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Drought risk and meteorological droughts

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1. The Urgent Need for Studying Drought Risks

It is estimated that by 2020, the world population will reach 7.5 billion and that much of this population growth will occur in the developing world. To meet the increasing global demand for cereals, the world's farmers will have to produce 40 percent more grain in 2020. Growth of world agricultural output is expected to fall to 1.5 percent per year over the next three decades and further to 0.9 percent per year in the succeeding 20 years to 2050, compared with 2.3 percent per year since 1961. Many of the least developed countries, particularly those located in marginal production environments, continue to experience low or stagnant agricultural productivity, rising food deficits, and rising levels of hunger and poverty. Today, 32 countries have high rates of undernourishment, high population growth rates, poor prospects for rapid economic growth and often meagre agricultural resources. The population of these poor countries is expected to increase from the current 580 million people to 1.39 billion by 2050. The challenge is to revive agricultural growth at the global level and extend it to those left behind. The causes are varied but civil strife and adverse weather predominate. This disturbing trend has many implications for food security of the growing populations of the world.

In the developing countries, where adoption of improved technologies is too slow to counteract the adverse effects of varying environmental conditions, climate fluctuations are indeed the main factors which prevent a regular supply and availability of food, the key to food security. It has been demonstrated that judicious application of meteorological, climatological and hydrological knowledge and information, including effective early warning systems, greatly assist the agricultural community to develop and operate sustainable agricultural systems and increase production in an environmentally sustainable manner.

There have been several intense droughts and heat waves in the recent years, such as those in Europe in 2003, southeast Australia in 2009, and Argentina in 2008/09, which have increased the concern that droughts may be increasing in frequency. Millions of people face drinking water shortages in southwestern China this year because of a once-a-century drought that has dried up rivers and threatens vast farmlands. From January to August 2010, serious to

severe rainfall deficiencies occurred over much of western Western Australia, and areas of lowest on record rainfall have intensified in southwestern parts. In southwest WA in particular, below average rainfall in the months of April to August has resulted in record or near record low rainfall in the region. This year in Russia, the highest recorded temperatures Russia has ever seen in 130 years of recordkeeping occurred, the most widespread drought in more than three decades and massive wildfires have stretched across seven regions, including Moscow. What are the implications of these droughts in Russia ? Russia is one of the largest grain producers and exporters in the world, normally producing around 100 million tons of wheat a year, or 10 percent of total global output. It exports 20 percent of this total to markets in Europe, the Middle East and North Africa. The Russian Government announced on 5 August 2010 that it would temporarily ban grain exports from Aug. 15 to Dec 31. The recent drought occurrences around the world are consistent with the WMO/UNEP Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, which stated that the world has been more drought-prone during the past 25 years and that climate projections indicate an increased frequency in the future.

In the context of climate variability and change, water scarcity and food security, there is an urgent need to develop better drought monitoring and early warning systems. Effective drought early warning systems must integrate precipitation and other climatic parameters with water information such as stream flow, snow pack, ground water levels, reservoir and lake levels, and soil moisture into a comprehensive assessment of current and future drought and water supply conditions. Closer cooperation is required therefore among authorities responsible for addressing drought issues at local, national and regional levels.

2. Understanding Droughts

Drought differs from other natural hazards in a variety of ways. Drought is a slow-onset natural hazard that is often referred to as a creeping phenomenon. It is an accumulated departure of precipitation from normal or expected (i.e., a long-term mean or average). This accumulated precipitation deficit may accumulate quickly over a period of time, or it may take months before the deficiency begins to show up in reduced stream flows, reservoir levels, or increased depth to the ground water table. Because of its creeping nature, the effects of drought are often slow to

appear, lagging precipitation deficits by weeks or months. Because precipitation deficits usually first appear as deficits in soil water, agriculture is often the first sector to be affected.

It is often difficult to know when a drought begins. Likewise, it is also difficult to determine when a drought is over and on what criteria this determination should be made. Is an end to drought signaled by a return to normal precipitation and, if so, over what period of time does normal or above-normal precipitation need to be sustained for the drought to be declared officially over? Since drought represents an accumulated precipitation deficit over an extended period of time, does the precipitation deficit need to be erased for the event to end? Do reservoirs and ground water levels need to return to normal or average conditions? Impacts linger for a considerable period of time following the return of normal precipitation, so is the end of drought signaled by meteorological or climatological factors, or by the diminishing negative impact on human activities and the environment?

Another factor that distinguishes drought from other natural hazards is the absence of a precise and universally accepted definition for it. There are hundreds of definitions, adding to the confusion about whether or not a drought exists and its degree of severity. Definitions of drought should be region and application or impact specific. Droughts are regional in extent and, as previously stated, each region has specific climatic characteristics. Droughts that occur in the North American Great Plains will differ from those that occur in Northeast Brazil, southern Africa, western Europe, eastern Australia, or the North China Plain. The amount, seasonality, and form of precipitation differ widely between each of these locations.

For example, the decade of the 1930's in the North American Great Plains started with dry years in 1930 and 1931. By 1934 extremely dry conditions covered over almost 80 percent of the United States. It was during this drought that the southern Great Plains was first characterized as the "Dust Bowl", a reputation it earned from the numerous dust storms that occurred in that region during 1935-37 (Hughes, 1976). Agriculture was devastated throughout the Great Plains as farmers could not grow any crops, the bare soils were exposed to the hot winds, and severe dust storms of disastrous proportions expanded across the nation. Poor agricultural practices and years of sustained drought caused the Dust Bowl. Plains grasslands had been deeply plowed and planted to wheat. During the years when there was adequate rainfall, the land produced bountiful crops. But as the droughts of the early 1930s deepened,

the farmers kept plowing and planting but nothing would grow. The ground cover that held the soil in place was gone. The Plains winds whipped across the fields raising billowing clouds of dust to the sky. The sky could darken for days, and even the most well sealed homes would have a thick layer of dust on the furniture. In some places the dust would drift like snow, covering both rural and urban areas.

