughts. The accuracy of MERRA-2 fields has been validated extensively (Reichle et al., 2017). The rootzone soil moisture (RZSM) obtained from MERRA-2 is model-

generated, relying on atmospheric forcings, soil properties, and model parameterizations. However, given the specific focus of our analysis, MERRA-2 reanalysis emerges as the optimal choice for obtaining RZSM among other datasets (Liu et al., 2023). For this analysis, the MERRA-2 daily fields of RZSM (m^3/m^3) precipitation (P) (mm/day), total evapotranspiration (ET) (mm/day), sensible heat flux (SH) (W/m^2), latent heat flux (LH) (W/m^2), and 2-m air-temperature (T_{air}) (K) from 1980 – 2019 are used. We also consider factors such as wet spell length which is defined as the number of consecutive days with P > 1mm, and dry spell length which refers to the number of days with no P. These durations of wet and dry spells play a significant role in influencing the moisture levels in the root zone.

2.3. Flash Drought Definition

In this study, we adopt the broad definition of FDs as established in Koster et al., 2019b, while diverging from their specific requirement that FDs exclusively develop over a 20-day period. The development of FDs varies across regions due to distinct geographical, climate and land cover factors. Instead our approach accommodates a variable development timescales for FDs, ranging from 15 to 45 days. Events that develop in less than 15 days are classified as mere water deficit. While there is no universally accepted timescale for FD duration (FD-Dur), we consider any event longer than 30 days as a hydrological drought. To identify FDs, we construct a cumulative distribution function (CDF) of RZSM at a specific location "j" and on a given day of the year "k". This CDF is based on RZSM from 200 values from days "k – 6," "k – 3," "k," "k + 3," and "k + 6," extracted from 1980 – 2019. This methodology offers several advantages, including its ability to effectively capture regional disparities and seasonal variations in the developed CDF. Moreover, the use of five additional sampling dates enhances data quality and helps mitigate noisy fluctuations when estimating RZSM percentiles. We employ a single, hydrology-based quantitative metric and dataset to identify FDs, acknowledging that different definitions and datasets could yield different results. Therefore, a FD is identified by;

- A decline in RZSM from above its 40^{th} percentile to below its 20^{th} percentile value.
- Simultaneously, there must be a reduction in ET from at least $4/5^{th}$ of the climatological ET to $3/5^{th}$ or lower of the climatological ET.
- The duration of the FD is considered the period starting when RZSM falls below the 20^{th} percentile and ending when it monotonically rises back above the 20^{th} percentile.
- To avoid overlapping events, only one FD event is considered within a given year.

This study primarily examines three FD characteristics: extent, onset, and duration:

- **FD-onset:** Measures the speed of FD development.
- **FD-Dur:** Measures the duration of FDs.
- **FD-extent:** Measures the expansion of FDs.

The FD-onset and FD-Dur are computed for each gridded pixel and subsequently aggregated to the watershed scale. We specifically focus on watersheds where at least 20 % of the area is undergoing FD characteristics. Likewise, FD-extent is determined by the number of pixels identified as FD relative to the total number of pixels in the watershed. A 40-year time series of the aggregated FD characteristics at watershed scale undergoes a linear trend analysis to ascertain the rate (slope of the trend), and only statistical significance trends ($p < 0.1$) are reported. While, the relationships between climate and FD characteristics are reported using Spearman correlation coefficients ($p < 0.1$). We consider both the mean and standard deviation (std) for all climatic variables specific to the analysis period to understand inter and intra-annual variations on FD characteristics. Furthermore, we assess the spatial variability of these drivers particularly in relation to driving FD-extent within the watersheds using coefficient of variation (CV).

3. Results and Discussions

3.1. Global Hotspots and Trends in Flash Droughts

The average FD-onset time falls within a range of ~ 17.23 to ~ 28.72 days, while the average FD-Dur spans from ~ 3.65 to ~ 21.09 days. It's worth noting that FDs exhibit both spatial expansion and contraction trends, Fig.1. Particularly, FDs in the Southern Hemisphere are expanding and intensifying more rapidly, as well as lasting for longer durations, compared to FDs in the Northern Hemisphere. While most watersheds are experiencing expansion in FD-extent, those in Central Asia are witnessing a reduction in FD-extent. However, globally on average, the rate of FD-extent expansion surpasses the rate of FD-extent reduction. This expansion can be attributed to a combination of below-average *P* and higher T_{air} anomalies, which contribute to rapid RZSM depletion. On the other hand, the shrinkage in FD-extent may result from not only increased mean *P* but also from greater water availability due to rising T_{air} in high mountain areas, which advance the timing of snowmelt and alter hydrological processes. A noteworthy finding is that, despite an increase in the average duration of wet spells, there has been a substantial reduction in both the mean and std of *P* on a global scale. This implies that there might not be a sufficient amount of *P* to adequately percolate and saturate the RZSM, which is essential for averting FD events. Additionally, there has been a global increase in the duration of dry spells.

3.1.1. South America

In South America, many watersheds exhibit all three FDs characteristics, making them hotspots. However, the rates of change and responses to climatic drivers vary across watersheds. Notably, FDs are developing more rapidly by an average of ~ 0.12 day/year, and persist longer by ~ 0.15 day/year, particularly in the southern parts of Brazil. The overall FD-extent in South America is increasing by ~ 3 % per year. Brazil which covers more than ~ 40 % of the Amazonian watershed, has an average FD-onset of ~ 21.95 days and FD-Dur of ~ 14.97 days. The key drivers of FD characteristics in this region include *P* deficit, elevated T_{air}, and shorter wet spells. These findings align with the concept of a heat-drought-heat cascade, where higher T_{air} levels elevate SH, subsequently leading to further T_{air} increases. This rise in T_{air}, intensifies evaporative demand resulting in increased desiccation of soils and vegetation, consistent with previous findings (Jimenez et al., 2018; Wunderling et al., 2022; Papastefanou et al., 2022). FD trends in the Amazonian watershed are consistent with deforestation patterns in the region (Staal et al., 2020). The local ET contributes ~ 20 % to ~ 45 % of the total *P* over the Amazonian region (Burde et al., 2006; Staal et al., 2018). Consequently, increased deforestation disrupts

local coupling and atmospheric circulation through land–atmosphere feedbacks (Goessling and Reick, 2011) These changes further impact *P* deficits and lead to higher T_{air} anomalies.

