

Definition of drought

According to the international meteorological community, drought can be defined in several ways. In particular, drought is a *'prolonged absence or marked deficiency of precipitation'*, a *'deficiency of precipitation that results in water shortage for some activity or for some group'* or a *'period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance'* (Heim, 2002; Trenberth et al., 2007). American Meteorological Society (1997) has defined three types of droughts: (i) *'Agricultural drought'* which is defined in terms of moisture deficits in upper layer of soil up to about one meter depth (ii) *'meteorological drought'* which refers to prolonged deficit of precipitation and (iii) *'hydrological drought'* which relates to low streamflow, lake and levels of groundwater. The American Meteorological Society (1997) policy statement was later replaced by another statement (American Meteorological Society, 2013) which besides the three types of drought above, covers also the *'socioeconomic drought'* which associates the supply and demand of some economic good with elements of meteorological, agricultural and hydrological drought (Heim 2002; Trenberth et al. 2007).

Drought indices

hello pridat referenci sombreok et al 1982 viz Kabubo-Mariara and Karanja (2007) A numerical measure is needed to compare severity of drought across different time periods or geographical locations. However, as a result of a large disagreement about a definition of drought, there is no single universal drought index. Instead of that a number of measures of drought has been developed (Heim, 2002). For an extensive overview of various drought indices see for example Heim (2002) or Keyantash and Dracup (2002).

Examples of early measures of drought are Wilhite and Glantz (1985), Munger (1916), Blumenstock (1942) or McQuigg (1954). Munger (1916) suggested to use length of period without 24-h precipitation of 1.27 mm. Wilhite and Glantz (1985) is based on a measure of precipitation over a given time period. Blumenstock (1942) proposed to measure severity of drought as a length of drought in days where the end of a drought is defined by occurrence of 2.54 mm of precipitation in 48 hours. McQuigg (1954) developed the Antecedent Precipitation Index (API) which is based on amount and timing of precipitation and it was used for forecasting of floods. Hence, the API is a reverse drought index.

The study of Palmer (1965) was a significant milestone in the history of quantification of drought severity. Palmer (1965) has developed the Palmer Drought Severity Index (PDSI) using a complex water balance model. The PDSI is based on a hydrological accounting system, which incorporate antecedent precipitation, moisture supply and moisture demand (Heim, 2002). As the PDSI suffers from several weaknesses (for details see e.g. Heim 2002), other indices were developed in the following decades. These include the standardized precipitation index (SPI) developed by McKee et al. (1993) and the standardized precipitation evapotranspiration index (SPEI) developed by Vicente-Serrano

et al. (2010). The SPI is based on cumulative probability of a given rainfall situation on a particular station. The SPEI is similar to SPI, but unlike SPI, the SPEI includes the role of temperature. It is based on water balance, therefore it can be compared to the self-calibrated PDSI (Vicente-Serrano et al., 2010).

Drought can be measured in absolute terms (e.g. lake levels or amount of soil moisture) or in relative measures, which is for example the PDSI (Trenberth et al., 2014). Because drought is defined based on one tail of probability distribution function of a drought measure, small decrease in mean can appear as a substantial increase in frequency of droughts. This has caused confusions and therefore usage of percentiles of soil moisture or streamflow is recommended as a better measure than mean (Trenberth et al., 2014).

Trenberth et al. (2014) discuss various formulations of the PDSI (Sheffield et al. 2012; Dai 2011). Sheffield et al. (2012) argue that the way how PDSI is formulated can have substantial effect on estimation of changes in severity of droughts over time. According to other studies, differences in formulation of the PDSI do not play big role and it is more important to formulate the index such that the required data are available and reliable (Trenberth et al., 2014; van der Schrier et al., 2011; Wang and Dickinson, 2012). Trenberth et al. (2014) attribute the differences between the results of Sheffield et al. (2012) and Trenberth et al. (2014) to disparities among various rainfall datasets and to different baseline periods they use rather than to different formulations of the PDSI.

Extreme events, disaster and hazards

Lavell et al. (2012) define extreme events as 'the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable'. Some authors define extreme events only in terms of meteorological phenomena (Easterling et al., 2000; Jentsch et al., 2007), others include also consequential physiological impacts or other effects on humans and ecosystems (Lavell et al., 2012; Young, 2002).

According to Lavell et al. (2012), disasters are defined as a 'severe alternations in the normal functioning of community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic or environmental effects that require immediate emergency response to satisfy critical human needs and that may acquire external support for recovery.' The hazardous physical events may be of natural, socio-natural, or purely anthropogenic origin (Lavell et al., 2012; Wisner et al., 2004).

