DROUGHT

# A global transition to flash droughts under climate change

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**Flash droughts have occurred frequently worldwide, with a rapid onset that challenges drought monitoring and forecasting capabilities. However, there is no consensus on whether flash droughts have become the new normal because slow droughts may also increase. In this study, we show that drought intensification rates have sped up over subseasonal time scales and that there has been a transition toward more flash droughts over 74% of the global regions identified by the Intergovernmental Panel on Climate Change Special Report on Extreme Events during the past 64 years. The transition is associated with amplified anomalies of evapotranspiration and precipitation deficit caused by anthropogenic climate change. In the future, the transition is projected to expand to most land areas, with larger increases under higher-emission scenarios. These findings underscore the urgency for adapting to faster-onset droughts in a warmer future.**

Droughts are periods of time with a persistent water deficit (*1*, *2*), which can cause devastating impacts on regional economies and environments (*3*–*5*), as well as on human health (*6*). Droughts mainly originate from large-scale internal climate variability, in which ocean-atmosphere teleconnections associated with phenomena such as the El Niño–Southern Oscillation, Pacific Decadal Variability, and Atlantic Multidecadal Variability play critical roles in drought formation and persistence over interannual to decadal time scales (*7*, *8*). For droughts that occur over shorter seasonal time scales, the dominant drivers can also include local or remote land-atmosphere feedbacks (*9*, *10*). The multiscale interactions among these different parts of the climate system raise challenges for drought forecasting and impact mitigation. Droughts are also influenced by anthropogenic forcings such as climate change (*2*, *11*), land use or land cover change, and human water consumption and management (*12*, *13*). As global warming accelerates the terrestrial water cycle (*14*, *15*), agricultural and hydrological droughts have increased substantially in many regions (*11*, *16*, *17*) and are projected to become more frequent, longer, and more severe in a warmer future (*2*, *11*, *18*). Such statements are based on analysis of droughts at seasonal, annual, or decadal time scales. However, recent studies have shown that droughts also occur frequently at subseasonal time scales worldwide (*4*, *5*, *19*–*24*) and can develop into severe droughts within a few weeks. These rapid-onset droughts are termed “flash droughts” in contrast with conventional droughts that evolve slowly. In addition to large precipitation deficits, flash droughts are also caused by abnormally high evapotranspiration that depletes soil water quickly (*25*–*29*), which challenges current drought monitoring and forecasting capabilities (*30*–*34*) that were developed to detect slowly evolving droughts.

The concept of flash droughts was proposed at the beginning of the 21st century but did not receive wide attention until the occurrence of the severe US drought in the summer of 2012 (*5*, *28*, *30*, *34*). This drought was regarded as one of the most severe US droughts since the 1930s Dust Bowl and caused more than US$30 billion of economic losses (*35*). One of the distinctive features of this drought was its extremely rapid onset, with many locations going from drought-free to extreme drought conditions within a month. This rapid intensification was unexpected, and no operational prediction models captured its onset (*30*). In this regard, some flash droughts can be considered as the onset stage of a long-term drought, the impacts of which are amplified by a subsequent persistent period of severe drought conditions (*23*, *30*, *36*). Moreover, even without a transition to seasonal drought, these rapidly evolving subseasonal droughts have substantial impacts on vegetation growth (*37*) and can trigger compound extreme events such as heat waves or wildfires. Previous studies have focused on the evolution and changing characteristics of flash droughts (*5*, *20*–*29*) and found that human-induced climate change has increased the frequency of flash droughts throughout southern Africa (*20*) and China (*21*). A recent study presents a 36-year climatology report of global flash droughts and shows substantial increases in flash droughts throughout several key regions (*38*). However, no consensus has been reached on whether there has been a transition from slow to flash droughts at the global scale, because the frequency of slower-developing droughts at subseasonal time scales may also increase. There is currently no robust evidence that drought intensification rates have increased globally, although several studies have speculated such increases by relating drought onset with global warming (*16*, *21*).

In this study, we investigated changes in the speed of global drought onset and the partitioning between flash and slow droughts. We divided subseasonal droughts into flash droughts (*21*, *28*) and slow droughts by onset speed measured by the declining rate of soil moisture and present their global distributions during the local growing season over the past 64 years. We then estimated the global trend of the ratio of the number of flash droughts to total subseasonal droughts and the global trend of the onset speed of subseasonal droughts and attributed these trends to anthropogenic climate change on the basis of the sixth Coupled Model Intercomparison Project (CMIP6) (*39*) climate model simulations (table S1). We also showed how these trends vary over different IPCC SREX (Intergovernmental Panel on Climate Change Special Report on EXtreme events) regions (*40*).

## Global distributions of flash and slow droughts

On the basis of estimates of soil moisture from three global reanalyses from 1951 to 2014, subseasonal drought events are identified as pentad-mean soil moisture declines from above the 40th percentile to below the 20th percentile and then increase to above the 20th percentile again [supplementary materials (SM), materials and methods]. The minimum duration for subseasonal droughts is 20 days to exclude dry spells that are too short to cause substantial impacts. We then divided the subseasonal droughts into flash and slow droughts depending on the rate of the reduction in soil moisture (*21*) during the onset stage (fig. S1). We used the ratio of flash drought events to the total number of subseasonal drought events, and the subseasonal drought onset speed (SM, materials and methods), to quantify the transition to flash droughts by determining whether there are significant trends in these two indices. Flash droughts tend to occur more often than slow droughts over humid regions with lower aridity (Fig. 1A and fig. S2), where flash-drought frequency is two to three times greater than other regions (fig. S3A). By contrast, slow drought occurrence has smaller spatial variability (fig. S3B). Flash droughts usually last for 30 to 45 days, whereas slow droughts usually last for 40 to 60 days (fig. S4). The uncertainty across

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