Our study further reveals that the expanding extent of FDs in the Amazon region is significantly influenced by CV in wet periods within the watershed. This finding is consistent with our understanding that a higher CV in wet spells within a watershed provides adequate time for percolation, facilitating subsurface and RZSM recharge. This enhances watershed connectivity, influences runoff patterns, and impacts streamflow responses. However, this process is nonlinear due to watershed heterogeneity in factors such as vegetation, soil types, and elevation variations (Singh et al., 2021). Therefore, the expanding extent of FDs in South American watersheds can be attributed to a combination of *P* deficit, higher T_{air}, shorter wet periods, and reduced spatial variability in wet periods.

3.1.2. Central Africa

Many watersheds across Africa are experiencing all three FD characteristics, akin to South America, marking them hotspots. This pattern is particularly evident in countries such as Congo, Angola, Zambia, Zimbabwe, South Africa, Lesotho, and Madagascar. These findings raise concerns that these regions may be entering a prolonged drought phase. The expansion of FDs in Africa is significantly influenced by a number of factors, including declining mean *P*, std *P*, higher mean T_{air} and SH, Fig.1. Additionally, both wet and dry spell periods play a role in FD-extent, in contrast to South America. These drivers have undergone substantial changes over the past four decades in the African region. For example, mean T_{air} has exhibited a consistent rise, increasing at a rate of ~ 0.03°K/year, while mean *P* has been on a declining trend at a rate of ~ 0.02 mm/year. Furthermore, wet spells have been contracting by ~ 0.1 day/year, while dry spells have been extending by ~ 0.04 day/year. These findings are consistent with previous research that has documented a surge in temperatures and the emergence of more intense and prolonged heatwaves across various African regions (Russo et al., 2016; Ceccherini et al., 2017; Engdaw et al., 2022).

African watersheds face unique challenges due to their relatively arid nature compared to South American or Asian watersheds. As a result, African vegetation may already be operating close to its physiological and ecological limits (Bennett et al., 2021). Additionally, ~ 50 % of Africa's rainfall originates from vegetation sources within watersheds. However, the reliance on vegetation-sourced *P* varies significantly among different watersheds, ranging from ~ 5 % to ~

68 % (Te Wierik et al., 2022). Any further temperature increases could result in a rapid escalation of ET from vegetation, further exacerbating the already arid conditions in Africa. This heightened sensitivity to T_{air} is also underscored by the strong correlation between the expansion of FD-extent and spatial variability in LH within the watershed. Additionally, FD-onset and FD-Dur are primarily driven by higher mean T_{air} and SH superseding the impact of mean *P*, Fig.2. In contrast to the Amazonian watersheds, FD-extent in African watersheds is influenced by the spatial CV of mean T_{air}, std T_{air}, and LH. This sets African watersheds apart from other regions.

3.1.3. Central Asia

Central Asian watersheds containing mountainous areas, including High Mountain Asia, Himalayan and the Tianshan Mountains, experience a noticeable reduction in FD-extent, with the strongest correlations with mean and std *P* and wet and dry spell lengths, Fig.1. However, FD-onset and FD-Dur show weak correlations with any drivers, Fig.2 (barplots). What sets this region apart is the contradictory nature of the trends in these drivers over the past four decades, in contrast to global patterns. For example, mean *P* has increased by ~ 0.03 mm/year, along with an increase in std *P* by ~ 0.02 mm/year. Additionally, wet spells have become longer by ~ 0.01 day/year, while dry spells have become shorter by ~ 0.05 day/year. Although mean T_{air} has increased, it has done so at a slower rate than global trends. Our findings are consistent with other studies (Wang et al., 2016; Roxy et al., 2017) which observed an increase in *P* in mountainous areas of Central and East Asia since the 1980s. This may be due to the sensitivity of mountain snowpack to T_{air}, which influences the phase of *P*. Rising temperatures have also advanced snowmelt, increasing total surface water availability. This has led to changes in the timing and volume of river discharge, impacting the hydrology of the region (Maurer et al., 2019; Khanal et al., 2021). Mountainous areas are complex systems where runoff is a mix of rainfall, snowmelt, and glacier melt. A study by Nepal, 2016 found that glacier melt runoff contributes ~ 39 % of streamflow during the monsoon season (June to September) in the Himalayan region. Nevertheless, the response to increase in T_{air} varies widely across different regions and elevations, depending on climate conditions (Blahušiaková et al., 2020). Despite the contrary characteristics of FDs in Central Asia compared to global trends, it continues to be recognized as a global hotspot and a region of heightened risk. This is because the fluctuations in climate and cryospheric conditions are expected to exacerbate snow droughts and events like

glacier outbursts and influence the seasonal water availability in downstream areas, potentially resulting in a heightened frequency of floods (Sattar et al., 2022; Taylor et al., 2023).