Hazard can be defined as 'the potential occurrence of a natural or human induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources' Lavell et al. (2012).

Economic Effects of Droughts

Shifts in staple food demand curve don't tend to be very large. Hence, when staple food become scarce, its price is usually subject to a massive increase (Brown and Kshirsagar, 2015; Brown, 2014). For low income groups, this often leads to a reduction in calorie intake, malnutrition and increased risk of related health problems (Golden et al., 2011; Handa and Mlay, 2006). Local food prices are therefore a good indicator of food scarcity and insecurity (Baffes et al., 2017; Brown and Kshirsagar, 2015). Brown and Kshirsagar (2015) investigate effects of weather disturbances and international price changes on local food prices which they use as a measure of food scarcity. They use a Kalman Filter approach (see Durbin and Koopman (2012) for more details) and they focus on regions which contain large segments of low income population including locations in Africa, South Asia and Latin America. They conclude that almost 20% of local market prices are affected by domestic weather disturbances, 9% of them are affected by international price change and 4% are affected by both of them. Based on whether or not international food price and weather shocks are significant in explaining local food prices, Brown (2014) groups food markets in selected developing countries into four categories as follows: significantly affected by both international food prices and weather, significantly affected by weather but not by international food prices, significantly affected by international food prices but not by weather and not significantly affected by either of them. Brown (2014) then discuss common characteristics of markets in each of these groups.

Ochieng et al. (2016) estimate effects of climate variability and change on agricultural production¹ using panel data in Kenya. According to their results, the effects are significant yet different for different crops. Temperature has positive effect on tea and negative effect on production of maize and crop. Furthermore, rainfall affects production of tea negatively. On the other hand, Vrieling et al. (2011) finds positive correlation between precipitation and agricultural productivity.

Lesk et al. (2016) estimate national production losses per disaster worldwide during 1964 – 2007 using superposed epoch analysis. Besides drought, they focus on extreme heat, cold and flood events. They conclude that on average 10.1% reduction of cereal production can be linked to droughts and 9.1% reduction is attributable to extreme heat. They did not find any significant effect of extreme cold and floods on production. Mehrabi and Ramankutty (2017) estimate cumulative crop production losses resulting from heat and drought disasters over the same time period (1964 – 2007). Their estimates are almost half of those of Lesk et al. (2016). The biggest losses are in Botswana, Paraguay, Nigeria, Angola and USA.

Nicolai-Shaw et al. (2017) quantify relation between soil moisture drought and temperature, precipitation, evapotranspiration and vegetation during growing season. Using superposed epoch analysis, they find strong link between soil moisture drought and temperature,

¹Mesured as value of yields per acre in farm household

precipitation and evapotranspiration. Vegetation indices show a delayed response. Schwalm et al. (2017) analyse length of post-drought recovery time in terms of gross primary productivity. According to their results the recovery times are strongly associated with climate and carbon cycle dynamics and the recovery is the longest in the tropics and high northern latitudes. They also conclude that drought impacts have increased over the 20th century. Both Nicolai-Shaw et al. (2017) and Schwalm et al. (2017) analyse effects of drought globally.

Sandstrom and Juhola (2017) question whether drought is actually a major cause of food insecurity in Ethiopia, Kenya and Somalia. They analyse causes of the food crisis identified in the humanitarian appeal documents. Majority of these documents consider food availability and food production as a major cause of food crisis. Sandstrom and Juhola (2017) argue that there is a tendency to explain failure of more complex food systems as 'droughts' and insufficient attention is paid to non-climatic drivers such as food prices or conflicts. Sandstrom and Juhola (2017) also find that a large share of humanitarian response budget is focused on emergency food aid in comparison to the share focused on interventions to build resilience. They suggest to increase the budget share focused on agricultural and livestock production to build resilience.

Ricardian and production function approach

A large literature has focused on application of the Ricardian approach in the context of climate change (including changes in precipitation) and its effects on crop revenues in Africa (Bello and Maman, 2015; Kabubo-Mariara and Karanja, 2007; Kurukulasuriya et al., 2008; Seo et al., 2008). According to Seo et al. (2008) and Kurukulasuriya et al. (2008), if the warming will be mild and wet, crop net revenue should increase. In case of more severe and dry scenario, the crop revenue is likely to decrease (Kurukulasuriya et al., 2008; Seo et al., 2008). Bello and Maman (2015) conclude that increase in temperature will affect net crop revenue negatively while increase in precipitation is likely to increase the revenue. According to Kabubo-Mariara and Karanja (2007), global warming will be harmful for crop production.

