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Niemeyer S.

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S. Niemeyer
European Commission, DG Joint Research Centre,
Institute for Environment and Sustainability,
T.P. 261, JRC-IES, I-21020 Ispra (VA), Italy

SUMMARY – In this paper drought indices from different disciplines and derived from different data sources are reviewed. For each category of meteorological, hydrological, agricultural, comprehensive, remote sensing-based, and combined drought indices the current state of development is described. While in the field of remote sensing-derived drought indices every year a large number of new indices is proposed, in function of new datasets that become available, the development of new drought indices based on meteorological and hydrological data is more focused on practical applications. The combination of drought indices from different domains seems to be the most promising, but also the most demanding way forward to draw a comprehensive picture of a drought situation.

Key words: Aggregate Drought Index (ADI), Reconnaissance Drought Index (RDI), Evapotranspiration Deficit Index (ETDI), Regional Streamflow Deficiency Index (RDI), Normalized Multi-Band Drought Index (NMDI), Vegetation Drought Response Index (VegDRI).

Introduction

Drought indices are indispensible tools to detect, monitor, and evaluate drought events. Droughts are common throughout the globe with a devastating damage potential on agriculture, economy, and society in many parts of the world. At the same time, due to the multi-discipline character of this natural hazard, a single, unique definition of a drought does not exist, but is subject to the domain of interest of the observer (e.g. Wilhite and Glantz, 1985; Maracchi, 2000; Tate and Gustard, 2000). Drought indices essentially face the same problem. As there is no single and uniquely accepted definition of a drought, there is no single and universal drought index, either.

The motivation to develop drought indices is manifold. From the scientific point of view, it is a challenging task to develop an indicator that allows for drought detection, monitoring, and evaluation of drought events. The exploitation of new technologies that provide novel datasets as well as the application of new or at least en-vogue methodologies from related disciplines are surely important drivers to develop drought indices, too. Equally important, however, has always been the requirements of the practitioner e.g. in agriculture or water resources management. Here, the emphasis is put on reliability and robustness of the index as well as on the aspect of routine data availability to construct it. This variety in motivation is mirrored in the variety of drought indices available in literature. In practical applications such as operational drought monitoring systems, however, it is essentially a very limited handful of drought indices that is applied. Restricted data availability, but also the intuitive disposition to rely on already proved methodologies might contribute to this limitation.

Drought indices have been developed by several generations of researchers during the 20th century in the domains of meteorology, hydrology, agricultural research and application, remote sensing, and water resources management. More than 80 drought indices have been easily identified by the author, and probably the total number is close to double. Reviews and classifications of drought indices have been produced regularly during the last decades, thus providing a good overview on the period's state of art and development. Examples of such reviews are – among others – Heim (2000, 2002), Vogt and Somma (2000), and Hayes *et al.* (2007), or the information available in the internet e.g. at the International Water Management Institute (IWMI, 2008).

This paper categorizes drought indices by their use of disciplinary data and gives a brief overview of existing drought indices in these categories. Examples of established drought indices show the current state in application, while the most recent drought indices in these fields are given in order to depict the current research front of this topic. The categorization should not be considered exhaustive, and often there is overlap between the disciplines. Hydrological modelling might produce datasets on soil moisture that are applied in the development of an agricultural drought index, or remote sensing data are used to observe purely meteorological drought phenomena. In order to account for the multi-disciplinary character of some drought indices, they are categorized as comprehensive and combined drought indices.

Development of drought indices

Meteorological drought indices

Besides the scientific perspective, the availability of suitable data to construct a drought index determines strongly the development of drought indices. The first generation of drought indices relied essentially on meteorological variables that were observed at synoptic meteorological stations. Accordingly, these indices were classified as meteorological drought indices. Examples of this type of drought indices are the Rainfall Anomaly Index (RAI; van Rooy, 1965), the Bhalme and Mooley Drought Index (BMDI; Bhalme and Mooley, 1980), the Standardized Anomaly Index of Katz and Glantz (1986), the Pálfai Aridity Index (PAI) developed and applied predominantly in Hungary (Pálfai, 1991), the Drought Severity Index (DSI) often used in the UK (Bryant *et al*., 1992), the most popular Standardized Precipitation Index (SPI; McKee *et al*., 1993), or the Effective Drought Index (EDI) that is considering the effective precipitation (Byun and Wilhite, 1999).

