

Article

Monitoring Meteorological and Hydrological Droughts at a Daily Scale: Simple Physical Models and Derived Indexes

Dian Yuan ¹ and Er Lu ^{1,2,*}

¹ Qinghai Provincial Key Laboratory of Plateau Climate Change and Corresponding Ecological and Environmental Effects, Department of Atmospheric Sciences, School of Ecology and Environmental Sciences, Qinghai Institute of Technology, Xining 810016, China; dyuan@qh.it.edu.cn

² Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology, Nanjing 210044, China

* Correspondence: elu@nuist.edu.cn

Abstract

The day-to-day monitoring of drought is required by decision-makers. Treating flood/drought as an instantaneous state, we have developed a physical model to describe the time change in the state, and proposed the derived WAP (Weighted Average of Precipitation) index, which uses precipitation only and monitors meteorological drought. Evaporation is implicitly included in the model as one of the dissipation components. In the present study, we modify the model to express evaporation explicitly, making the “flood extent” forced by both precipitation and evaporation. The derived WAPE index serves as a water-balance-based drought indicator that reflects the day-to-day variation in moisture conditions, with particular emphasis on soil drying processes. Compared with WAP, WAPE captures further changes in drought extent during dry periods, corresponding to soil moisture evolution. The WAPE reasonably describes two real physical processes: (1) during dry spells with strong evaporation, drought tends to be aggravated; and (2) when local drought is severe and evaporation weakens, drought may be locally mitigated due to the restoring force from horizontal and vertical soil moisture gradients. The daily-resolution and physically based nature of the WAPE index also suggests its potential applicability to the identification and dynamic monitoring of flash droughts under climate warming.

Keywords: meteorological and hydrological droughts; day-to-day monitoring; drought index; physical processes; precipitation and evaporation

Academic Editors: Panxing He, Jianhua Xiao, Haijun Deng, Jiejie Sun and Nir Krakauer

Received: 28 April 2026

Revised: 19 June 2026

Accepted: 1 July 2026

Published: 2 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Drought is a major natural disaster worldwide, which has a great impact on socio-economic aspects such as agriculture and wildfires. In the context of climate warming, as the hydrological cycle accelerates, droughts occur frequently across all continents [1–4].

In climate service and research, it is necessary to measure and monitor droughts. However, drought is a complex phenomenon that is difficult to accurately describe [5]. Because of the complexity and difficulty, a large number of studies have been carried out

on the issue, around the understanding, concepts, depictions, and definitions of droughts [6,7]. Nevertheless, a uniform method for defining, monitoring and quantifying the severity of drought conditions does not exist [8].

Many drought indexes have been proposed with emphasis on different aspects such as precipitation deficiency, soil moisture, evaporation, and vegetations. The Palmer Drought Severity Index (PDSI) is a previously widely used meteorological drought index [9,10]. In addition to precipitation, the PDSI also needs temperature and other local hydrological quantities. Because of the complexity of the index and its numerous significant limitations, there have been difficulties with operational monitoring [11].

In recent years, the concept of “flash drought” has attracted increasing attention [12]. Flash droughts are characterized by rapid onset and intensification within weeks to months [13], typically triggered by precipitation deficits combined with anomalously high evaporative demand [14]. Under climate warming, flash droughts have become more frequent globally, with a 109% increase in China during 1979–2010 [15]. Notably, temperature is projected to surpass precipitation as the dominant driver of flash droughts in most regions, including northern and southeastern Asia [16], while the onset of the flash drought season is advancing at about one day per decade [17]. However, existing monitoring indices often operate at pentad or monthly scales and cannot capture the day-to-day evolution of flash droughts—a gap that the WAPE index, with its daily-resolution and physically based framework incorporating both precipitation and evaporation, is well suited to address.

The lack of precipitation is the key factor to drought. The Standardized Precipitation Index (SPI), which uses only precipitation, has later been utilized as a main tool in operational monitoring [6]. The literature and the qualitative drought index evaluation both suggest that the Standardized Precipitation Index and deciles/percentiles are the most suitable for monitoring meteorological drought [8]. However, the SPI and the subsequently proposed Standardized Precipitation Evaporation Index (SPEI) are multiscale indices that can be applied across different aggregation periods [1,18]. While they are sometimes used for short-term drought assessment, they are not ideally suited for true daily-resolution monitoring because they require a predefined timescale and treat all precipitation days within that period equally. In order to better arrange mitigation activities, decision-makers need to know the drought situation in the present day and the drought tendency in the coming days (based on prediction of precipitation), rather than just knowing an averaged drought situation over a longer period. Thus, they do require drought be monitored at shorter scales, and it would be better if the monitoring is on a day-to-day basis [11].

Based upon understanding this issue, Lu [19] proposed a method, the Weighted Average of Precipitation (WAP), for the day-to-day monitoring of drought (and flood as well). With the idea that the flood/drought extent is a hydro-meteorological state of a land-atmosphere system and thus should possess a value at every moment, Lu [19] established a simple physical model to examine the time change rate of the flood extent. The rationale of the model is that the flood extent is forced by precipitation, while it is dissipated by evaporation, along with the other components, e.g., the runoff and percolation. Using the standardized WAP (SWAP), Lu [11] monitored the 2011 severe drought over China. The graphic representation of the daily SWAP can present the details of the day-to-day variation in the spring drought around the Yangtze River basin, which illustrate how the drought emerged, persisted, and eased over the region.