Deschenes and Greenstone (2007) use a production function approach (as an alternative to the Ricardian approach) to estimate economic impact of climate change, including impact of change in precipitation on agricultural profit in the United States. Deschenes and Greenstone (2007) conclude that effect of global warming on agriculture should be positive in the US. In particular, agricultural yields should increase by 1.3 billion US dollars or 4%. However, the estimated 95% confidence interval is from -0.5 to 3.1 billion US dollars, hence, the estimated effect is not very large.

CGE

Robinson et al. (2010) use a Social Accounting Matrix (SAM) based CGE model to simulate impacts of food production and price shocks on household consumption in Ethiopia. They model a drought (or a disease) as a 20% reduction in crop productivity and a 20% decrease in livestock capital in lowland plains and drought-prone highlands in Ethiopia and they conclude that this would cause a real income loss on order of 2.3% of Ethiopia's GDP. They also consider two alternative scenarios, i.e. variations in food aid and change in international prices.

Willenbockel (2011) uses the GLOBE Computable General Equilibrium model of the global economy to estimate food prices for various 2030 scenarios. According to his results, climate change will lead to substantial increase in both domestic and world market crop prices in comparison to baseline scenario in the absence of climate change. However, the increase in prices can be substantially mitigated if appropriate adaptation measures will be taken in sub-Saharan Africa (Willenbockel, 2011).

Trends

Strong downwards trend in precipitation has been observed in the tropics from 10°N to 10°S, especially after 1977 (Trenberth et al., 2007). During the period 1900 – 2005, the climate has become wetter in many parts of the world (eastern parts of America, northern Europe, northern and central Asia) but it has become much drier in Mediterranean, Sahel, southern Africa and parts of Southern Asia. Furthermore, increased frequency of heavy rain events has been observed also in the areas with decline in total rainfall (Trenberth et al., 2007). Trenberth et al. (2014) argue that as a consequence of global warming, dry areas have strong tendency to get drier while wet areas are getting wetter.

References

- American Meteorological Society (1997). Meteorological drought policy statement. Technical report.
- American Meteorological Society (2013). Drought - an information statement of the american meteorological society. Technical report.
- Baffes, J., Kshirsagar, V., and Mitchell, D. (2017). What drives local food prices? evidence from the tanzanian maize market. *The World Bank Economic Review*.
- Bello, G. H. M. and Maman, M. N. M. (2015). A ricardian analysis of the impact of temperature and rainfall variability on ag-riculture in dosso and maradi regions of niger republic. *Agricultural Sciences*, 6:724–733.
- Blumenstock, G. (1942). *Drought in the United States analyzed by means of the theory of probability*. US Department of Agriculture.
- Brown, M. E. (2014). *Food security, food prices and climate variability*. Routledge.
- Brown, M. E. and Kshirsagar, V. (2015). Weather and international price shocks on food prices in the developing world. *Global Environmental Change*, 35(Supplement C):31 – 40.
- Dai, A. (2011). Characteristics and trends in various forms of the palmer drought severity index during 19002008. *Journal of Geophysical Research: Atmospheres*, 116(D12).
- Deschenes, O. and Greenstone, M. (2007). The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *The American Economic Review*, 97(1):354–385.
- Durbin, J. and Koopman, S. J. (2012). *Time series analysis by state space methods*, volume 38. OUP Oxford.
- Easterling, D. R., Meehl, G. A., Parmesan, C., Changnon, S. A., Karl, T. R., and Mearns, L. O. (2000). Climate extremes: observations, modeling, and impacts. *science*, 289(5487):2068–2074.
- Golden, C. D., Fernald, L. C. H., Brashares, J. S., Rasolofoniaina, B. J. R., and Kremen, C. (2011). Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. *Proceedings of National Academy of Sciences of the United States of America*, 108(49):1965319656.
- Handa, S. and Mlay, G. (2006). Food consumption patterns, seasonality and market access in mozambique. *Development Southern Africa*, 23(4):541–560.