3.2. Flash Drought Characteristics under Climate and Land Cover Classes

Among the 30 Köppen climate classes (Beck et al., 2018), we observed notable changes in all three FD characteristics for Tropical Wet Savanna (Aw), Temperate (Cfb, Cfc), and Mediterranean (Csb) climates (Table 1). The most significant expansion in FD-extent is observed in the Aw climate class, indicating an annual increase of ~ 0.6 %. Our findings align with previous studies (Yuan et al., 2023) that have indicated regions with humid and semi-humid climates are more susceptible to FDs. When *P* deficits coincide with positive T_{air} anomalies, it intensifies atmospheric water demand, leading to accelerated SM depletion, particularly within these climate regions. Of the 15 International Geosphere–Biosphere Programme (IGBP) land cover classes, regions with Evergreen Broadleaf forests (EBFs) have experienced all three FD characteristics, and are expanding at ~ 0.39 % per year. EBFs maintain their foliage year-round and often do not shed leaves even during severe water deficits, which makes them more prone to drought (Anderson et al., 2018; Fu et al., 2013; Wang et al., 2016; Zhou et al., 2011). This is also likely due to a trend towards increased aridity and longer dry seasons in recent decades within EBFs (Boisier et al., 2015). Other land cover classes showing changes include Closed Shrublands, Savannas, Grasslands, and Croplands. FD-extent in Savannas are expanding, while FDs in other Grasslands are developing at a faster rate and lasting longer (Table. 1). This is similar to the findings of Wang et al., 2019, who ranked the impacts of drought on different grassland types as follows: Closed Shrublands, Non-woody grassland, Savannas, Open Shrublands, Woody Savannas. Although we observe accelerated FD-onset and longer FD-Dur in cropland regions, we do not find any evidence of expansion for FD-extent.

3.3. Implications for Enhancing an Early Warning System

It is well-established that disasters are not just natural occurrences, but also have social dimensions. Disasters happen when communities are not prepared for the consequences of natural hazards. Fortunately, there are many national and international early warning systems that can help identify emerging droughts, such as Climate Engine, the Drought Early Warning System, the Global Drought Information System etc., (Funk et al., 2019). However, FDs pose complex challenges for management and early warning systems because they can develop

rapidly. This rapid intensification of drought conditions reduces the lead time available for preparation and mitigation.

Recent research by Christian et al., 2023 shows that croplands are at risk of more frequent FDs, due to the influence of future climate change. Therefore, to support existing early warning systems, we present a vulnerability map based on four decades of historical data for watersheds that are prone to FDs and exhibiting one or combination of FD characteristics. The map (Fig.3) indicates the vulnerability of watersheds to future droughts, and thus their susceptibility to cascading and compounding disasters. Many of these regions, to say the least include Central America, Europe, Southeast Australia, Pakistan, and Central Africa, which have already experienced drought-related events such as flash floods, extreme heat, and wildfires.

4. Conclusions

In this study, we conducted a comprehensive analysis of flash droughts (FDs) at the watershed scale, using 40 years of long-term reanalysis data to provide valuable insights into their spatial and temporal characteristics. We focused on three key aspects of FDs: their areal extent, onset time, and duration. Our findings revealed notable disparities in FD patterns among different watersheds. For instance, South American watersheds are currently experiencing the expansion and intensification of FDs. These trends primarily result from the dual impact of rising temperatures and declining precipitation. In the Central Africa watersheds, analogous vulnerabilities exist, but the influence of increasing temperatures outweighs diminishing precipitation in shaping FD characteristics. Conversely, Central Asian watersheds exhibit a mixed response in FD characteristics, largely driven by an unprecedented increase in precipitation. Climatic conditions and the lengths of wet and dry spells significantly affected FD-extent, underlining the geophysical connectivity within a watershed. Particularly noteworthy is the contrast between Southern Hemisphere and Northern Hemisphere watersheds, with the former experiencing FDs that expand more rapidly and endure longer, aligning with shifts in precipitation and temperature patterns. Furthermore, our analysis explored the roles of climate and land cover classes in shaping FD characteristics. Climates characterized as humid and semi-humid, such as Tropical Wet Savanna, displayed heightened susceptibility to FDs due to intricate interactions involving monsoons, temperature anomalies, and precipitation deficits. Land cover types such as Evergreen Broadleaf forests and Grasslands exhibited all three FD characteristics, emphasizing their vulnerability to prolonged drought conditions. Our findings can supplement

existing early warning systems and preparedness measures, especially in regions prone to FDs. As FDs can rapidly intensify, reducing the lead time available for mitigation, our vulnerability map based on historical data can aid in identifying regions susceptible to FDs and cascading disasters. Even though, our study is based on a specific hydrology-based FD definition and the use of MERRA-2 data, our primary aim was to comprehensively explore statistically significant rate-of-change trends in all three FD characteristics at the watershed scale globally, which is a novel approach that has not been undertaken in this manner before. While, the scalability of FD identification across datasets and definitions is beyond the scope of this study, it is recognized as a critical aspect that will be the subject of future research.

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References

Ahmad, S. K., Kumar, S. V., Lahmers, T. M., Wang, S., Liu, P-W., Wrzesien, M. L., Bindlish, R., Getirana, A., Locke, K. A., Holmes, T. R., and Otkin, J. A. (2022). Flash Drought Onset and Development Mechanisms Captured With Soil Moisture and Vegetation Data Assimilation. Water Resources Research, 58(12), p.e2022WR032894.

Anderson, L. O., Ribeiro Neto, G., Cunha, A. P., Fonseca, M. G., Mendes de Moura, Y., Dalagnol, R., Wagner, F. H., and de Aragão, L. E. O. E. C. (2018). Vulnerability of Amazonian forests to repeated droughts. Philosophical Transactions of the Royal Society B: Biological Sciences, 373(1760), p.20170411.

Ballesteros-Cánovas, J. A., Trappmann, D., Madrigal-González, J., Eckert, N., and Stoffel, M. (2018). Climate warming enhances snow avalanche risk in the Western Himalayas. Proceedings of the National Academy of Sciences, 115, 3410–5.

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., and Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data, 5, 180214.