The Reconnaissance Drought Index (RDI) proposed by Tsakiris *et al*. (2007) is one of the most recent developments in the field of meteorological drought indices. Essentially, it relates precipitation to the potential evapotranspiration at a location, and can be considered as an extension of the SPI. By standardization and normalization it receives the same drought severity classes as the SPI. However, Tsakiris *et al*. (2007) state that especially the characterization of drought severity could be improved in test areas of the Mediterranean region as compared to SPI.

Comprehensive drought indices

With the development of the classical and still highly popular Palmer Drought Severity Index (PDSI; Palmer, 1965), a more comprehensive picture of the water cycle and its elements was drawn to characterize a drought event. For this type of drought index, besides meteorological parameters, typically information on soil moisture – in case of PDSI the available water content of the soil – was added. Palmer proposed also derivates of the PDSI such as the Palmer Modified Drought Index (PMDI) developed for the US National Weather Service for operational real-time application, the Palmer Hydrological Drought Index that considers hydrological impacts on reservoirs or groundwater levels that have a longer time dimension than the original PDSI, and the moisture anomaly or Z-index [see Heim (2002) for a detailed comparison]. The latter index is lacking the back-looking procedure of the PDSI and is considering the moisture conditions of the current month as compared to the average conditions only.

While the PDSI and its derivates have been evaluated and criticized in numerous studies (e.g. Alley, 1984), several authors proposed improvements of the PDSI until today, such as the self-calibrated PDSI (Wells *et al.,* 2004), or a PDSI with modified potential evapotranspiration derivation, replacing the original, but arguable Thornthwaite method by a Penman-Monteith term (e.g. Burke *et al*., 2006) or a Priestley-Taylor formulation (Mavromatis, 2007).

The new comprehensive multivariate Aggregate Drought Index ADI has been proposed by Keyantash and Dracup (2004). This index considers information from meteorology (precipitation), hydrology (streamflow, reservoir storage), and land surface (evapotranspiration, soil moisture, snow water content). Measured data input is preferred to simulation results, which is however not always possible, especially in the case of soil moisture. The derivation of the ADI includes principle component analysis to extract the strongest signal from the correlation of the input variables that explains the largest fraction of variance. In a test case for California, considerable correlation was found with the PDSI, although the ADI behaved more conservative than the PDSI, as it takes more elements of the hydrological cycle into account to determine a drought situation. The authors describe the advantages of the ADI as the comprehensive character and the straightforward mathematical formulation that allows for an operational application.

Agricultural drought indices

Starting from the PDSI and specializing on soil moisture and actual evapotranspiration led to the development of explicit agricultural drought indices, such as the Crop Moisture Index (CMI) developed by Palmer (1968) that is looking at evapotranspiration rather than precipitation deficits. More recent agricultural drought indices are the Soil Moisture Drought Index (SMDI; Hollinger *et al.*, 1993) or the Crop Specific Drought Index (CSDI; Meyer *et al.*, 1993), with applications to corn (Meyer *et al.*, 1993) and soybean (Meyer and Hubbard, 1995).

Recently, two new agricultural drought indices have been proposed by Narasimhan and Srinivasan (2005). Their intention was to develop a drought index at a high spatial (4 km) and temporal (daily to weekly) resolution as required to reflect short-term dry conditions important for local agricultural applications, and to make use of simulation results of the distributed hydrological SWAT model in the region of application. The proposed Soil Moisture Deficit Index (SMDI) is computed as the weekly soil moisture normalized by long-term statistics. Weekly values are then added on an incremental basis to account for the duration of a drought. The SMDI is computed separately for different soil depths in order to consider the varying rooting depth for different crops and stages of plant development. The Evapotranspiration Deficit Index (ETDI) is computed similar to the SMDI, but considers the water stress ratio of potential to actual evapotranspiration instead of soil moisture.

