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Drought: Precipitation, Evapotranspiration, and Soil Moisture

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Abstract

Drought is the major hydrological disaster for human society, and encompasses multiple hydrological components. There are numerous definitions of drought, many of which do not include transpiration or evaporation (evapotranspiration, ET). We describe here the role of ET in drought, and why ET is important to consider when assessing drought. We emphasize the dynamic roles of ET, precipitation, and soil moisture, with a focus on the vegetation response during water stress. Finally, we conclude with a case study example of drought in Amazonia.

INTRODUCTION

Drought ranks as one of the most expensive natural disasters in terms of human welfare and food security. For example, in the United States the annual cost of drought relief measures has been estimated between US$6 and US$8 billion. Droughts can cover very large areas and last for several years with so-called megadroughts documented from medieval times.[1] In general terms, drought is caused by extremes within the natural variability of climate, but can be exacerbated by human activity (e.g., deforestation). The literature on drought is extensive, with definitions categorically ranging from meteorological (or, climatological, atmospheric), agricultural, hydrologic, and socio-economic (e.g., management based),[2–5] but we focus here on the vegetation transpiration and evaporation (or, actual evapotranspiration, ET) component of drought.[6] From a vegetation perspective in general, physical drought is the drying of soil such that the overlying vegetation experiences physiological water stress manifested in a reduction of productivity, loss of leaves/needles, and, ultimately, mortality. As such, a given soil moisture content (SMC) would correspond to different classes of drought depending on the ability of vegetation to adapt to decreased soil moisture. For instance, some species or stages of succession may have plants with deep roots that can tap deep sources of soil moisture, even the groundwater table, so the ability of these plants to withstand what would otherwise be considered a drought may, in fact, not be considered a drought for some time.[7] Other species, however, may be poorly adapted to low levels of soil moisture through sparse root distribution, low water use efficiency, or high temperature sensitivity, and thus may enter into a drought much more quickly than other, better adapted, species.

SMC is inherently coupled directly to precipitation (PPT) and ET, with PPT as the moisture input, and ET as the moisture withdrawal; soil water holding capacity acts as the intermediate "bucket" size if considering a bucket model of SMC change. Among those three variables (i.e., SMC, PPT, ET), the end members of SMC can be outlined: 1) for two areas with equivalent PPT and ET, SMC may be different because of different SMC retention properties (e.g., sandy soils may hold less water than soil with more clay); 2) for two areas with equivalent soils and PPT, SMC may be different because of different ET; and 3) for two areas with equivalent soils and ET, SMC may be different because of different PPT. The same exercise can be applied for areas to have similar SMC (e.g., two areas with equivalent soils, one with high PPT and high ET, and the other with low PPT and low ET). By this definition, and with reference to the title of this entry, ET can vary under drought or non-drought situations, although ET will go to zero under persistent and intense drought. Between the ET components, transpiration will go to zero as drought persists (assuming no deep water sources), because stomata close to avoid water loss (assuming no leaky stomata),[8] and plants will maintain respiration through carbon stores; evaporation from the soil surface will also go to zero as the soil dries out (assuming no hydraulic lift/redistribution from deep water sources).[9] The role of ET in drought is particularly pertinent in already water-limited environments where increasing temperatures over time accelerate ET, which leads to greater drought severities.[10]

Plants are typically able to withstand relatively short periods of SMC decline, so a given day with no PPT and high ET may not be considered a drought. Although there are different metrics of drought that take ET into account such as the widely used Palmer Drought Severity Index,[2]

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which uses the potential ET, it is the *cumulative water deficit* (CWD) that plants respond to – that is, the summation of days in which the soil water deficit (SWD) is below a critical water stress threshold. SWD may be calculated as follows:

IF PPT – ET > 0, THEN $\text{SWD}_1 = 0$,
ELSE $\text{SWD}_1 = \text{P} - \text{ET} + \text{SWD}_0$

where the subscripts indicate adjacent time steps. The maximum CWD (MCWD) reached during the time period of interest relative to the time-averaged climatological MCWD may be considered "drought."[11] Both the length of the CWD and the MCWD in a given period must surpass the long-term means of the two for that period to be considered a drought, although a corresponding vegetation water stress response is also necessary.