Bennett, A. C., Dargie, G. C., Cuni-Sanchez, A., Tshibamba Mukendi, J., Hubau, W., Mukinzi, J. M., Phillips, O. L., Malhi, Y., Sullivan, M. J. P., Cooper, D. L. M., Adu-Bredu, S., Affum-Baffoe, K., Amani, C. A., Banin, L. F., Beeckman, H., Begne, S. K., Bocko, Y. E., Boeckx, P., Bogaert, J., Brncic, T., Chezeaux, E., Clark, C. J., Daniels, A. K., de Haulleville, T., Djuikouo Kamdem, M-N., Doucet, J-L., Evouna Ondo, F., Ewango, C. E. N., Feldpausch, T. R., Foli, E. G., Gonmadje, C., Hall, J. S., Hardy, O. J., Harris, D. J., Ifo, S. A., Jeffery, K. J., Kearsley, E., Leal, M., Levesley, A., Makana, J-R., Mbayu Lukasu, F., Medjibe, V. P., Mihindu, V., Moore, S., Nssi Begone, N., Pickavance, G. C., Poulsen, J. R., Reitsma, J., Sonké, B., Sunderland, T. C. H., Taedoumg, H., Talbot, J., Tuagben, D. S., Umunay, P. M., Verbeeck, H., Vleminckx, J., White, L. J. T., Woell, H., Woods, J. T., Zemagho, L., and Lewis, S. L. (2021). Resistance of African tropical forests to an extreme climate anomaly. Proceedings of the National Academy of Sciences, 118, e2003169118.

Blahušiaková, A., Matoušková, M., Jeníček, M., Ledvinka, O., Kliment, Z., Podolinská, J., and Snopková, Z. (2020). Snow and climate trends and their impact on seasonal runoff and hydrological drought types in selected mountain catchments in Central Europe. Hydrological Sciences Journal, 65, 2083–96.

Boisier, J. P., Ciais, P., Ducharne, A., and Guimberteau, M. (2015). Projected strengthening of Amazonian dry season by constrained climate model simulations. Nature Climate Change, 5, 656–60.

Burde, G. I., Gandush, C., and Bayarjargal, Y. (2006). Bulk Recycling Models with Incomplete Vertical Mixing. Part II: Precipitation Recycling in the Amazon Basin. Journal of Climate, 19, 1473–89.

Ceccherini, G., Russo, S., Ameztoy, I., Marchese, A. F., and Carmona-Moreno, C. (2017). Heat waves in Africa 1981–2015, observations and reanalysis. Natural Hazards and Earth System Sciences, 17, 115–25.

Chen, L. G., Gottschalck, J., Hartman, A., Miskus, D., Tinker, R., and Artusa, A. (2019). Flash Drought Characteristics Based on U.S. Drought Monitor. Atmosphere, 10, 498.

Christian, J. I., Basara, J. B., Otkin, J. A., Hunt, E. D., Wakefield, R. A., Flanagan, P. X., and Xiao, X. (2019). A methodology for flash drought identification: Application of flash drought frequency across the United States. Journal of Hydrometeorology, 20(5), pp.833-846.

Christian, J. I., Basara, J. B., Hunt, E. D., Otkin, J. A., Furtado, J. C., Mishra, V., Xiao, X., and Randall, R. M. (2021a). Global distribution, trends, and drivers of flash drought occurrence. Nature Communications, 12, 6330.

Christian, J. I., Basara, J. B., Hunt, E. D., Otkin, J. A., Furtado, J. C., Mishra, V., Xiao, X., and Randall, R. M. (2021b). Global distribution, trends, and drivers of flash drought occurrence. Nature Communications, 12, 6330.

Christian, J. I., Basara, J. B., Otkin, J. A., and Hunt, E. D. (2019). Regional characteristics of flash droughts across the United States. Environmental Research Communications, 1, 125004.

Christian, J. I., Martin, E. R., Basara, J. B., Furtado, J. C., Otkin, J. A., Lowman, L. E. L., Hunt, E. D., Mishra, V., and Xiao, X. (2023). Global projections of flash drought show increased risk in a warming climate. Communications Earth & Environment, 4, 1–10.

Eltahir, E. A. B., and Yeh, P. J-F. (1999). On the asymmetric response of aquifer water level to floods and droughts in Illinois. Water Resources Research, 35, 1199–217.

Engdaw, M. M., Ballinger, A. P., Hegerl, G. C., and Steiner, A. K. (2022). Changes in temperature and heat waves over Africa using observational and reanalysis data sets. International Journal of Climatology, 42, 1165–80.

Feng, S., and Fu, Q. (2013). Expansion of global drylands under a warming climate. Atmospheric Chemistry and Physics, 13, 10081–94.

Ford, T. W., and Labosier, C. F. (2017). Meteorological conditions associated with the onset of flash drought in the Eastern United States. Agricultural and Forest Meteorology, 247, 414–23.

Funk, C., Shukla, S., Thiaw, W. M., Rowland, J., Hoell, A., McNally, A., Husak, G., Novella, N., Budde, M., Peters-Lidard, C., Adoum, A., Galu, G., Korecha, D., Magadzire, T., Rodriguez, M., Robjhon, M., Bekele, E., Arsenault, K., Peterson, P., Harrison, L., Fuhrman, S., Davenport, F., Landsfeld, M., Pedreros, D., Jacob, J. P., Reynolds, C., Becker-Reshef, I., and Verdin, J. (2019). Recognizing the Famine Early Warning Systems Network: Over 30 Years of Drought Early Warning Science Advances and Partnerships Promoting Global Food Security. Bulletin of the American Meteorological Society, 100, 1011–27.

Fu, R., Yin, L., Li, W., Arias, P.A., Dickinson, R.E., Huang, L., Chakraborty, S., Fernandes, K., Liebmann, B., Fisher, R., and Myneni, R.B. (2013). Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. Proceedings of the National Academy of Sciences, 110(45), pp.18110-18115.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., Silva, A. M. da, Gu, W., Kim, G-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M., and Zhao, B. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). Journal of Climate, 30, 5419–54.

Goessling, H. F., and Reick, C. H. (2011). What do moisture recycling estimates tell us? Exploring the extreme case of non-evaporating continents. Hydrology and Earth System Sciences, 15, 3217–35.

Hobbins, M. T., A. Wood, D. J. McEvoy, J. L. Huntington, C. Morton, M. Anderson, and C. Hain (2016). The Evaporative Demand Drought Index. Part I: Linking drought evolution to variations in evaporative demand. J. Hydrometeor., 17, 1745–1761.

Immerzeel, W. W., Pellicciotti, F., and Bierkens, M. F. P. (2013). Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. Nature Geoscience, 6, 742–5.