Temperature, wind, and relative humidity are also important factors to include in characterizing drought from one location to another. Definitions also need to be application specific because drought impacts will vary between sectors. Drought means something different to a water manager, agricultural producer, hydroelectric power plant operator, and wildlife biologist. Even within sectors, there are many different perspectives of drought because impacts may differ markedly. For example, the impacts of drought on crop yield may differ greatly for maize, wheat, soybeans, and sorghum because they are planted at different times during the growing season and have different water requirements and different sensitivities at various growth stages to water and temperature stress.

3. Space and Time Characteristics of Drought

Droughts differ from one another in three essential characteristics: intensity, duration, and spatial coverage. Intensity refers to the degree of the precipitation shortfall and/or the severity of impacts associated with the shortfall. It is generally measured by the departure of some climatic parameter (e.g., precipitation), indicator (e.g., reservoir levels) or index (e.g., Standardized Precipitation Index) from normal and is closely linked to duration in the determination of impact. Many indices and indicators exist and are widely used for monitoring drought. Another distinguishing feature of drought is its duration. Droughts usually require a minimum of two to three months to become established but then can continue for months or years. The magnitude of drought impacts is closely related to the timing of the onset of the precipitation shortage, its intensity, and the duration of the event.

Droughts also differ in terms of their spatial characteristics. The areas affected by severe drought evolve gradually, and regions of maximum intensity (i.e., epicenter) shift from season to season and from year to year. In larger countries, such as Brazil, China, India, the United States, or Australia, drought would rarely, if ever, affect the entire country. During the severe

drought of the 1930s in the United States, for example, the area affected by severe and extreme drought reached 65 per cent of the country in 1934. This is the maximum spatial extent of drought in the period from 1895 to 2010. The climatic diversity and size of countries such as the United States suggests that drought is likely to occur somewhere in the country each year. In fact, on average 14% of the country is affected by severe to extreme drought annually. From a planning perspective, the spatial characteristics of drought have serious implications for agriculture, energy, transportation, health, recreating and tourism, and other sectors.

4. Types and Definitions of Drought

All types of drought originate from a deficiency of precipitation. Droughts are commonly classified by type as meteorological, agricultural, and hydrological. Meteorological drought is usually defined by a threshold of precipitation deficiency over some predetermined period of time. The threshold chosen (e.g., 75% of normal) and duration period (e.g., 6 months) will vary by location according to the needs or application of the user. Meteorological drought is a natural event and results from multiple causes, which will vary from region to region. Other drought types (i.e., agricultural and hydrological) place greater emphasis on the human or social aspects of drought, highlighting the interaction or interplay between the natural characteristics of meteorological drought and human activities that depend on precipitation to provide adequate water supplies to meet societal and environmental demands.

Agricultural drought is defined more commonly by the availability of soil water to support crop and forage growth than by the departure of normal precipitation over some specified period of time. There is not a direct relationship between precipitation and infiltration of precipitation into the soil. Infiltration rates vary according to antecedent moisture conditions, slope, soil type, and the intensity of the precipitation event. Soils also vary in their characteristics, with some soils having a high soil water holding capacity while others have a low water holding capacity. Soils with a low water holding capacity are more drought-prone. These areas will be more vulnerable to agricultural drought.

Hydrological drought is even further removed from the deficiency of precipitation since it is normally defined by the departure of surface and subsurface water supplies from some average condition at various points in time. Like agricultural drought, there is not a direct

relationship between precipitation amounts and the status of surface and subsurface water supplies in lakes, reservoirs, aquifers, and streams because these components of the hydrological system are used for multiple and competing purposes (e.g., irrigation, recreation, tourism, flood control, transportation, hydroelectric power production, domestic water supply, protection of endangered species, and environmental and ecosystem management and preservation). There is also considerable time lag between departures of precipitation and the point at which these deficiencies become evident in surface and subsurface components of the hydrologic system (Figure 1). Recovery of these components is slow because of long recharge periods for surface and subsurface water supplies. In some drought-prone areas, such as the western United States, snow pack accumulated during the winter months is the primary source of water during the summer. Reservoirs increase the resilience of this region to drought because of their ability to store large amounts of water as a buffer during single- or multi-year drought events.

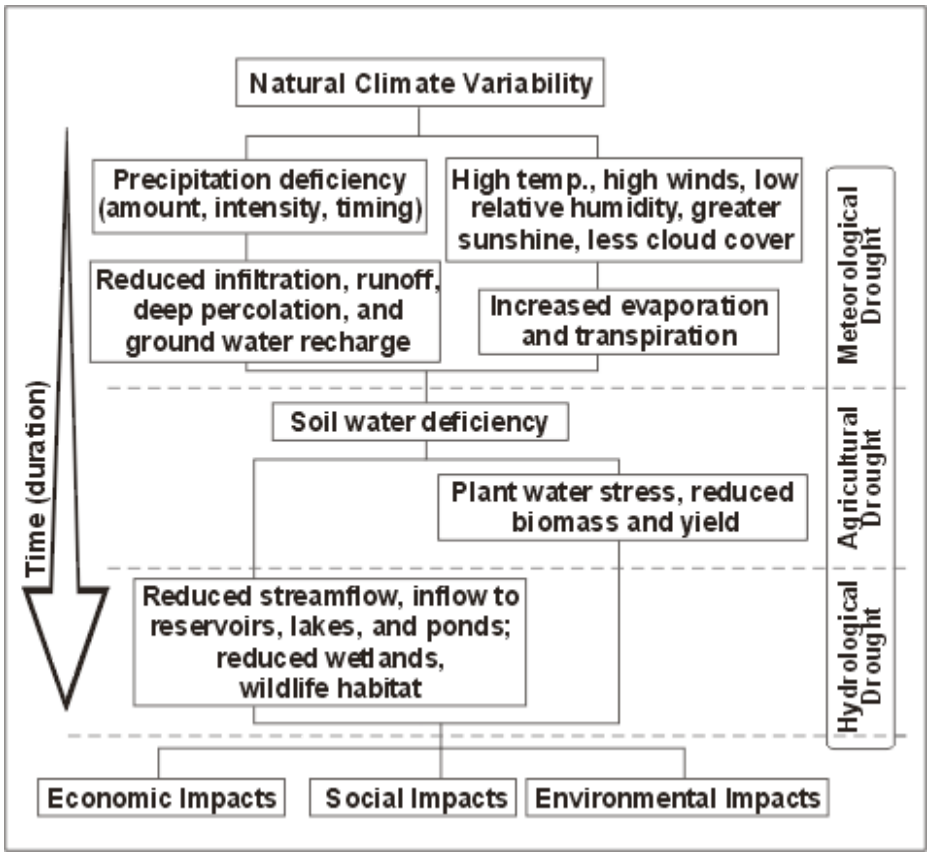

Figure 1. Drought types in relation to the duration of the event. The most immediate impacts of drought usually occur in the agricultural sector following by impacts in the water supply sector as dry conditions continue. (Source: National Drought Mitigation Center, University of Nebraska)