An example of MCWD drought and vegetation response is shown in the *Science* paper by Phillips et al.,[11] "Drought sensitivity of the Amazon rainforest." Here, we describe how measurements of anomalously low PPT indicated the possibility of an intense drought over Amazonia – the lowest PPT at the time, in fact, in the past 100 years. With few soil moisture measurements available, SWD was constructed from measured PPT, estimated ET using meteorological measurements,[12,13] and measurements of the soil water holding capacity. We calculated MCWD at 136 sites where we also observed vegetation response, and determined that sites experiencing the greatest hydrologic drought as defined by MCWD also had the greatest vegetation response, specifically mortality and biomass loss. It can be seen at one of the sites, for example (Fig. 1), that PPT varies seasonally, as does CWD, but in 2005 (also 1997 and 2001) CWD spikes well beyond the mean CWD for the 10-year record. In this analysis, the length and peak (MCWD) of the CWD spike vary by site and are proportional to the vegetation response (e.g., mortality).

CONCLUSION

Evaporation and transpiration are critical components to drought, although many traditional definitions of drought ignore ET. Vegetative drought inherently implies a response from vegetation, and this response must be calculated from a cumulative water deficit, as ET > P adds up over time, drying out the soil. In the absence of soil moisture measurements, soil moisture may be calculated from precipitation and ET. Even with soil moisture measurements, the understanding of the bioclimatic variables controlling ET helps elucidate and predict how drought will change given changes in the controlling factors.

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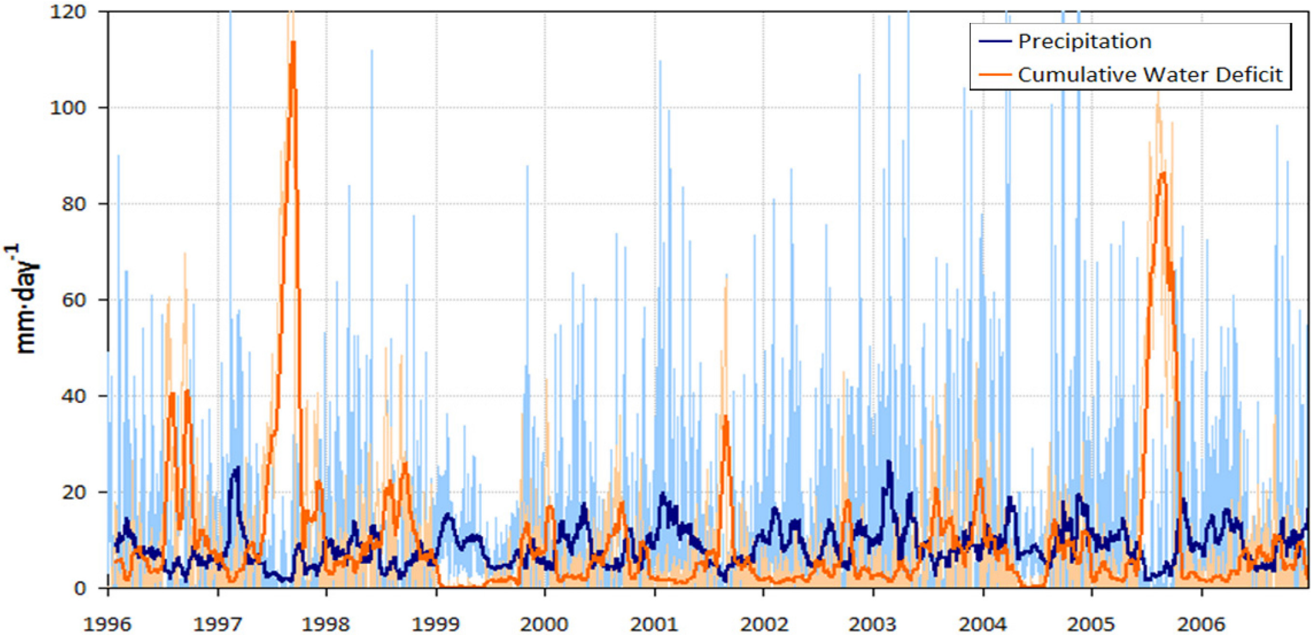

Fig. 1 Precipitation (black) and cumulative water deficit (gray) over 10 years for a site in Amazonia, described in Phillips et al.[11] The light colors are the daily values, and the dark colors are the 30-day moving averages.

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