Jimenez, J. C., Libonati, R., and Peres, L. F. (2018). Droughts Over Amazonia in 2005, 2010, and 2015: A Cloud Cover Perspective. Frontiers in Earth Science, 6.

Khanal, S., Lutz, A. F., Kraaijenbrink, P. D. A., van den Hurk, B., Yao, T., and Immerzeel, W. W. (2021). Variable 21st Century Climate Change Response for Rivers in High Mountain Asia at Seasonal to Decadal Time Scales. Water Resources Research, 57, e2020WR029266.

Konapala, G., and Mishra, A. (2020). Quantifying Climate and Catchment Control on Hydrological Drought in the Continental United States. Water Resources Research, 56, e2018WR024620.

Konapala G and Mishra A (2020). Quantifying Climate and Catchment Control on Hydrological Drought in the Continental United States. Water Resources Research, 56, e2018WR024620.

Konapala, G., and Mishra, A. (2020). Quantifying Climate and Catchment Control on Hydrological Drought in the Continental United States. Water Resources Research, 56, e2018WR024620.

Koster, R. D., Schubert, S. D., Wang, H., Mahanama, S. P., and DeAngelis, A. M. (2019a). Flash Drought as Captured by Reanalysis Data: Disentangling the Contributions of Precipitation Deficit and Excess Evapotranspiration. Journal of Hydrometeorology, 20, 1241–58.

Koster, R. D., Schubert, S. D., Wang, H., Mahanama, S. P., and DeAngelis, A. M. (2019b). Flash Drought as Captured by Reanalysis Data: Disentangling the Contributions of Precipitation Deficit and Excess Evapotranspiration. Journal of Hydrometeorology, 20, 1241–58.

Liu, E., Zhu, Y., Calvet, J.C., Lü, H., Bonan, B., Zheng, J., Gou, Q., Wang, X., Ding, Z., Xu, H. and Pan, Y. (2023). Evaluation of model-derived root-zone soil moisture over the Huai river basin. Hydrology and Earth System Sciences Discussions, pp.1-39.

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., and Bierkens, M. F. P. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Climate Change, 4, 587–92.

Maurer, J. M., Schaefer, J. M., Rupper, S., and Corley, A. (2019). Acceleration of ice loss across the Himalayas over the past 40 years. Science Advances, 5, eaav7266.

Mo, K. C., and Lettenmaier, D. P. (2015). Heat wave flash droughts in decline. Geophysical Research Letters, 42, 2823–9.

Mo, K. C., and Lettenmaier, D. P. (2016). Precipitation Deficit Flash Droughts over the United States. Journal of Hydrometeorology, 17, 1169–84.

Nepal, S. (2016). Impacts of climate change on the hydrological regime of the Koshi river basin in the Himalayan region. Journal of Hydro-environment Research, 10, 76–89.

Osman, M., Zaitchik, B. F., Badr, H. S., Christian, J. I., Tadesse, T., Otkin, J. A., and Anderson, M. C. (2021). Flash drought onset over the contiguous United States: sensitivity of inventories and trends to quantitative definitions. Hydrology and Earth System Sciences, 25(2), pp. 565-581.

Otkin, J. A., M. C. Anderson, C. Hain, and M. Svoboda. (2014). Examining the relationship between drought development and rapid changes in the Evaporative Stress Index. Journal of Hydrometeorology., 15, 938–956.

Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C., and Basara, J. B. (2018). Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States. Bulletin of the American Meteorological Society, 99, 911–9.

Papastefanou, P., Zang, C. S., Angelov, Z., de Castro, A. A., Jimenez, J. C., De Rezende, L. F. C., Ruscica, R. C., Sakschewski, B., Sörensson, A. A., Thonicke, K., Vera, C., Viovy, N., Von Randow, C., and Rammig, A. (2022). Recent extreme drought events in the Amazon rainforest: assessment of different precipitation and evapotranspiration datasets and drought indicators. Biogeosciences, 19, 3843–61.

Pendergrass, A. G., Meehl, G. A., Pulwarty, R., Hobbins, M., Hoell, A., AghaKouchak, A., Bonfils, C. J. W., Gallant, A. J. E., Hoerling, M., Hoffmann, D., Kaatz, L., Lehner, F., Llewellyn, D., Mote, P., Neale, R. B., Overpeck, J. T., Sheffield, A., Stahl, K., Svoboda, M., Wheeler, M. C., Wood, A. W., and Woodhouse, C. A. (2020). Flash droughts present a new challenge for subseasonal-to-seasonal prediction. Nature Climate Change., 10, 191–9.

Reichle, R. H., Draper, C. S., Liu, Q., Girotto, M., Mahanama, S. P. P., Koster, R. D., and Lannoy, G. J. M. D. (2017). Assessment of MERRA-2 Land Surface Hydrology Estimates. Journal of Climate, 30, 2937–60.

Roxy, M. K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P., and Rajeevan, M. (2017). A threefold rise in widespread extreme rain events over central India. Nature Communications, 8, 708.

Russo, S., Marchese, A. F., Sillmann, J., and Immé, G. (2016). When will unusual heat waves become normal in a warming Africa? Environmental Research Letters, 11, 054016.

Sattar, A., Haritashya, U. K., Kargel, J. S., and Karki, A. (2022). Transition of a small Himalayan glacier lake outburst flood to a giant transborder flood and debris flow. Scientific Reports, 12, 12421.

Singh, N. K., Emanuel, R. E., McGlynn, B. L., and Miniat, C. F. (2021). Soil Moisture Responses to Rainfall: Implications for Runoff Generation. Water Resources Research, 57, e2020WR028827.

Staal, A., Flores, B. M., Aguiar, A. P. D., Bosmans, J. H. C., Fetzer, I., and Tuinenburg, O. A. (2020). Feedback between drought and deforestation in the Amazon. Environmental Research Letters, 15, 044024.

Staal, A., Tuinenburg, O. A., Bosmans, J. H. C., Holmgren, M., van Nes, E. H., Scheffer, M., Zemp, D. C., and Dekker, S. C. (2018). Forest-rainfall cascades buffer against drought across the Amazon. Nature Climate Change, 8, 539–43.