5. Meteorological Drought

What do we mean when we talk about meteorological drought? Meteorological drought is defined usually on the basis of the degree of dryness (in comparison to some “normal” or average amount) and the duration of the dry period (Wilhite and Glantz, 1985). Definitions of meteorological drought must be considered as region specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. For example, some definitions of meteorological drought identify periods of drought on the basis of the number of days with precipitation less than some specified threshold. This measure is only appropriate for regions characterized by a year-round precipitation regime such as a tropical rainforest, humid subtropical climate, or humid mid-latitude climate. Locations such as Manaus, Brazil; New Orleans, Louisiana (U.S.A.); and London, England, are examples. Other climatic regimes are characterized by a seasonal rainfall pattern, such as the central United States, northeast Brazil, West Africa, and northern Australia. Extended periods without rainfall are common in Omaha, Nebraska (U.S.A.); Fortaleza, Ceará (Brazil); and Darwin, Northwest Territory (Australia), and a definition based on the number of days with precipitation less than some specified threshold is unrealistic in these cases. Other definitions (such as monsoon regions) may relate actual precipitation departures to average amounts on monthly, seasonal, or annual time scales. In some instances, there could be an overlap between meteorological and agricultural drought, and even hydrological drought, but this is not often the case. What is known however is that the start of any agricultural or hydrological drought starts with the onset of a meteorological drought, which then persists long enough to impact the agricultural and/or hydrological sectors. Meteorological drought indices can be used in the context of a drought early warning system in order to inform decision makers of drought in a timely fashion. Some of the more common indices are described below.

6. Purposes of a Meteorological Drought Index

Drought indices are an attempt to quantify and capture the severity of drought on the landscape by assimilating data on rainfall, snowpack, streamflow, and other water supply indicators into a comprehensible numerical value. A drought index value is typically a single number, which is typically far more useful than raw data for near-real time decision making. Other typical uses of a drought index include the identification of thresholds that indicate a drought’s onset, severity,

magnitude (duration) and eventually its decay. In addition, indices can also be used as a "ground truthing" mechanism for models/assimilations and remotely sensed products like satellite vegetation indices or hybrid radar derivatives as well.

7. Meteorological Drought Indices in Use

There are several indices that measure how much precipitation for a given period of time has deviated from historically established norms. Although none of the major indices is inherently superior to the rest in all circumstances, some indices are better suited than others for certain uses. Most decision makers and resource managers find it useful to consult and integrate one or more indices before making a decision in a convergence of evidence approach. What follows is a brief introduction of some of the more common meteorological drought indices being used around the world today.

7.1 Percent of Normal

The percent of normal precipitation is one of the simplest measurements of rainfall for a location. Analyses using the percent of normal are very effective when used for a single region or a single season. Percent of normal is also easily misunderstood and gives different indications of conditions, depending on the location and season. It is calculated by dividing actual precipitation by a normal precipitation—typically a 30-year mean—and multiplying this result by 100%. This can be calculated for a variety of time scales. Usually these time scales range from a single month to a group of months representing a particular season, to an annual or water year. Normal precipitation for a specific location is considered to be 100%.

One of the disadvantages of using the percent of normal precipitation is that the mean, or average, precipitation is often not the same as the median precipitation, which is the value exceeded by 50% of the precipitation occurrences in a long-term climate record. The reason for this is that precipitation on monthly or seasonal scales does not have a normal distribution. Use of the percent of normal comparison implies a normal distribution where the mean and median are considered to be the same. An example of the confusion this could create can be illustrated by the long-term precipitation record in Melbourne, Australia, for the month of January. The median January precipitation is 36 mm, meaning that in half the years less than 36 mm is

recorded, and in half the years more than 36 mm is recorded. However, a monthly January total of 36 mm would be only 75% of normal when compared to the mean, which is often considered to be quite dry. Because of the variety in the precipitation records over time and location, there is no way to determine the frequency of the departures from normal or compare different locations. This makes it difficult to link a value of a departure with a specific impact occurring as a result of the departure, inhibiting attempts to mitigate the risks of drought based on the departures from normal and form a plan of response (Willeke et al. 1994).

7.2 Deciles

Arranging monthly precipitation data into deciles is another drought-monitoring technique. It was developed by Gibbs and Maher (1967) to avoid some of the weaknesses within the "percent of normal" approach. The technique they developed divided the distribution of occurrences over a long-term precipitation record into tenths of the distribution. They called each of these categories a *decile*. The first decile is the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. These deciles continue until the rainfall amount identified by the tenth decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are grouped into five classifications as shown in Table 1.

Table 1. Decile classifications as per Gibbs and Maher (1967)

Decile Classifications	
Deciles 1-2 lowest 20%	much below normal
Deciles 3-4 next lowest 20%	below normal
Deciles 5-6 middle 20%	near normal
Deciles 7-8 next highest 20%	above normal
Deciles 9-10 highest 20%	much above normal

The decile method was selected as the meteorological measurement of drought within the Australian Drought Watch System because it is relatively simple to calculate and requires less data and fewer assumptions than the Palmer Drought Severity Index (Smith et al. 1993). In this system, farmers and ranchers can only request government assistance if the drought is shown to be an event that occurs only once in 20–25 years (deciles 1 and 2 over a 100-year record) and has lasted longer than 12 months (White and O'Meagher, 1995). This uniformity in drought classifications, unlike a system based on the percent of normal precipitation, has assisted Australian authorities in determining appropriate drought responses. One disadvantage of the decile system is that a long climatological record is needed to calculate the deciles accurately.

