Fine-scale evaluation of the drought hazard in a tropical climate: Case study in Sri Lanka

Bradfield Lyon¹ and Lareef Zubair
International Research Institute for Climate and Society
The Earth Institute at Columbia University, Palisades, NY, USA

and

Vidhura Ralapanawe and Zeenas Yahiya
Foundation for Environment, Climate and Technology
Digana Village, Rajawella, Sri Lanka

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¹ Corresponding Author
Dr. Bradfield Lyon
International Research Institute for Climate and Society
The Earth Institute at Columbia University
Palisades, NY 10964
e-mail: blyon@iri.columbia.edu
Abstract

In regions of climatic heterogeneity fine-scale estimates of meteorological hazards such as drought are needed for both planning and management of mitigating actions. As new high resolution climatic data sets become available for real time monitoring, a fundamental question is whether such data can be used to identify drought hazard events associated with drought disasters. Here a retrospective analysis for Sri Lanka is presented using high resolution station-based rainfall data for the period 1960-2000. Records of district-level drought relief payments provided a proxy for disaster risk at fairly high spatial resolution allowing for the construction of a static drought risk map and comparisons with meteorological drought indicators through time and across the region. With tropical rainfall generally characterized by a mixture of unimodal and bimodal distributions, different measures of meteorological drought were examined based on monthly rainfall observations at 284 stations gridded to 10-km resolution.

A statistically significant relationship was found between meteorological drought occurrence and drought relief across the four main climate zones in Sri Lanka. Drought hazard persistence showed marked spatial variability and seasonality re-enforcing the need for the drought analysis to match the scale of societal impacts. Overall the study demonstrates the viability of fine-scale, meteorological drought monitoring for real time dynamic drought risk assessment in a tropical setting.
1. Introduction

Drought is one of the most important natural hazards affecting human populations around the globe (Wilhite 2000). Yet no universal definition of drought exists, as the concept fundamentally refers to insufficient water supply relative to demand, both exhibiting considerable geographic and temporal variations. From a hydro-meteorological perspective, a number of indices have been developed which emphasize different aspects of drought (e.g. deficient rainfall, soil moisture, or stream flow on varying time scales) at a particular location (Palmer 1965; Heim 2002; Keyantash and Dracup 2002). From a hazards assessment standpoint it is not clear which of these hydro-meteorological measures should be most closely related to the occurrence of drought disasters. In addition, the practical use of any of these indices is constrained by the availability of reliable data and in regions of climatic heterogeneity estimates of drought require a consistent spatial density of observations through time. This latter point is especially pertinent if drought information is to be used for planning or management activities on the regional scale.

In recent years, fine scale climatic data (e.g. at 20km resolution) have become available from satellite and ground based sources for Africa and South Asia (e.g. the Famine Early Warning Systems Network (FEWS NET) maintained by the United States Geological Survey (USGS), http://igskmncnwb015.cr.usgs.gov/adds/). The quality of these experimental data sets is currently being evaluated. In this study we take advantage of good quality, fine scale (station-based) rainfall data for Sri Lanka to evaluate the
occurrence of drought hazards. Reliable 40-year records of district-level drought relief payments are utilized to assess the temporal and spatial variability of drought impacts. With marked variations in climatological annual rainfall and seasonality across Sri Lanka, the implications of seasonality on drought indicators can be assessed to a large extent using these data. Identification of meteorological drought measures most closely associated with historical drought disasters is a main goal of the study.

At present, real-time drought monitoring is undertaken predominantly in temperate regions due to the availability of historical data. Drought monitoring efforts in much of the tropics face the joint difficulties of sparse ground based monitoring networks and the problem of timely access to data. However, drought is an important hazard in the tropics where the poor are disproportionately affected, being dependent on rains for access to water for personal needs, ecosystem services and agriculture. The particular difficulties arising in the tropics therefore bears further analysis. To varying degree, the annual cycle of tropical rainfall is a mixture of unimodal and bimodal distributions, posing a challenge in identifying the occurrence of drought. Deficient rainfall and attendant drought in one mode may or may not be compensated for by precipitation in the subsequent mode, determining whether a short-lived or comparatively extended drought is played out. In addition, drought may be modulated by rainfall occurring between these dominant modes. Thus any drought monitoring scheme needs to capture droughts occurring on single to multi-season timescales and for practical use, it needs to show a quantifiable relationship with drought-related disasters.
2. The Study Area