Compared to PDSI and SPI, the two new indices SMDI and ETDI show in general a high correlation, indicating a satisfying identification of drought events. In detail, ETDI and SMDI for low soil depths were better correlated to short-term SPI (1-3 months), while the SMDI for deeper soil layers corresponded better to the more slowly reacting PDSI and SPI of 6-12 months.

Marletto *et al.* (2005) proposed recently another new agricultural drought index called DTx for regional application. It is based on the daily transpiration deficit as computed by a water balance model, and describes the integrated deficit of transpiration of a crop for a period of x days; e.g. DT180 indicates the deficit of the 180 precedent days. When compared to SPI this index showed advantages, as it takes into account not only the precipitation deficit, but also the effects of landuse, soils, and especially the climatic conditions that govern the crop's transpiration.

Hydrological drought indices

Another class of drought indices has been developed in the hydrological domain. In classical hydrology it has been preferred to analyse streamflow data from gauging stations by sophisticated methods, like e.g. flow duration curves or recession analysis, that resulted in low flow indices such as Q90 or the Base Flow Index (Institute of Hydrology, 1980); see Tallaksen and van Lanen (2004) for overview.

Following this approach, Stahl (2001) developed a Regional Streamflow Deficiency Index (RDI) to detect regional drought events from timeseries of measured discharge data. This two-step methodology firstly computes a deficiency indicator from individual streamflow timeseries, taking into account the 90% exceedance threshold (Q90) derived from the flow duration curve. In a second step, the deficiency indicator of an individual gauging station is compared to the neighbouring stations of the region. Only if a substantial number of stations show a similar pattern of low flows, a regional drought event is detected. This methodology has been applied e.g. in France by Prudhomme and Sauquet (2007).

From the entire water cycle perspective, hydrology-oriented drought indices have been developed in order to characterize the comprehensive picture of the water balance in a catchment area for water management purposes, with special focus on discharge producing processes such as snow accumulation and melt. While the already mentioned Palmer Hydrological Drought Index (PHDI) does not account for snow accumulation, the Surface Water Supply Index (SWSI) of Shafer and Dezman (1982) does. The SWSI is probably the best-known example of a hydrological drought index.

Weghorst (1996) proposed the Reclamation Drought Index (RDI) for the operational detection of drought events and for the triggering of relief, if a certain severity level was reached. The RDI takes into account air temperature for the demand side, and precipitation, reservoir storage, streamflow, and snowpack for the supply side, as well as the duration of a drought event. Opposite to the two new agricultural drought indices, the focus of the RDI is to identify onset and end of a drought period in a more conservative way, i.e. not taking into account short term variations. As a result, although also computed on a monthly basis, the RDI behaves more slowly even compared to the PHDI.

Remote sensing-based drought indices

The development of Earth observation satellites from the 1980s onwards equipped with sensors mainly in the optical domain opened a new road for drought monitoring and detection. The new technologies allowed for the derivation of truly spatial information at global or regional coverage with a consistent method and a high repetition rate. Numerous indices were developed to describe the state of the land surface, mainly of vegetation, with the potential to detect and monitor anomalies such as droughts. A good overview on the first generation of remote sensing based drought monitoring is given in Gutman (1990), while Kogan (1997) provides an update almost one decade later. A recent review is given by Bayarjargal *et al*. (2006).

The most prominent vegetation index is certainly the Normalized Difference Vegetation Index (NDVI; Tucker, 1979) that was first applied to drought monitoring by Tucker and Choudhury (1987). This study triggered several derivates for drought monitoring such as the Vegetation Condition Index (VCI; Kogan, 1990, 1995), the anomaly of the NDVI called NDVIA (Anyamba *et al.,* 2001), or the Standardized Vegetation Index SVI (Peters *et al.,* 2002).