7.3 Standardized Precipitation Index (SPI)

The understanding that a deficit of precipitation has different impacts on groundwater, reservoir storage, soil moisture, snowpack, and streamflow led McKee et al. (1993) to develop the Standardized Precipitation Index (SPI). The SPI was designed to quantify the precipitation deficit for multiple time scales. These time scales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee et al. (1993) originally calculated the SPI for 3–, 6–, 12–, 24–, and 48–month time scales.

The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, thus wet periods can also be monitored using the SPI.

McKee et al. (1993) used the classification system shown in Table 2 to define drought intensities resulting from the SPI. McKee et al. (1993) also defined the criteria for a drought event for any of the time scales. A drought event occurs any time the SPI is continuously

negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude".

Table 2. Classification of drought intensities according to SPI values (McKee et al. 1993)

SPI Values	
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

Based on an analysis of stations across Colorado, McKee determined that the SPI is in mild drought 24% of the time, in moderate drought 9.2% of the time, in severe drought 4.4% of the time, and in extreme drought 2.3% of the time (McKee et al. 1993). Because the SPI is standardized, these percentages are expected from a normal distribution of the SPI. The 2.3% of SPI values within the "Extreme Drought" category is a percentage that is typically expected for an "extreme" event (Wilhite 1995). In contrast, the Palmer Index reaches its "extreme" category more than 10% of the time across portions of the central Great Plains. This standardization allows the SPI to determine the rarity of a current drought, as well as the probability of the precipitation necessary to end the current drought (McKee et al. 1993).

Figure 2 illustrates three characterizations of drought for three different countries based on precipitation departures from normal, deciles, and the Standardized Precipitation Index (SPI).

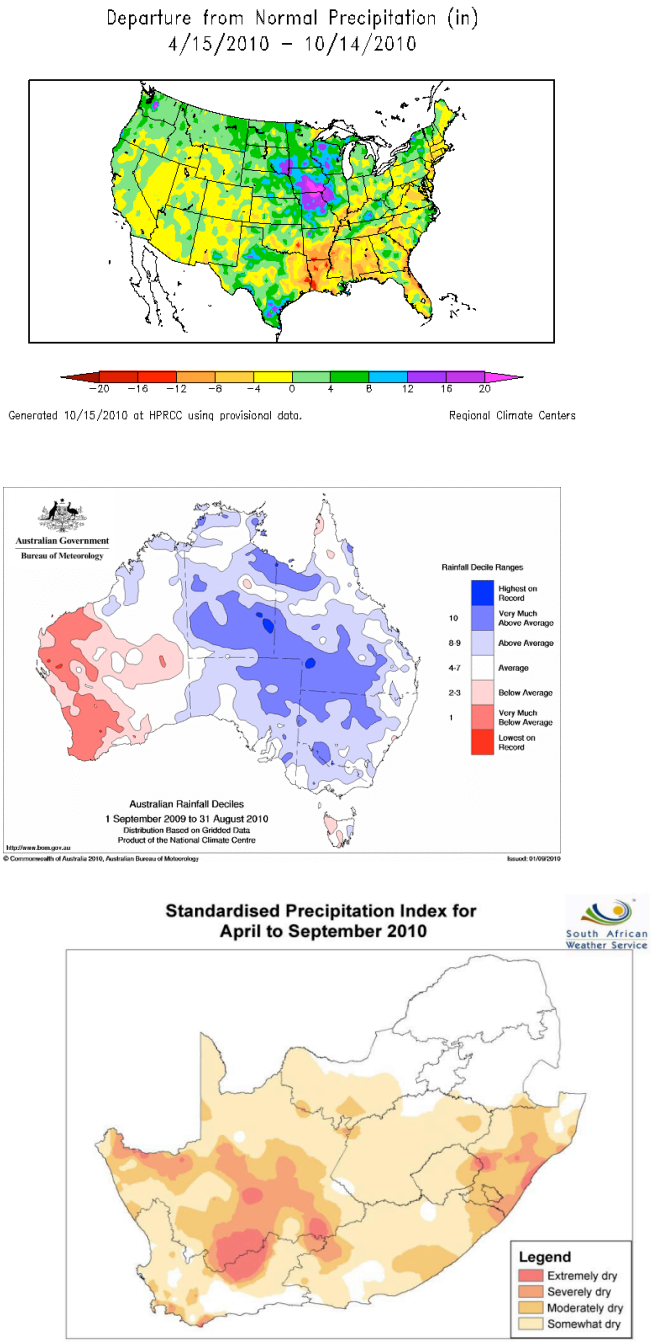

Figure 2. Characterizations of drought conditions based on departure from normal precipitation (United States), deciles (Australia), and the Standardized Precipitation Index (South Africa). Other indices and indicators may also be used in each of these countries to characterize drought conditions. (Source: High Plains Regional Climate Center, Australian Bureau of Meteorology, and the South African Weather Service)

7.4 Palmer Drought Severity Index (The Palmer; PDSI)

In 1965, Palmer developed an index to "measure the departure of the moisture supply" (Palmer, 1965). Palmer based his drought index on the supply-and-demand concept of the water balance equation, taking into account more than only the precipitation deficit at specific locations. The objective of the Palmer Drought Severity Index (PDSI), as this index is now called, was to provide measurements of moisture conditions that were standardized so that comparisons using the index could be made between locations and between months (Palmer 1965). Palmer developed the PDSI to include the duration of a drought (or wet spell). His motivation was as follows: an abnormally wet month in the middle of a long-term drought should not have a major impact on the index, or a series of months with near-normal precipitation following a serious drought does not mean that the drought is over. Therefore, Palmer developed criteria for determining when a drought or a wet spell begins and ends, which adjust the PDSI accordingly. Palmer arbitrarily selected the classification scale of moisture conditions (Table 3) based on his original study areas in central Iowa and western Kansas (Palmer, 1965). Ideally, the Palmer Index is designed so that a -4.0 in South Carolina has the same meaning in terms of the moisture departure from a climatological normal as a -4.0 in Idaho (Alley, 1984). The Palmer Index has typically been calculated on a monthly basis, and a long-term archive of the monthly PDSI values for every climate division in the United States exists with the National Climatic Data Center from 1895 through the present.