Sri Lanka has an area of approximately 65,000 km² and a population of 19.5 million (Department of Census and Statistics 2001). Four climatologically homogenous regions (Figure 1) have been identified based on the seasonality of rainfall (Puvaneswaran and Smithson 1993). The principal topographic feature in Sri Lanka is an anchor-shaped mountain massif in the south-central part of the country. This mountain massif separates the Eastern and Western climatic regions. Annual rainfall is greatest along the western slopes in the southwest with a relatively drier climate along the Eastern slopes and in Northern and Southern regions (Zubair and Ropelewski 2006). With an average annual rainfall of roughly 1,800 mm Sri Lanka may appear unlikely to experience drought. However, the distribution of rainfall through the year is strongly bimodal with relative peaks occurring roughly in the April-June (AMJ) and October-December (OND) seasons, which renders large areas prone to drought impacts from February to April, and on into September if the April to June season is unusually dry.

While the country is prone to multiple natural hazards (Zubair et al. 2006), drought is the most significant hazard in terms of people affected and relief provided. For example, the protracted drought of 2001-2002 had severe consequences for public health, agriculture and water resources, and led to 1-2% drop in the GDP growth rate. Losses from hydro-electricity cuts alone were estimated at 1-2 billion USD and several drought emergencies were declared in Districts across the country. Disaster management in Sri Lanka is carried out by the Department of Social Services under the Ministry of Social Welfare. Relief work for disasters is the responsibility of the parent body, the Ministry of Social
Welfare. Historically, relief payments are issued from weeks to within a few months of drought impacts.

3. Data and Meteorological Drought Estimates

Monthly rainfall data covering the period January 1960 to December 2000 were obtained from the Sri Lanka Department of Meteorology and secondary sources for 284 stations across the country. These data were utilized to generate gridded analyses at a spatial resolution of 10km using the Weaver interpolation scheme developed at the US Climate Prediction Center. The Weaver analysis scheme is a simplified version of Cressman (1959) analysis, performing un-weighted spatial interpolation without the use of radii of influence. When used to interpolate to an equally spaced lat./long. grid, only observations located within each grid box are used to calculate the interpolated value for that grid box. Further details of the Weaver scheme are available at [http://ingrid.ldeo.columbia.edu/dochelp/StatTutorial/Interpolation/](http://ingrid.ldeo.columbia.edu/dochelp/StatTutorial/Interpolation/). Drought disaster data at the District level (25 in Sri Lanka) were obtained from the Sri Lanka Department of Social Services, the Sri Lanka Department of Census and Statistics, and the Central Bank of Sri Lanka. The disaster incidence data also contained relief expenditures which were incorporated in the study.

While multiple drought indices are in use (Keyantash and Dracup 2002), those presented here were chosen for their computational simplicity while also providing useful results. Indices based on variables such as stream flow, vegetation condition, or soil
moisture estimates were either not available at adequate spatial resolution or lacked reliability and/or sufficient historical extent for the analysis. All the meteorological estimates of drought are therefore based solely on monthly rainfall observations across Sri Lanka. To take into account spatial variations in climatological rainfall, absolute measures of rainfall variability were avoided. Instead, time series of accumulated monthly rainfall anomalies (departures from a 1971-2000 base period mean) were assessed for time intervals of 3, 6, 9, and 12 months at each station using overlapping, running sums. Monthly values of these sums were then expressed as a percentage of average annual precipitation at each station. The percentage of annual precipitation was used instead of sub-yearly totals to avoid inflated percentages during relatively dry seasons that do not necessarily represent a correspondingly large quantity of water. For comparison, the standardized precipitation index (SPI; McKee et al. 1993) was also computed for the same time intervals. Time series for all indices and for each station were then used to construct gridded analyses of these various measures at 10 km resolution.

Given the bimodal behavior of climatological rainfall in Sri Lanka, weighted versions of the above indices (excluding the SPI) were also examined to test the importance of timing of rainfall anomalies in determining drought impacts. The monthly weights used are larger for climatological “wet” seasons and take into account monthly rainfall variability at each station to allow for comparisons at locations across the country. Mathematically, the weighted sums used to construct the time series at a given station may be written as:
\[ S_N = \frac{1}{\bar{P_A}} \sum_{i=1}^{N} \frac{P'_i}{\alpha_i} \] (1)

where \( P' \) is the precipitation anomaly for the \( i \)th month in the \( N \)-month sum (here \( N \) is 3, 6, 9, or 12) which has been weighted by the coefficient of variation (standard deviation divided by the mean) of monthly precipitation, \( \alpha_i \), computed over the 1971-2000 base period. As with the un-weighted measures, the sum is then expressed as a percent of the annual average precipitation, \( \bar{P}_A \). The weighting scheme is mathematically equivalent to that used in previous studies of tropical drought by Lyon (2004) and Lyon and Barnston (2005).