In addition to the information derived from the optical domain, also the thermal channels of Landsat Thematic Mapper (TM) and the Advanced Very High Resolution Radiometer (AVHRR) sensors were exploited, resulting in the retrieval of land surface temperature estimates (LST). Applying the thermal channels to drought monitoring, Kogan (1995) proposed the Temperature Condition Index (TCI). Most promising was the final combination of optical and thermal information into the Vegetation Temperature Index (VTI) or Vegetation Health Index VHI by Kogan (1997, 2000). Exploiting the strongly negative correlation between vegetation indices based on visible or near infrared information (predominantly NDVI) on the one hand and brightness or land surface temperature on the other hand for drought applications has been and is still a wide field of study [e.g. Carlson *et al*. (1994), Moran *et al*. (1994), but also McVicar and Bierwirth (2001), Bayarjargal *et al*. (2006)].

While Carlson *et al*. (1994) exploited the slope of the LST versus NDVI relationship, Moran *et al*. (1994) constructed a so-called Vegetation Index / Temperature Trapeziod (VITT) as an extension of the Crop Water Stress Index (CWSI) proposed earlier by Jackson *et al*. (1981) that did not take into account remote sensing data yet. Furthermore, two explicit drought indices have been constructed on the basis of the NDVI/LST reflectance space: (i) the Vegetation Temperature Condition Index VTCI (e.g. Wan *et al.,* 2004) as the ratio of LST differences among pixels with a given NDVI value in a sufficient large area; and (ii) the Temperature Vegetation Dryness Index TVDI (Sandholt *et al.,* 2002) that is built on an empirical relationship between LST and NDVI. Critical to both indices is the determination of the "dry and wet edges" and "warm and cold edges" of the LST/NDVI spaces, respectively, as the normalization of the LST/NDVI relationship depends strongly on the extremes observed of the calibration period.

Recently, Ghulam *et al*. (2007a,b) tried to exploit the relationship between NDVI and broad-band albedo, replacing LST, and applied their methodologies to data derived from the Enhanced Thematic Mapper Plus (ETM+) and Moderate Resolution Imaging Spectrometer (MODIS) sensors. Ghulam *et al*. (2007a) proposed the Vegetation Condition Albedo Drought Index (VCDAI), but stated some considerable problems related to the amount and variety of input data needed to define the entire NDVI/albedo spectral space for dry and wet as well as for densely and hardly vegetated surfaces. Then Ghulam *et al*. (2007b) proposed the Perpendicular Drought Index (PDI) that is again exploiting the near-infrared and red spectral reflectance space. This index is derived directly from the atmospherically corrected reflectances in the near infrared and red band and a perpendicular geometrical construction on the two bands' reflectance space. The PDI was then improved by Ghulam *et al*. (2007c) into the Modified Perpendicular Drought Index (MPDI) in that it included the fraction of vegetation of a pixel that accounted for soil moisture and vegetation growth. Consequently, according to the authors, the MPDI outperformed the PDI on vegetated surfaces.

This kind of technology-driven derivation of drought indices followed –and is still closely following– the development of new sensors. While the first generation of remote sensing-based drought indices relied on the few optical bands as provided by the NOAA AVHRR or Landsat TM sensors, a new generation attempts to make use of the multi-band capabilities of e.g. the MODIS sensor on board Terra/Aqua satellites. A recent example of the latter category is the Normalized Multi-Band Drought Index (NMDI) as proposed by Wang and Qu (2007). The NMDI is based on one near infrared and two short-wave infrared channels, exploiting the slope of the two water-sensitive absorption bands 6 and 7 of MODIS. It is essentially an improvement of the Normalized Difference Water Index (NDWI) proposed by Gao (1996) that was relying on two bands, one in the near and one in the short-wave infrared.

A fairly different approach to exploit remote sensing data to construct a drought index has been presented very recently by Liu *et al*. (2008). The authors proposed a Remote Sensing Drought Risk Index (RDRI) on the basis of a linear combination of three cloud indices that describe the length of the continuous absence of clouds (hence no precipitation), the ratio between cloudy and non-cloudy days, and the length of the longest continuous cloud cover. The methodology was applied to data of the Chinese operational meteorological FY-2c satellite, and – according to the authors – outperformed the Vegetation Condition Index (VCI; Kogan, 1990, 1995) derived from MODIS on the percentage of correctly identified droughts in an application in China during 2005/06.