The PDSI is a meteorological drought index, and it responds to weather conditions that have been abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by the PDSI ends without taking into account streamflow, lake and reservoir levels, and other longer-term hydrologic impacts (Karl and Knight, 1985). The PDSI is calculated based on precipitation and temperature data, as well as the local Available Water Content (AWC) of the soil. From the inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer. Human impacts on the water balance, such as irrigation, are not considered. Complete descriptions of the equations can be found in the original study by Palmer (1965) and in the more recent analysis by Alley (1984). In near-real time, Palmer's index is no longer a meteorological index but becomes a hydrological index referred to as the Palmer Hydrological Drought Index (PHDI) because it is based on moisture

Table 3. Classification of drought severity according to Palmer Drought Severity Index (Palmer, 1965)

Palmer Classifications	
4.0 or more	extremely wet
3.0 to 3.99	very wet
2.0 to 2.99	moderately wet
1.0 to 1.99	slightly wet
0.5 to 0.99	incipient wet spell
0.49 to -0.49	near normal
-0.5 to -0.99	incipient dry spell
-1.0 to -1.99	mild drought
-2.0 to -2.99	moderate drought
-3.0 to -3.99	severe drought
-4.0 or less	extreme drought

inflow (precipitation), outflow, and storage, and does not take into account the long-term trend (Karl and Knight, 1985).

In 1989, a modified method to compute the PDSI was begun operationally (Heddinghaus and Sabol, 1991). This modified PDSI differs from the PDSI during transition periods between dry and wet spells. Because of the similarities between these Palmer indices, the terms *Palmer Index* and *Palmer Drought Index* have been used to describe general characteristics of the indices.

The Palmer Index is popular and has been widely used for a variety of applications across the United States. It is most effective measuring impacts sensitive to soil moisture conditions, such as agriculture (Willeke et al. 1994). It has also been useful as a drought monitoring tool and has been used to trigger actions associated with drought contingency plans (Willeke et al. 1994). Alley (1984) identified three positive characteristics of the Palmer Index that contribute to its popularity: (1) it provides decision makers with a measurement of the

abnormality of recent weather for a region; (2) it provides an opportunity to place current conditions in historical perspective; and (3) it provides spatial and temporal representations of historical droughts. Several states, including New York, Colorado, Idaho, and Utah, use the Palmer Index as one part of their drought monitoring systems.

There are also considerable limitations when using the Palmer Index, and these are described in detail by Alley (1984) and Karl and Knight (1985). Drawbacks of the Palmer Index include:

- The values quantifying the intensity of drought and signaling the beginning and end of a drought or wet spell were arbitrarily selected based on Palmer's study of central Iowa and western Kansas and have little scientific meaning.
- The Palmer Index is sensitive to the AWC of a soil type. Thus, applying the index for a climate division may be too general.
- The two soil layers within the water balance computations are simplified and may not be accurately representative of a location.
- Snowfall, snow cover, and frozen ground are not included in the index. All precipitation is treated as rain, so that the timing of PDSI or PHDI values may be inaccurate in the winter and spring months in regions where snow occurs.
- The natural lag between when precipitation falls and the resulting runoff is not considered. In addition, no runoff is allowed to take place in the model until the water capacity of the surface and subsurface soil layers is full, leading to an underestimation of runoff.
- Potential evapotranspiration is estimated using the Thornthwaite method. This technique has wide acceptance, but it is still only an approximation.

Several other researchers have presented additional limitations of the Palmer Index. McKee et al. (1995) suggested that the PDSI is designed for agriculture but does not accurately represent the hydrological impacts resulting from longer droughts. Also, the Palmer Index is applied within the United States but has little acceptance elsewhere (Kogan, 1995). One explanation for this is provided by Smith et al. (1993), who suggested that it does not do well in regions where there are extremes in the variability of rainfall or runoff. Examples in Australia and South Africa were given. Another weakness in the Palmer Index is that the "extreme" and "severe" classifications of drought occur with a greater frequency in some parts of the country

Use of PDSI in the United States Department of Agriculture (USDA)

The PDSI was used by USDA and a number of states to trigger drought relief programs, and was used to start or end drought contingency plans (Willeke et al. 1994). Several states, including New York, Colorado, Idaho, and Utah used the Palmer Index as one part of drought monitoring systems; and, a number of states included the PDSI in their criteria for evaluating drought in their state drought plans.

During periods of drought, state governments also issued bans on open burning in an effort to reduce the risk of wildfire, based on the PDSI. In an example application of a climate forecast for the Northern Rockies, seasonal temperature forecasts using Pacific sea surface temperatures and proxies for soil moisture (PDSI) allow managers to anticipate extreme fire seasons in the Northern Rockies with a high degree of reliability. As is often the case with climate forecasts however, forecasts for the Northern Rockies do not provide a large degree of precision: while they can indicate whether a mild or active wildfire season is likely, they cannot provide a precise estimate of the level of area burned or suppression expenditures given a mild or extreme forecast (Westerling et al. 2003).

The U.S. Department of Agriculture (USDA) Forest Service has developed statistical relationships between number and location of large fire events in the West and climate, drought, and fire index variables. They found that a model to predict large fire occurrences using monthly mean temperature and the Palmer drought severity index showed potential to distinguish areas of high probability of large fires from areas of low to moderate probability of large fires. The model was superior to predictions based on historical fire frequency.