4. Drought Incidence and Hazard Risk

4.1. Spatial Distribution

A drought disaster risk map was constructed for Sri Lanka by summing the occurrence of drought disasters (1960-2000), at the district level, after weighting them in proportion to their associated relief expenditures. The weights were based on three categories of relief: the top third relief payments had a weighting factor of 1.5; the middle third, 1.0 and bottom third, 0.5. The resultant risk map (Figure 1) shows marked spatial variability, with relatively low drought disaster risk in the Western slopes and higher risk in the North, East and Southern regions. The highest drought disaster risk occurs in Anuradhapura District (Northern region) followed by Badulla and Batticaloa
(Eastern region). How does drought risk compare with meteorological drought occurrence? One measure of the spatial variation in meteorological drought is found by mapping the relative occurrence of drought “events”, identified (at a given point) when a given drought index exceeds prescribed thresholds of magnitude and duration. Several such analyses were generated based on different drought measures, thresholds, and durations. Results based on events defined using the 6 and 9 month SPI (not shown) for different index thresholds and durations showed a minimum occurrence of drought in the Eastern region and comparatively too high an occurrence in the Western region. A generally good correspondence with the spatial variations in the drought risk map was found using the 6 or 9 month moving average precipitation indices described earlier, with results for both shown in Figure 2. Meteorological drought events are seen to be less frequent in the southwestern portions of Sri Lanka with greater frequency to the north, east and southeast, consistent with a generally similar drought risk pattern (Figure 1).

To compare the occurrence of drought disasters with measures of meteorological drought through time, the disaster information and drought indices were first aggregated to the scale of the four climatologically homogeneous regions (Figure 1). Periods of below average rainfall in the resulting time series were then compared with the occurrence (or non-occurrence) of drought relief payments. Results using the 6 or 9 month accumulated precipitation anomalies generally showed the best correspondence based on the number of “hits”. The good correspondence with these indices suggests rainfall deficits during both modes in the annual cycle may be important to the occurrence of disasters. The weighted (i.e., using eqn. (1)) and un-weighted moving
average time series showed generally similar results, with the weighted index having a somewhat higher correspondence with disasters in the relatively dry northern climate zone. Time series of the weighted 9 month precipitation index are shown in Figure 3 where black bars indicate the occurrence of drought relief (aggregated over all included districts within each climate zone). The relative length of the black bars is proportional to the relief expenditure, again classified into three severity levels based on the Department of Social Services relief data.

For all four regions drought relief payments generally occur during periods with contemporaneous negative index values, especially when the index drops below roughly -15% to -20%. For the purpose of illustration, if a -15% threshold is used as a predictor of drought relief, each time series also reveals some false alarms when drought (by this definition) developed but relief did not occur (for example, in all four regions a period of fairly substantial drought occurred in the mid 1970s with no relief payments). Of course, factors other than climate may also be playing a role in such cases such as fiscal, political pressure on the government and civil unrest. Nonetheless, if a deficit of 15% or more lasting three or more consecutive months in a given calendar year are used as criteria, the probability of correctly identifying the observed occurrence of drought disasters within that year (and three months into the start of the following year) by chance is $p < 0.05$ for all four regions based on a Fisher Exact test (Sheskin 2004). Considering the first three months of the subsequent year recognizes there may be a lag between meteorological drought occurrence and subsequent government relief which was occasionally seen when droughts occurred near the end of a given calendar year.
4.2. Seasonality