Combined drought indices

The latest generation of drought indices developed in the last decade tries to incorporate and exploit a maximum of information that is readily available and proofed to be useful in specialized drought indices. The combination of meteorological data with remote sensing derived land surface information is typical for this type of drought indices. This combination is already performed operationally on a manual basis within the US Drought Monitor (NDMC, 2008), however without a single reproducible quantitative drought index that comprises all information.

The recently developed Vegetation Drought Response Index (VegDRI; Brown *et al.,* 2008) is the first and prominent example and probably currently the most comprehensive drought index available. VegDRI combines NDVI datasets as derived from NOAA AVHRR with climate-based SPI and PDSI drought indices as derived from observations from selected stations of the synoptic network. It thus overcomes the deficiencies of either data source, i.e. for the NDVI the lack of discrimination of vegetation stress from sources other than drought, and for the climate data their dependence on the density of the network stations and the inevitable spatial interpolation of point station data. Additional static biophysical information such as elevation, landuse, soil water capacity, or percentage of irrigated agriculture is included in the derivation of VegDRI, too. The index was designed for operational near-real time use in the US with a spatial resolution of the underlying NDVI dataset of 1 km and a temporal update every 14 days.

Due to its comprehensive character the computation of VegDRI is rather demanding with respect to data organization and processing. From all input data collected in a database three seasonal (spring, summer, autumn) linear regression models are built with which the final maps of VegDRI are produced. The index is currently under evaluation and will be made public within the next few years as an objective and operational drought monitoring tool at the US National Drought Mitigation Centre. According to Brown *et al*. (2008), the first results on 15 states in the central US compare qualitatively well to the manually generated Drought Monitor products.

Conclusions

The overview on the development of drought indices given in this paper indicates the directions in which future developments will point. Most progress is made in the field of exploiting novel remote sensing information, as data of new sensors become available. Here, some authors provide new indices on a yearly basis or even more frequently. Not only the derivation of drought indices from single new sensors, but also the combination of different sensors will surely remain a wide field for research in this domain.

From the recent developments of agricultural drought indices it can be deduced that practitioners prefer to get hands on indices that are simple to apply and as specific as possible to their crops. This tendency will probably be enforced by the increasing establishment of drought management plans in almost all parts of the world, mainly on the basis of hydrological catchment areas. Here, specific drought indices are required in order to define indicators, thresholds, and triggers for practical management of water resources in case of drought. These indices have to describe best the local and regional conditions of the hydrological cycle, and have to comply with the already available data that are measured routinely.

On the other hand, drought observatories on the continental scale will aim at applying drought indicators that produce a consistent image of the hydric state of the land surface over the entire area, and that use a consistent set of input data such as from remote sensing. Both continental and local applications do not exclude each other, but will be complementary and will provide valuable insight into the phenomenon of droughts from different perspectives.

Common to all newly developed drought indices is the issue of validation. Often, the new indices are compared to old, already established indices with good agreement, although the initial idea was to develop an index with a better performance. Furthermore, the validation exercise is mostly restricted to a few test cases in specific regions and periods. While there is clearly a need for targeted drought indices as mentioned before, it is equally important that the boundary conditions and limitations, under which a new index has been developed and tested, are explicitly described. Frequently especially the criteria to evaluate the performance of the drought index, which are certainly application dependent, are omitted or marginalized. For an external user, however, it is often more important to know about these boundary conditions of a new drought index than the choice of the index itself.

When compiling this paper it was striking that certain acronyms of drought indices were already occupied twice or even three-times for different indices (e.g. RDI). While the confusion created by the different meanings of the same abbreviation might be still minor to the expert community, it might be a first indication that the "market of drought indices" is slowly saturating, and that it will be increasingly difficult to maintain a good overview. Instead of developing more new single drought indices, the combination into more comprehensive and integrative drought monitoring and detection tools seems to be the more promising way.

To this end, the combination of remote sensing derived drought indices and those derived from climatic networks such as VegDRI, possibly in combination with a comprehensive low-flow analysis from (measured and/or simulated) streamflow data would be the most desirable way to paint a full picture of a drought situation. Here, most of the future work on the derivation of new drought indices should be directed to.

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