

Analysis of Drought Characteristics in the Huang-Huai-Hai Plain Based on the SPEI-PM Index (Postprint)

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Date: 2017-04-11T00:00:00+00:00

Abstract

Using monthly meteorological data from 45 weather stations in the Huang-Huai-Hai Plain from 1961 to 2014, the Standardized Precipitation Evapotranspiration Index (SPEI) was calculated based on the Penman-Monteith evapotranspiration model. The drought variation trends, occurrence frequency, and persistence characteristics in the Huang-Huai-Hai Plain over the past 54 years were analyzed, and the relationship between the SPEI index and agricultural drought area in Henan, Hebei, and Shandong provinces was investigated. The results show that: (1) After adopting the Penman-Monteith evapotranspiration formula, the SPEI drought index shows an overall increasing trend in the Huang-Huai-Hai Plain, indicating a tendency toward wetter conditions; (2) The drought evolution over the past 54 years exhibits significant interdecadal differences, with the highest drought frequency in the 1960s and relatively low drought frequency in the early 21st century (2000-2014); (3) Drought occurrence in the Huang-Huai-Hai Plain is characterized by persistence, with the most severe persistent droughts occurring in the 1960s, featuring an average drought duration of approximately 2.6 months, which decreased to 1.5 months in the early 21st century; (4) Inter-annual variations in agricultural drought area in Henan, Hebei, and Shandong provinces indicate a decreasing trend in drought area, with the annual average affected area, disaster area, and complete crop failure area after 2000 decreasing by 58.0%, 44.4%, and 49.1%, respectively, compared to before 2000; (5) Agricultural drought area exhibits a moderate or stronger correlation with SPEI, with the correlation coefficient r between SPEI and the affected area, disaster area, and complete crop failure area in Shandong Province reaching above -0.7, indicating that the SPEI index based on the Penman-Monteith evapotranspiration model has good applicability in the Huang-Huai-Hai Plain.

Full Text

Preamble

ACTA ECOLOGICA SINICA

ChinaXiv Partner Journal

Vol. 37, No. 6, Mar. 2017

DOI: 10.5846/stxb201511102274

Analysis of Drought Characteristics Based on the SPEI-PM Index in the Huang-Huai-Hai Plain

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Abstract

The quantitative analysis of drought is crucial for drought risk assessment. The Standardized Precipitation Evapotranspiration Index (SPEI) has been widely used as an effective approach to quantitatively analyze the trends, duration, frequency, and severity of drought. However, calculating evapotranspiration accurately remains a major challenge for reliable SPEI results. Most previous studies calculated SPEI based on empirical evapotranspiration equations, such as the Thornthwaite method, rather than the physically-based Penman-Monteith equation. Moreover, the majority of studies analyzed the spatio-temporal patterns of the index without establishing linkages between the climatic drought index and actual cropland drought areas.

This study utilized SPEI based on the Penman-Monteith equation (SPEI-PM) to explore variations in drought frequency and duration during 1963–2014 in the Huang-Huai-Hai Plain (3H Plain). The relationship between SPEI and actual field drought areas was established using Pearson correlation analysis for Henan, Hebei, and Shandong provinces separately. The results showed that SPEI exhibited upward trends at 1-, 3-, 6-, and 12-month scales in most areas of the 3H Plain, with significant wetting trends ($p < 0.1$) in northern regions at 1- and 3-month scales. Drought frequency was highest during the 1960s and lowest during 2000–2014. The longest drought durations occurred in the 1960s, with mean drought duration declining from 2.6 months in the 1960s to 1.5 months during 2000–2014. Annual drought areas in Henan, Hebei, and Shandong provinces decreased, which could be partly attributed to lower drought frequency and shorter duration detected by SPEI. Correlation analyses indicated that the Dec-SPEI-12 index series had medium to high correlation with observed cropland drought

areas. For example, Pearson's r between Dec-SPEI-12 and drought area in Shandong Province was -0.7, -0.7, and -0.8 for affected, disaster, and no-harvest areas, respectively. The study suggests a wetting trend in the 3H Plain during the past 54 years, attributed to decreasing evapotranspiration calculated by the Penman-Monteith model. The high correlation between the climatic drought index and actual drought areas indicates that SPEI could serve as a reference or trigger for establishing a drought warning system in the 3H Plain.