The seasonality of drought occurrence and relief was examined for the markedly different climate zones of the west and north. The total number of drought relief payments made within these climate zones was first compared with the climatological monthly mean rainfall (Figure 4). The western region (4a) clearly receives more annual rainfall, with both regions showing bimodality in the annual cycle of precipitation. Neither region had drought relief payments made during the relative dry June to August season. Relief payments to the western districts were evenly divided between fall and spring, while a greater number of relief payments were made during the spring in the northern districts. Again using the 9 month moving average rainfall index, the relative frequency of being in a meteorological drought event by calendar month was assessed for these two zones. The relative frequency is generally smaller in the west than in the north (Figure 4b) with no pronounced seasonality in the former region. By contrast, meteorological drought is more likely to occur during the boreal spring in the north with a minimum from mid to late summer. A generally consistent relationship is therefore found between the seasonal occurrence of meteorological drought and the timing of drought relief payments, with the northern zone showing a tendency for both to be most frequent in winter and spring.
5. Conclusions

An example of using high resolution meteorological data for drought hazard mapping in Sri Lanka has been presented. The high spatial resolution of these data has allowed for an analysis across regions with significant climate heterogeneity. Although the meteorological drought indices employed were all solely based on precipitation, a statistically significant relationship was found between the number of drought relief payments made (a proxy for drought risk) and temporal variations of a 9 month accumulated rainfall anomaly index. Similarities in the geographical patterns of relative drought risk and meteorological drought occurrence were also encouraging. The effectiveness of a 9 month rainfall index in identifying drought disasters suggest the latter may occur in association with rainfall deficits which persist beyond the seasonal peaks of a strongly bimodal rainfall distribution. The explicit identification of drought disasters and their associated rainfall variations suggests that vulnerability to drought is similar across the island and that drought relief seems to be not unduly influenced by political considerations. Thus there is the potential for drought hazard risk to be forecast (probabilistically) through a combination of real time climate monitoring and seasonal climate predictions (appropriately downscaled). Whether used in a predictive setting or not, the results from the spatial hazard and disaster risk mapping may be useful for local authorities as well as international relief organizations concerned with drought planning and management in Sri Lanka. The success in identifying drought disasters based on rainfall indices in Sri Lanka provides promise for other tropical locations as new, high resolution satellite data becomes available.
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References


Figure Captions

*Fig. 1* - Drought disaster risk map for Sri Lanka constructed by aggregating the number of drought relief payments made to each district (1960-2000). Major droughts, as categorized by the size of the relief payment made by the Department of Social Services, are weighted by a factor of 1.5, medium droughts by 1.0 and minor droughts by 0.5 in generating the map. The four climatically homogeneous regions (East, West, North and South) as identified by Puvaneswaran and Smithson (1993) are delineated by the thick black lines.

*Fig. 2* - The relative frequency (normalized to have a maximum of 1) of drought events identified when a) the 6 month moving average precipitation index was 15% or more below the annual average for 5 or more consecutive months and b) the 9 month index was more than 20% below the annual average for 5 or more months.

*Fig. 3* - Time series (1960-2000) of the de-trended 9 month weighted precipitation anomaly index averaged over the, a) Western slopes, b) Northern Plains, c) Eastern Plains, and d) Southern Slopes. Vertical black bars indicate the occurrence of drought relief payments; their length is proportional to the payment amount.

*Fig. 4* - (a) The number of drought relief payments made to districts in the northern and western climate zones (1960-2000) along with the climatological average monthly rainfall. (b) The relative frequency of meteorological drought conditions, by month, for both regions based on the 9 month rainfall index.
Figure 1 Drought disaster risk map for Sri Lanka constructed by aggregating the number of drought relief payments made to each district (1960-2000). Major droughts, as categorized by the size of the relief payment made by the Department of Social Services, are weighted by a factor of 1.5, medium droughts by 1.0 and minor droughts by 0.5 in generating the map. The four climatically homogeneous regions (East, West, North and South) as identified by Puvaneswaran and Smithson (1993) are delineated by the thick black lines.
Figure 2 The relative frequency (normalized to have a maximum of 1) of drought events identified when a) the 5 month precipitation index was 15% or more below the annual average rainfall for 5 or more consecutive months and b) the 9 month index was more than 20% below the annual average for 5 or more months.
Figure 3 Time series (1960-2000) of the de-trended 9 month weighted precipitation anomaly index averaged over the, a) Western slopes, b) Northern Plains, c) Eastern Plains, and d) Southern Slopes. Vertical black bars indicate the occurrence of drought relief payments; their length is proportional to the payment amount in 3 categories.
Figure 4 (a) The number of drought relief payments made to districts in the northern and western climate zones (1960-2000) along with the climatological average monthly rainfall. (b) The relative frequency of meteorological drought conditions, by month, for both regions based on the 9 month rainfall index.