The actuarial performance of the U.S. crop insurance program in these regions, however, has historically been substantially better than in other regions of the country, suggesting that the conditions necessary for significant moral hazard are likely to be stronger elsewhere (Chen and Miranda, 2006. Similarly, crop producers are more likely to abandon their crop, with or without insurance, if weather worsens during the growing season. Here, the monthly PDSI data were used to account for weather effects on abandonment. A dummy variable, Unfavorable Weather, is created to represent the weather factor in the model. If the averaged monthly PDSI between the assumed planting time and seasonal mid-point is greater than or equal to 3.00 (beyond very wet) or less than or equal to -3.00 (beyond severe drought), Unfavorable Weather is equal to one; otherwise, Unfavorable Weather is zero. A positive relationship between Unfavorable Weather and crop abandonment ratio is expected in this study.

than in others (Willeke et al., 1994). “Extreme” droughts in the Great Plains occur with a frequency greater than 10%. This limits the accuracy of comparing the intensity of droughts between two regions and makes planning response actions based on a certain intensity more difficult.

However, a peculiarity of the Palmer index is backtracking; i.e., values previously reported for past months may be changed on the basis of the newly-calculated values for the present month. Thus, using the index as an "operational" index is problematic because it may not be known until a later date whether the Palmer index is actually in a dry or wet spell (Heddinghaus and Sabol, 1991). Due to this tendency to change the index values, the index may not be representative of current conditions, since at a later time, the values of the index may change.

9. Standardized Precipitation Index (SPI) - the Consensus Index for Meteorological Drought

WMO, along with the US National Drought Mitigation Centre (NDMC) and the School of Natural Resources at the University of Nebraska-Lincoln, the NOAA/National Integrating Drought Information System, the U.S. Department of Agriculture, and the UNCCD Secretariat organized an Inter-Regional Workshop on Indices and Early Warning Systems for Drought at the University of Nebraska from 8 to 11 December 2009. One of the main objectives of the workshop was to develop a consensus standard index for the meteorological drought. More than 50 experts from over 20 countries who attended the workshop came to a consensus and announced via the ‘Lincoln Declaration on Drought Indices’ that the Standardized Precipitation Index (SPI) be used to characterize meteorological droughts around the world. The National Meteorological and Hydrological Services (NMHSs) around the world are encouraged to use the SPI to characterize meteorological droughts and provide this information on their websites, in addition to the indices currently being utilized within their region.

The full Lincoln Declaration on Drought Indices can be found on the WMO’s web site at: http://www.wmo.ch/pages/prog/wcp/agm/meetings/wies09/documents/Lincoln_Declaration_Drought_Indices.pdf

The SPI (McKee et al., 1993, 1995) is a powerfully flexible index that is simple to calculate. In fact, precipitation is the only required input parameter. In addition, it is just as

effective in analyzing wet periods/cycles as it is for dry periods/cycles. An option for running the program exists for both the Windows and UNIX environments. The Windows program version is described here.

9.1 Data needs and characteristics of SPI

The SPI calculation for any location is based on the long-term precipitation record for a desired period, or window. The windows typically range from 1-24 months, but can go out for as many months as desired. Given the usual small sample size involved using most site data though, it is recommended that the user stays within a 1-24-month period when calculating the SPI (Guttman, 1994). This long-term record is fitted to a probability density function, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, thus wet periods can also be monitored using the SPI.

Ideally, at least 20-30 years of serially complete monthly values are needed with 50-60 years (or more) being more optimal and preferred (Guttman, 1994). The program can be run with missing data but it will affect the confidence of results depending on how much data are missing relevant to the available length of record.

Even though a serially complete data set is optimal, it is good to see in the neighborhood of 90% or 95% completeness of records. In reality, many users don't have this luxury and have to settle for less (70-90% complete) unless they look to estimation techniques to fill in the period of record gaps. Of course, long and pristine data records aren't practical or typical in many cases so the user needs to be aware of the statistical limitations of extreme events when dealing with shorter periods of records for various locations. In the end, the user has to make a subjective decision as to what tolerance of missing data they are willing to incorporate into the SPI calculations and analyses. Depending on the user confidence and method of calculation, the use of estimated data is acceptable. Again, this should be related to the amount of data that needs to be estimated, naturally, the fewer estimated data used, the more confident one can feel about the results.

The PC-based code (at no cost) and supporting documentation for SPI can be obtained from the NDMC at: http://drought.unl.edu/monitor/spi/program/spi_program.htm. Alternatively, the free UNIX version of the SPI can be found at Colorado State University at: http://ccc.atmos.colostate.edu/standardizedprecipitation.php. In addition, if one has access to daily or weekly precipitation, the SPI can be run on a weekly time frame by downloading the free weekly SPI at: http://greenleaf.unl.edu/downloads. For the Greenleaf downloads, one needs to have access to Firefox 2.0 or IE 7+ to open that page. If weekly data are available, one could look into the self-calibrating PDSI (scPDSI).

Some key points about SPI are as follows:

- Because the SPI is normalized, wetter and drier climates can be represented in the same way, thus wet periods can also be monitored using the SPI.
- Not as applicable to climate change analysis due to lack of temperature as an input parameter.
- The SPI was designed to quantify the precipitation deficit for multiple time scales
- These time scales reflect the impact of drought on the availability of the different water resources as was the initial intent of the creators
- Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. So, for example, a 1- or 2-month SPI is applicable for meteorological drought, anywhere from 1-month to 6-months for agricultural drought and something like 6-months out to 24-months or more for hydrological drought analyses and applications.

The probability of recurrence of different categories of droughts and the severity of drought event using SPI are shown in Table 4.

Table 4. Probability of Recurrence of Different Categories of Droughts using SPI

SPI	Category	# of times in 100 yrs.	Severity of event
0 to -0.99	Mild dryness	33	1 in 3 yrs.
-1.00 to -1.49	Moderate dryness	10	1 in 10 yrs.
-1.5 to -1.99	Severe dryness	5	1 in 20 yrs.
< -2.0	Extreme dryness	2.5	1 in 50 yrs.

9.2 Strengths and Weaknesses of SPI

Strengths:

- Flexible: can be computed for multiple time scales
- Shorter time scale SPIs (i.e. 1-, 2- or 3-month SPI) can provide early warning of drought and help assess drought severity
- Spatially consistent; can be compared equally between different locations in different climates for any given SPI value (negative or positive)

Probabilistic nature gives it historical context, which is well suited for decision making.