Keywords: SPEI; Penman-Monteith equation; drought index; drought frequency; Huang-Huai-Hai Plain

1. Materials and Methods

1.1 Regional Overview

The Huang-Huai-Hai Plain (112°33' E–120°17' E, 31°14' N–50°25' N) is located south of the Yanshan Mountains and north of the Huai River, comprising alluvial plains of the Hai and Huai rivers and some hilly areas. It is a semi-humid region with annual precipitation of 500–800 mm, showing a spatial pattern of decreasing from south to north. Annual potential evapotranspiration reaches 1000 mm, placing most of the region in precipitation deficit and making it one of China's major drought disaster areas. As a critical grain production base, the dominant cropping system is winter wheat-summer maize rotation, with wheat and maize planting areas accounting for 45% and 30% of the national total, respectively. According to China's agricultural zoning system, the 3H Plain is classified as a semi-humid, warm-temperature, intensive irrigation farming region, subdivided into six agricultural sub-regions: (I) Taihang Mountain Piedmont Plain Irrigated Double-Cropping Area; (II) Bohai Rim Export-Oriented Double-Cropping and Fishery Area; (III) Hai River Low Plain Water-Deficient Irrigated Double-Cropping with Dryland Area; (IV) Western Shandong Plain Irrigated Double-Cropping with Single-Cropping Area; (V) Huang-Huai Plain and Nanyang Basin Irrigated and Dryland Double-Cropping Area; and (VI) Jiang-Huai Plain Wheat-Rice Area.

1.2 Data Sources

Monthly meteorological data from 1961–2014 were obtained from the China Meteorological Administration, including precipitation (mm), mean temperature (°C), maximum temperature (°C), minimum temperature (°C), wind speed at 2 m (m/s), relative humidity (%), sunshine hours (h), latitude, longitude, and elevation. Historical drought disaster data were sourced from the Disaster Database of the Planting Management Department, Ministry of Agriculture, including annual affected, disaster, and no-harvest areas for Henan, Hebei, and Shandong provinces with continuous and long-term records.

1.3 Methods

SPEI Calculation: SPEI is calculated as the normalized difference between monthly precipitation and potential evapotranspiration. We used the FAO-56 Penman-Monteith equation to calculate monthly potential evapotranspiration (ET_0):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where Δ is the slope of the saturation vapor pressure curve (kPa/°C), R is net radiation at the crop surface (MJ/m²/day), G is soil heat flux density (MJ/m²/day), γ is the psychrometric constant (kPa/°C), T is mean air temperature (°C), u_2 is wind speed at 2 m height (m/s), e_s is saturation vapor pressure (kPa), and e_a is actual vapor pressure (kPa).

The monthly water balance deficit D is calculated as:

$$D_i = P_i - ET_{0i}$$

where P is monthly precipitation. For a given time scale k , the cumulative deficit is:

$$D_i^k = \sum_{l=0}^{k-1} (P_{i-j-l} - ET_{0,i-j-l})$$

The D series is fitted to a three-parameter Log-Logistic probability distribution. The cumulative probability is then transformed to a standard normal distribution to obtain SPEI. SPEI has multiple time scales, with SPEI-1, SPEI-3, SPEI-6, and SPEI-12 representing short to long time scales, respectively. Drought classification follows the standard shown in .

Trend Analysis: The Mann-Kendall (MK) non-parametric test was used to detect trends in annual mean SPEI at 45 meteorological stations. Trend significance was assessed at 90% and 95% confidence levels.

Drought Frequency and Persistence: Drought frequency (p) was calculated as $p = n/N \times 100\%$, where n is the number of drought events ($SPEI < -1.0$) and N is the total number of observations. Drought duration was defined as the number of consecutive months with $SPEI < -1.0$.

Correlation Analysis: Pearson correlation coefficients were calculated between monthly SPEI series at different time scales and provincial drought-affected, disaster, and no-harvest areas to quantify the relationship between meteorological drought indices and actual agricultural drought.

2. Results

2.1 Drought Index Trend Changes

[Figure 2: see original paper] shows the spatial distribution of SPEI trends across the 3H Plain. A trend coefficient less than 0 indicates drying, while greater than 0 indicates wetting. The absolute value exceeding 1.64 (1.96) indicates significance at the 90% (95%) confidence level. Results show that at all time scales, the number of stations with upward trends exceeds those with downward trends, accounting for 75.6%, 73.3%, 77.8%, and 77.8% of stations for SPEI-1, SPEI-3, SPEI-6, and SPEI-12, respectively. The wetting trend is most pronounced in northern and central 3H Plain, with 9, 8, 11, and 11 stations reaching 95% significance for SPEI-1, SPEI-3, SPEI-6, and SPEI-12, respectively. Drying trends are scattered, mainly in Beijing-Tianjin and northern Anhui regions, though most are not statistically significant.