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., and Stooksbury, D. (2002). The drought monitor. Bulletin of the American Meteorological Society, 83, 1181–90.

Taylor, C., Robinson, T. R., Dunning, S., Rachel Carr, J., and Westoby, M. (2023). Glacial lake outburst floods threaten millions globally. Nature Communication, 14, 487.

Te Wierik, S. A., Keune, J., Miralles, D. G., Gupta, J., Artzy-Randrup, Y. A., Gimeno, L., Nieto, R., and Cammeraat, L. H. (2022). The Contribution of Transpiration to Precipitation Over African Watersheds. Water Resources Research, 58, e2021WR031721.

Tyagi, S., Zhang, X., Saraswat, D., Sahany, S., Mishra, S. K., and Niyogi, D. (2022). Flash Drought: Review of Concept, Prediction and the Potential for Machine Learning, Deep Learning Methods. Earth's Future, 10, e2022EF002723.

Van Lanen, H. a. J., Wanders, N., Tallaksen, L. M., and Van Loon, A. F. (2013). Hydrological drought across the world: impact of climate and physical catchment structure. Hydrology and Earth System Sciences, 17, 1715–32.

Van Loon, A. F., and Laaha, G. (2015). Hydrological drought severity explained by climate and catchment characteristics. Journal of Hydrology, 526, 3–14.

Wang, W., Wang, J., Liu, X., Zhou, G., and Yan, J. (2016). Decadal drought deaccelerated the increasing trend of annual net primary production in tropical or subtropical forests in southern China. Scientific Reports, 6(1), p. 28640.

Wang, J., Zhang, M., Wang, S., Ren, Z., Che, Y., Qiang, F., and Qu, D. (2016). Decrease in snowfall/rainfall ratio in the Tibetan Plateau from 1961 to 2013. Journal of Geographical Sciences., 26, 1277–88.

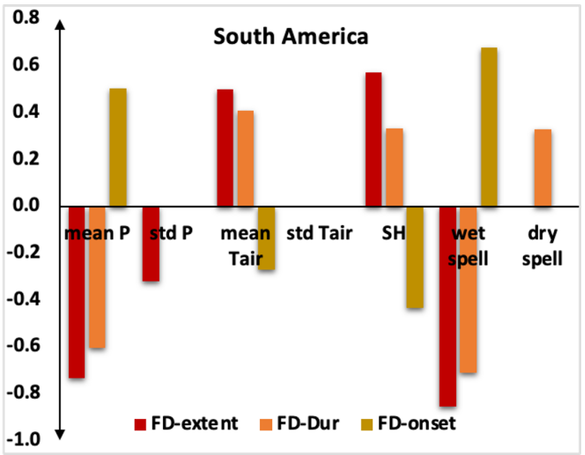
Wang, Q., Yang, Y., Liu, Y., Tong, L., Zhang, Q., and Li, J. (2019). Assessing the Impacts of Drought on Grassland Net Primary Production at the Global Scale. Scientific Reports, 9, 14041.

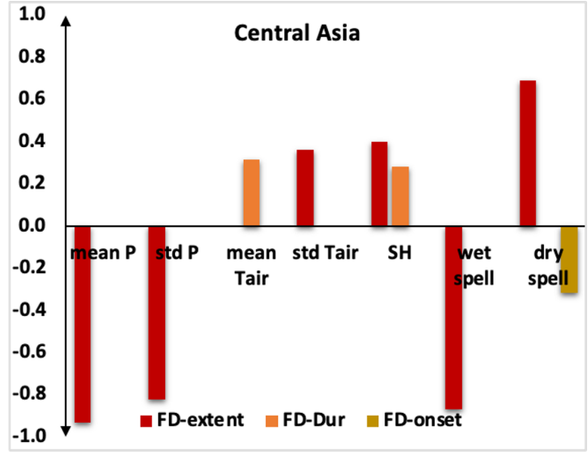
Wunderling, N., Staal, A., Sakschewski, B., Hirota, M., Tuinenburg, O. A., Donges, J. F., Barbosa, H. M. J., and Winkelmann, R. (2022). Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest. Proceedings of the National Academy of Sciences, 119, e2120777119.