Weaknesses:

- Precipitation-based only;
- No soil water balance-component, thus no ET/PET can be calculated.
- Lack of PET makes application on climate changes studies unadvised (see SPEI potential below)

A new variation of the SPI index by Vicente-Serrano et al. (2010) attempts to address this issue

by including a temperature component through the calculation of their new SPI index called the Standardized Precipitation Evapotranspiration Index (SPEI). The inputs required are precipitation, mean temperature and latitude of the site(s) to run the program on. More details about SPEI are available at: http://digital.csic.es/handle/10261/10002.

9.3 Applications Around the World

The SPI has been distributed and is being applied in at least 80 countries around the world. Figure 3 below shows the distribution over the past decade by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln. The SPI is being used in either a research or operational mode as part of drought early warning systems and networks through various meteorological/hydrological services, government agencies and academic/research institutions.

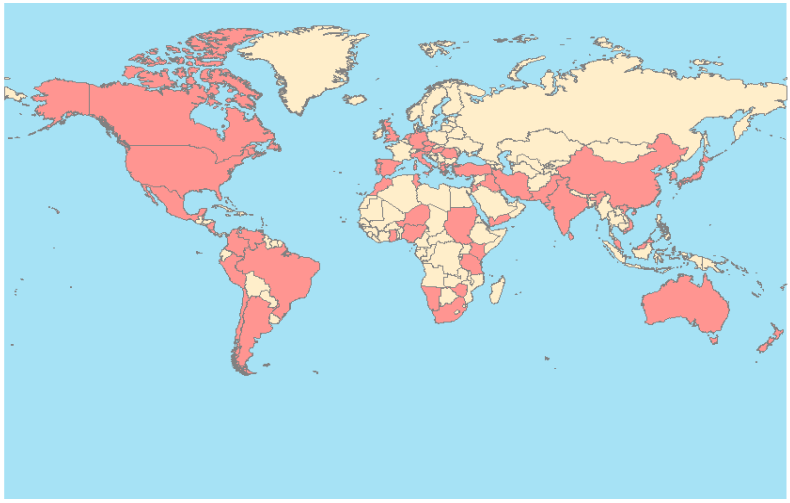

Figure 3. Graphical depiction of SPI use around the world

9.4 Mapping Capabilities

There are multiple ways to map meteorological variables, which would include the standard drought indicators and indices. Most drought-related data originate as point ("station-based" or "site-specific") data. These data serve their purposes, but it is often in map form that the data best communicate a message based on a geographic context to the decision maker trying to understand drought severity and spatial extent. The point data itself can be placed onto a map,

and derivative products or characteristics of that site can be provided for additional information. This could include, for example, a time series plot of the indicator or index. The limitation of this level of spatial detail is that information on what is taking place between points is not available.

In order to generate a continuous map of the SPI, one mapping technique used is to generate an interpolated surface of estimated values at locations between sites based on mathematical relationships of the SPI between the original point data. Often this produces a map that appears "natural", but is still based on the data from specific points and is only as accurate as the original data and the interpolation technique. There is no single interpolation method that can be applied to all situations, and the most commonly-used interpolation techniques include Kriging, Spline, and Inverse Distance Weighting (IDW). Each interpolation technique has its advantages and disadvantages. The Kriging method, which had its origins in geological applications and the mining industry, assumes that there is a relationship between points that is non-random and changes over space. The Spline method is used when minimizing the overall surface curvature is important. Inverse Distance Weighting (IDW) is used when the data points are scattered but dense enough to represent local variations. The data, as the name implies, are weighted to favor data closer in proximity to the point being processed.

Another technique that has been used for drought monitoring is to map point data to grid cells. These gridded data products appear less "natural" than interpolated products, but they are easier to use for comparative purposes because of the common grid cell sizes. In the U.S., gridded products for monitoring drought indices such as the SPI are becoming much more common, while in other locations, particularly Africa, there has been a long history of using gridded information to determine drought conditions. The Famine Early Warning System (FEWS), and similar networks, has utilized gridded data in the analyses they use. There are multiple examples of gridded meteorological drought products existing in the United Kingdom, Europe, Australia, China, and the United States.

To develop a gridded map product, the point data are aggregated up to a grid cell resolution selected for the product using a mathematical relationship. An interpolated surface is then created between the grid cells (and not the point data). As an example, in a partnership with NOAA's High Plains Regional Climate Center, the National Drought Mitigation Center is mapping the Standardized Precipitation Index at state-level, regional, and national scales

across the United States. These maps are being generated using a technique called the Grid Analysis and Display System (GrADS). Discrete station-based SPI data are interpolated, using a Cressman objective analysis methodology, to a grid cell at a resolution of 0.4 degrees.

The interpolated map product for the 30-day Standardized Precipitation Index, ending on 17 October 2010, for the 48 continental United States is shown in Fig. 4. The data show clearly the intensity of drought in south central United States.

The interpolated global map product for the 3-month Standardized Precipitation Index, ending in September 2010, produced by the International Research Institute for Climate and Society is shown in Fig. 5. The advantage of using SPI for depicting global drought risk is evident from this map as it shows clearly the drought risk in the Russia, the impacts of which were described in the introductory section.