- Heim, R. R. (2002). A review of twentieth-century drought indices used in the united states. *Bulletin of the American Meteorological Society*, 83(8):1149–1165.
- Jentsch, A., Kreyling, J., and Beierkuhnlein, C. (2007). A new generation of climate-change experiments: events, not trends. *Frontiers in Ecology and the Environment*, 5(7).
- Kabubo-Mariara, J. and Karanja, F. K. (2007). The economic impact of climate change on kenyan crop agriculture: A ricardian approach. *Global and planetary change*, 57(3):319–330.
- Keyantash, J. and Dracup, J. A. (2002). The quantification of drought: an evaluation of drought indices. *Bulletin of the American Meteorological Society*, 83(8):1167–1180.
- Kurukulasuriya, P., Mendelsohn, R., et al. (2008). A ricardian analysis of the impact of climate change on african cropland. *African Journal of Agricultural and Resource Economics*, 2(1):1–23.
- Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., Muir-Wood, R., and Myeong, S. (2012). *Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change.* Cambridge University Press.
- Lesk, C., Rowhani, P., and Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature*, 529.
- McKee, T. B., Doesken, N. J., Kleist, J., et al. (1993). The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th Conference on Applied Climatology*, volume 17, pages 179–183. American Meteorological Society Boston, MA.
- McQuigg, J. (1954). A simple index of drought conditions. *Weatherwise*, 7(3):64–67.
- Mehrabi, Z. and Ramankutty, N. (2017). The cost of heat waves and droughts for global crop production. *bioRxiv*.
- Munger, T. T. (1916). Graphic method of representing and comparing drought intensities. *Monthly Weather Review*, 44(11):642–643.
- Nicolai-Shaw, N., Zscheischler, J., Hirschi, M., Gudmundsson, L., and Seneviratne, S. I. (2017). A drought event composite analysis using satellite remote-sensing based soil moisture. *Remote Sensing of Environment*.
- Ochieng, J., Kirimi, L., and Mathenge, M. (2016). Effects of climate variability and change on agricultural production: The case of small scale farmers in kenya. *NJAS - Wageningen Journal of Life Sciences*, 77(Supplement C):71 – 78. Social science perspectives on the bio-economy.

- Palmer, W. C. (1965). *Meteorological drought*, volume 30. US Department of Commerce, Weather Bureau Washington, DC.
- Robinson, S., Willenbockel, D., Ahmed, H., and Dorosh, P. (2010). Implications of food production and price shocks for household welfare in ethiopia: a general equilibrium analysis.
- Sandstrom, S. and Juhola, S. (2017). Continue to blame it on the rain? conceptualization of drought and failure of food systems in the greater horn of africa. *Environmental Hazards*, 16(1):71–91.
- Schwalm, C., Anderegg, W., Michalak, A. M., Fisher, J. B., Biondi, F., Koch, G., Litvak, M., Shaw, J., Wolf, A., Huntzinger, D., Schaefer, K., Cook, R., Wei, Y., Fang, Y., Hayes, D., Huang, M., Jain, A., and Tian, H. (2017). Global patterns of drought recovery. *Nature*, 548.
- Seo, S. N., Mendelsohn, R., Dinar, A., Hassan, R., and Kurukulasuriya, P. (2008). A ricardian analysis of the distribution of climate change impacts on agriculture across agro-ecological zones in africa. Technical Report 4599, World Bank. Policy Research Working Paper.
- Sheffield, J., F.Wood, E., and Roderick, M. L. (2012). Little change in global drought over the past 60 years. *Nature*, 491:435–438.
- Trenberth, K. E., Dai, A., Van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., and Sheffield, J. (2014). Global warming and changes in drought. *Natural Climate Change*.
- Trenberth, K. E., Jones, P. D., et al. (2007). *IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S. and D. Qin, M. Manning and Z. Chen and M. Marquis and K.B. Averyt and M.Tignor and H.L. Miller (eds.)]*. Cambridge University Press.
- van der Schrier, G., Jones, P. D., and Briffa, K. R. (2011). The sensitivity of the pdsi to the thornthwaite and penman-monteith parameterizations for potential evapotranspiration. *Journal of Geophysical Research: Atmospheres*, 116(D3).
- Vicente-Serrano, S. M., Beguera, S., and Lopez-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, 23(7):1696–1718.
- Vrieling, A., de Beurs, K. M., and Brown, M. E. (2011). Variability of african farming systems from phenological analysis of ndvi time series. *Climatic Change*, 109(3):455–477.

- Wang, K. and Dickinson, R. E. (2012). A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability. *Reviews of Geophysics*, 50(2).
- Wilhite, D. A. and Glantz, M. H. (1985). Understanding: the drought phenomenon: the role of definitions. *Water international*, 10(3):111–120.
- Willenbockel, D. (2011). Exploring food price scenarios towards 2030 with a global multi-region model. *Oxfam Policy and Practice: Agriculture, Food and Land*, 11(2):19–62.
- Wisner, B., Blaikie, P., Cannon, T., and Davis, I. (2004). At risk: natural hazards, people’s vulnerability and disasters.
- Young, P. C. (2002). Advances in real-time flood forecasting. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 360(1796):1433–1450.