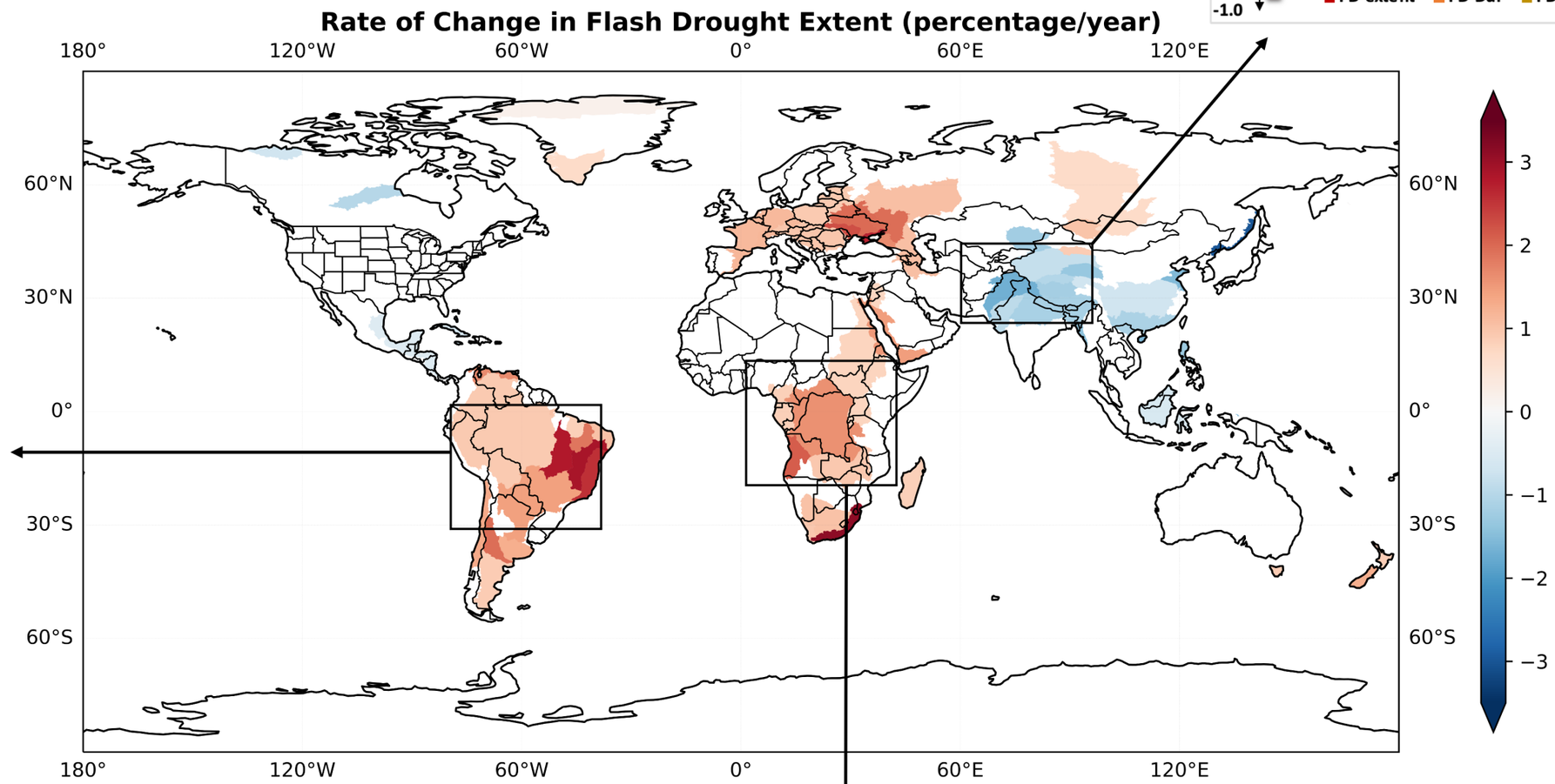
Yuan, X., Wang, Y., Ji, P., Wu, P., Sheffield, J. and Otkin, J.A.,(2023). A global transition to flash droughts under climate change. Science, 380(6641), pp.187-191.

Zhou, G., Wei, X., Wu, Y., Liu, S., Huang, Y., Yan, J., Zhang, D., Zhang, Q., Liu, J., Meng, Z. and Wang, C. (2011). Quantifying the hydrological responses to climate change in an intact forested small watershed in Southern China. Global Change Biology, 17(12), pp.3736-3746.

Figure1.


South America
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
mean P
std P
mean Tair
std Tair
SH
wet spell
dry spell
FD-extent
FD-Dur
FD-onset


Central Asia
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
mean P
std P
mean Tair
std Tair
SH
wet spell
dry spell
FD-extent
FD-Dur
FD-onset


Rate of Change in Flash Drought Extent (percentage/year)
180°
120°W
60°W
0°
60°E
120°E
60°N
30°N
0°
30°S
60°S
3
2
1
0
−1
−2
−3

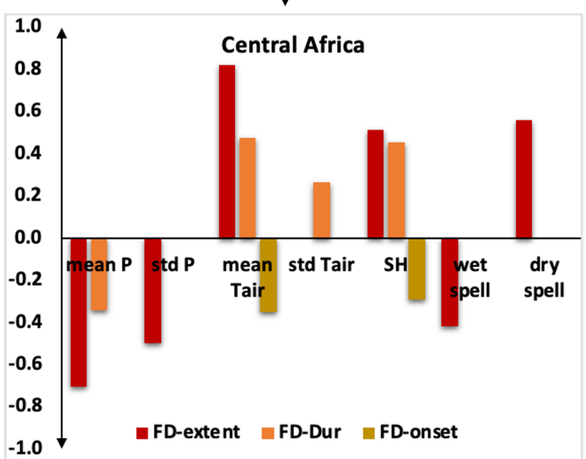
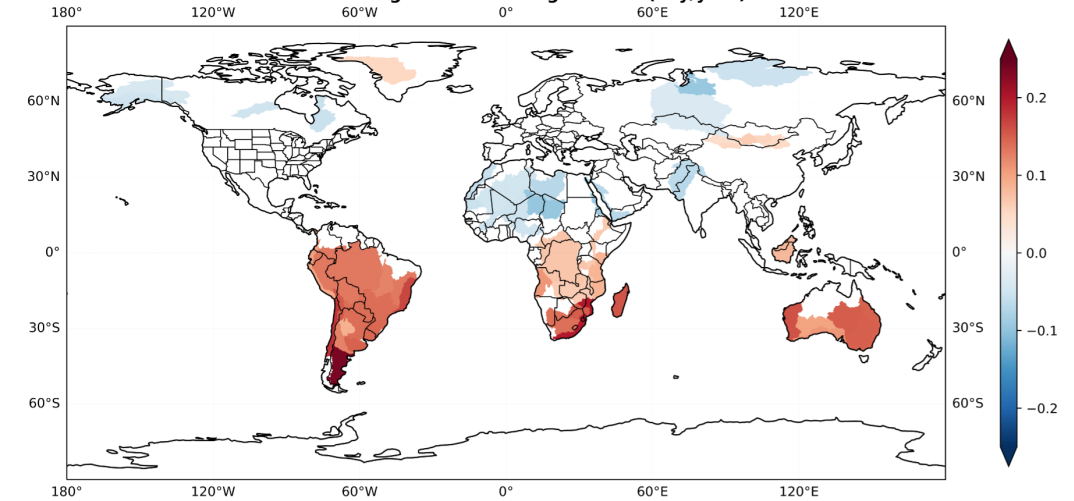

Central Africa
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
mean P
std P
mean Tair
std Tair
SH
wet spell
dry spell
FD-extent
FD-Dur
FD-onset

Figure2.