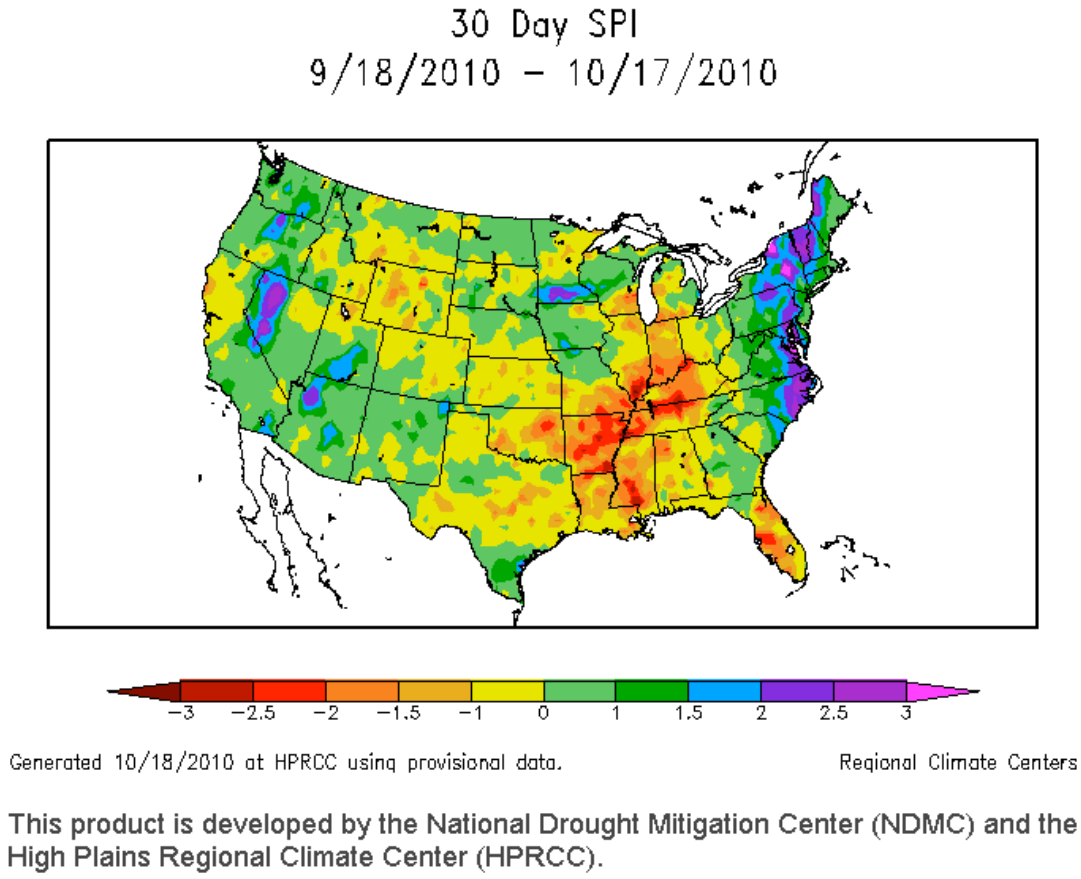

Figure 4. interpolated map product for the 30-day Standardized Precipitation Index, ending on 17 October 2010, for the 48 continental United States

(http://www.hprcc.unl.edu/maps/current/index.php?action=update_product&product=SPIData)

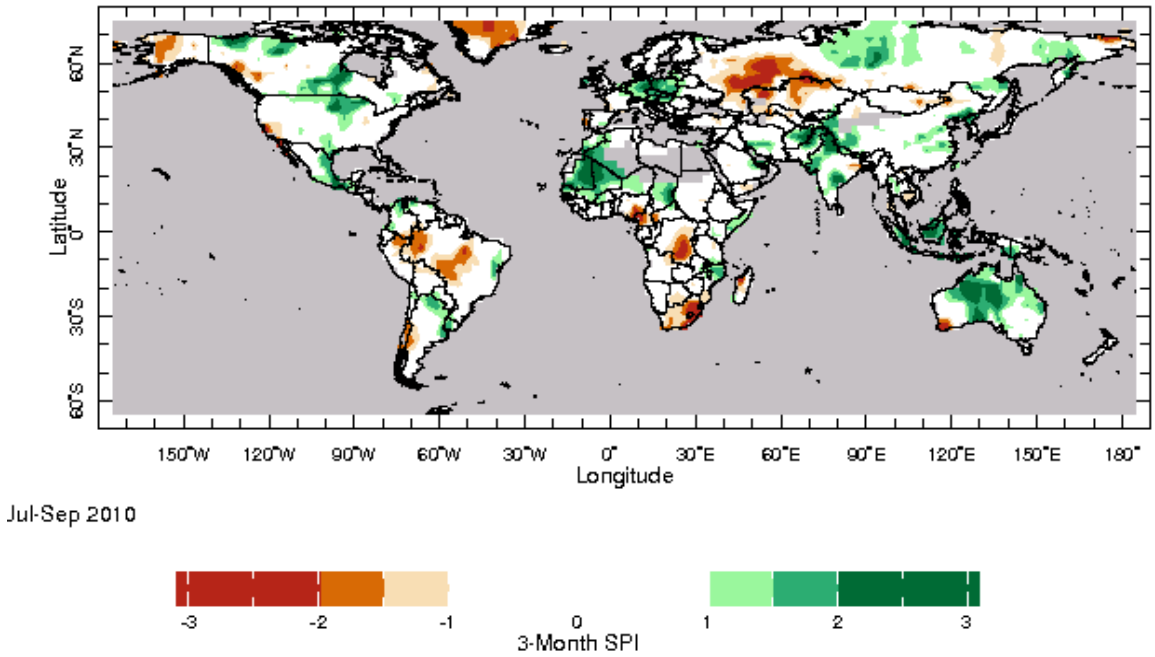

Figure 5. interpolated global map product for the 3-month Standardized Precipitation Index, ending in September 2010, produced by the International Research Institute for Climate and Society. In this example, a 2.5 by 2.5 degree latitude/longitude grid was used [http://iridl.ldeo.columbia.edu/maproom/.Global/.Precipitation/SPI.html]

The keys for successful mapping of meteorological drought depend on the quality of the data. Drought indicator and index data quality is determined by several factors, including the timing as to when the data are recorded, the quality of the historical data at a station, the transmission of data in near real time, the maintenance of the station network, the availability for the data to be accessed and used, and the ability to measure precipitation in cold temperatures, particularly in more northern or alpine locations. Some of these issues are related to the ability to provide the data in a timely fashion, which can be very important with meteorological drought. Finally, the data density plays a huge role in terms of the spatial resolution that can be achieved mapping drought.

Because of all the complexities involving meteorological drought data, and the characteristics of mapping techniques, it is important that a decision maker understand these factors (both the pros and the cons) when interpreting maps of drought severity and spatial extent using the SPI or any other index.

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