2.2 Drought Evolution Characteristics

To analyze the 1961–2014 drought evolution, Hovmöller-type diagrams were used to visualize multi-scale SPEI variations across six agricultural sub-regions [Figure 3: see original paper]. Short time scales (SPEI-1, SPEI-3) show frequent fluctuations, reflecting short-term precipitation impacts. Long time scales (SPEI-12) reveal interannual variations with longer cycles. Drought exhibits clear interdecadal characteristics, occurring mainly in the mid-late 1960s (1966–1968), early 1980s (1980–1984), and late 1990s (1998–1999). These patterns align with historical drought records (e.g., 1966–1969, 1981–1982, 1989–1991, 1996–1999, 2002–2003) and previous research.

2.3 Drought Frequency and Persistence Characteristics

Interdecadal variations in drought frequency are consistent across sub-regions. The 1960s had the highest drought frequency (21.88–35.83% across scales), while 2000–2014 had the lowest (3.33–15.00%). Sub-region III (Hai River Low Plain) showed the highest frequency in the 1960s (31.25% at SPEI-1 scale), while sub-region V (Huang-Huai Plain) showed the lowest frequency in the 2000s (3.33% at SPEI-12 scale).

Drought persistence shows strong interdecadal patterns [Figure 4: see original paper]. The 1960s experienced the most severe persistent droughts, with 57.8% of stations having maximum durations exceeding 5 months and 26 stations reaching 11-month durations. The 1970s and 1980s also had severe persistence, while the 2000–2014 period showed the weakest persistence, with average duration decreasing from 2.6 months (1960s) to 1.5 months. The top 10 longest drought events include an 11-month severe drought in Langfang (1975–1976) and a 9-month extreme drought in Tanggu (1988–1989).

2.4 Relationship Between SPEI and Actual Drought Areas

Drought-affected, disaster, and no-harvest areas in Henan, Hebei, and Shandong showed fluctuating but overall decreasing trends from 1961-2014 [Figure 5: see original paper]. Average annual affected area decreased by 58.0% (Henan), 44.4% (Hebei), and 49.1% (Shandong) after 2000 compared to pre-2000 levels. This decline is partly attributable to reduced drought frequency and duration, as indicated by SPEI.

Correlation analysis reveals that SPEI-12 (December values) has the strongest relationship with agricultural drought areas [Figure 6: see original paper]. For Shandong Province, Pearson's r between Dec-SPEI-12 and affected, disaster, and no-harvest areas reached -0.7, -0.7, and -0.8, respectively. Correlation strength increases with time scale, stabilizing after 6 months. The negative correlation indicates that lower SPEI values (drier conditions) correspond to larger drought-affected areas. The relationship is strongest for winter wheat growing seasons (June SPEI-2 for heading to grain-filling stage), when drought impacts are most critical.

3. Discussion

This study's finding of a wetting trend in the 3H Plain contrasts with previous research using the Thornthwaite-based SPEI (SPEI-Th), which indicated drying trends in northern China. This discrepancy arises from different evapotranspiration models: Thornthwaite calculates increasing potential ET due to temperature sensitivity, while Penman-Monteith shows decreasing ET in the 3H Plain, consistent with pan evaporation observations. The Penman-Monteith equation, which incorporates both energy and aerodynamic components, is considered more physically robust, especially in northern China where wind speed and humidity effects are significant. Studies by Xu et al. [14] and Yu et al. [10] demonstrated that SPEI-Th overestimates temperature effects and underestimates drought severity in arid regions.

While SPEI-PM effectively captures meteorological drought, linking it to agricultural drought requires consideration of crop-specific water requirements. Actual crop water availability depends on effective precipitation and actual evapotranspiration, not potential ET. Future research should incorporate crop coefficients (K_c) to adjust ET_0 for specific crops and growth stages, as recommended by FAO, to better characterize agricultural drought.

4. Conclusions

1. The SPEI based on the Penman-Monteith evapotranspiration model shows an upward trend (wetting) across the 3H Plain at 1-, 3-, 6-, and 12-month scales during 1963-2014, contrasting with drying trends from Thornthwaite-based SPEI. This difference is attributed to decreasing potential ET calculated by Penman-Monteith.

2. SPEI-PM effectively captures historical drought events in the 3H Plain, with the 1960s showing the highest drought frequency and most severe persistence. Average drought duration decreased from 2.6 months in the 1960s to 1.5 months in 2000–2014.
3. Drought frequency and persistence have declined significantly since the 1960s across all six agricultural sub-regions, with the 2000–2014 period showing the lowest frequency.
4. Correlation analysis demonstrates that SPEI-12 has moderate to high correlation with actual agricultural drought areas in Henan, Hebei, and Shandong provinces ($r = -0.5$ to -0.8), indicating good capability to represent agricultural drought conditions. December SPEI-12 shows the strongest correlation, as early-year drought losses largely determine annual impacts.
5. The Penman-Monteith-based SPEI is recommended for drought monitoring and warning systems in the 3H Plain due to its physical robustness and strong relationship with actual drought impacts.

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