Rate of Change in Flash Drought Onset (day/year)



Rate of Change in Flash Drought Duration (day/year)

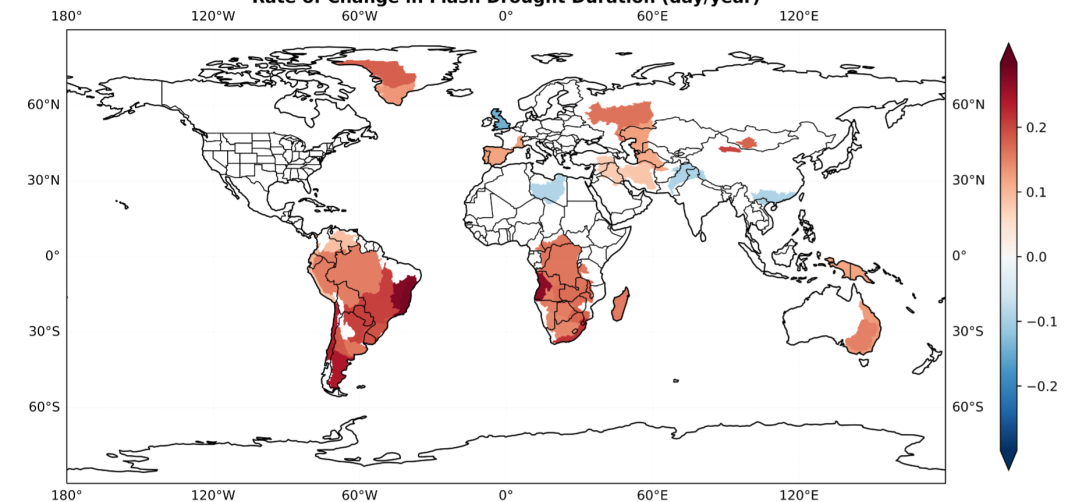
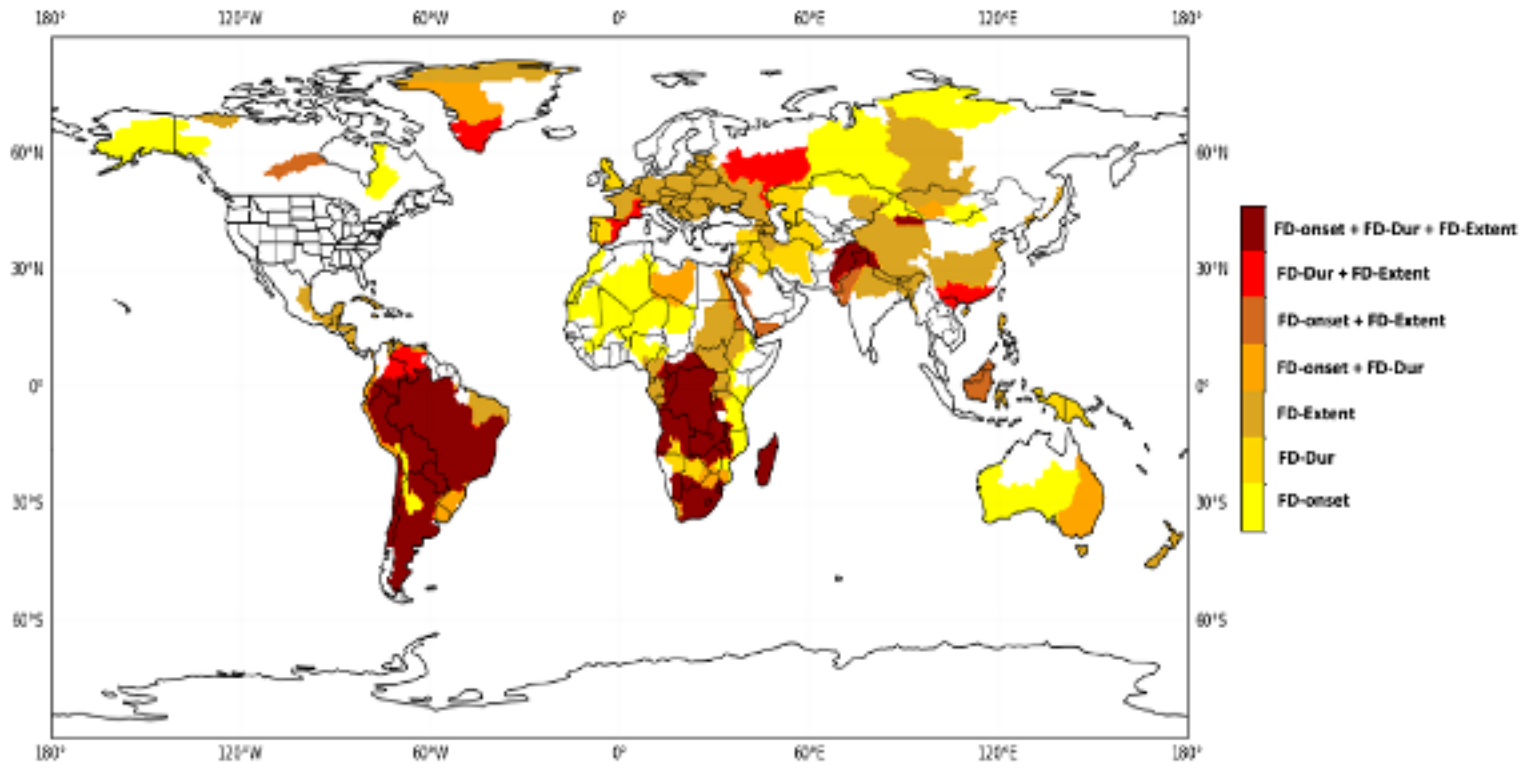


Figure3.


180°
120°W
60°W
0°
60°E
120°E
180°
60°N
30°N
0°
30°S
60°S
FD-onset + FD-Dur + FD-Extent
FD-Dur + FD-Extent
FD-onset + FD-Extent
FD-onset + FD-Dur
FD-Extent
FD-Dur
FD-onset