Many researchers have utilized the WAP and SWAP methods in their studies [4,20–22]. The WAP, along with the EIDR method [23], which monitor extreme precipitation events, simultaneously determining the time period they lasts and the geographic region

they affect, have been utilized as key and fundamental methods in eight published documents, as a China National Standard, for measuring and monitoring different types of disasters. Among them, “Grades of Meteorological Drought” is a major document guiding the meteorological drought monitoring at a daily scale nationwide.

In this WAP method, considering that precipitation is the most fundamental influencing factor for drought and flood, as a first-order approximation, only precipitation appears explicitly in the model, as the primary catalyst. Evaporation is expressed implicitly, alongside other dissipating factors. As a result, in the final formula of the index, only precipitation data is used as the input. The WAP index is a combination of the precipitation of the present day and the precipitation of previous days, with the weights decaying with the number of the days prior to the present day.

In the present study, we aim further develop the method. As a second-order approximation, we prefer that the evaporation can also be used for the monitoring. With this, we may extend the monitoring from meteorological drought to hydrological drought. The fundamental consideration for the development is that by using WAP, when the effect of the earlier precipitation has decayed, the flood extent tends to be zero. At this time, the soil may still be wet. In the later days, if it continues to be clear, the soil may become dry gradually. However, the value of the WAP index will continue to be close to zero during these clear days. The goal of the development is to further discern the dry period, and make the monitoring results of the dry period more reasonable.

This can be realized through modifying the original simple physical model for the WAP. In order to use the data of evaporation, now in the new model we express evaporation explicitly. Thus, the flood/drought extent is forced by both precipitation and evaporation. With the modified model, we obtain a new derived index, the Weighted Average of Precipitation minus Evaporation (WAPE), which can perform the day-to-day monitoring of hydrological drought.

The simple physical model and the WAP index for monitoring meteorological drought are introduced briefly in Section 2. In Section 3, the model is modified to incorporate evaporation, and thus we propose the WAPE index for monitoring hydrological drought. In Section 4, monitoring results from WAP and WAPE are compared through a specially designed precipitation–evaporation process. Some real examples comparing the monitoring of meteorological droughts and hydrological droughts are presented in Section 5. A summary and discussion are given in Section 6.

2. Data and Methods

2.1. Data

The dataset of the ERA5 reanalysis, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), which is available at the website <https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets> (accessed on 1 June 2024), is used in Section 5. It starts from 1979, with a horizontal resolution of $1^\circ \times 1^\circ$ in latitude and longitude. The data used in the calculations include the daily precipitation and evaporation. In this study, E (evaporation) denotes actual evapotranspiration from ERA5 reanalysis.

2.2. Methods

Precipitation is the most fundamental influencing factor for drought. As a first-order approximation, Lu [19] used precipitation only to monitor meteorological drought. A breakthrough idea in the study is that the drought/flood extent should be treated as an instantaneous state, like pressure and temperature, and thus needs to possess a value at each single moment.

The simple physical model proposed in Lu [19] is

$$\frac{df(t)}{dt} = -bf(t) + P(t), \quad (1)$$

where f is the “flood extent”, which is always positive, with large values for floods and small values for droughts, and P is the precipitation. The fundamental consideration of the model is that the change rate of the flood extent f is forced by the precipitation P . Meanwhile, it can be dissipated by the water cycle components of runoff, evaporation, and percolation. With a simple parameterization, the overall effect of these components is represented with the term $-bf$, where $b > 0$, which measures the strength of the dissipation. Here “flood extent” is used since the role of precipitation in (1) is to “increase” the extent of “flood”. The f can indicate both flood and drought, with large values for flood and small values for drought.

After some mathematical processing, which includes the integration of the equation, the discretization of the obtained integral for using daily precipitation data, and the truncation of the time series for practical use, the f is finally expressed with the daily precipitation. Based on this derived f , the index for monitoring the meteorological drought is defined as the Weighted Average of Precipitation (WAP), which is expressed as

$$WAP \equiv \sum_{n=0}^N a^n P_n / \sum_{n=0}^N a^n, \quad (2)$$

where $a = \exp(-b\Delta t)$, n is the number of the days prior to the present day (day 0), and Δt is the temporal resolution of the precipitation data, which is 1 day for the day-to-day monitoring.

The a is between 0 and 1 ($0 < a < 1$). So the coefficient a^n decreases with the n . Due to the decay of the coefficient, only limited data of precipitation, the total $(N+1)$ days, are required for the calculation of the index. The WAP is then expressed as

$$WAP = (1-a) \sum_{n=0}^N a^n P_n. \quad (3)$$

The WAP contains an adjustable parameter a , and this reflects the flexibility of the index. The value of the a can be locally determined, by considering the surface and soil condition, i.e., how long (e.g., one month or two months) it needs to take for the contribution of heavy precipitation to the flood/drought index to become very small. The analytical derivation and the calculations in Lu [19] illustrate that the WAP is not very sensitive to the change in the value of the a , e.g., a change from 0.85 to 0.95. For the large-scale monitoring and assessment of meteorological drought, $a = 0.9$ is suggested. The N is determined with the value of the a and the precision for the calculation. It is suggested to take $N = 44$.

The SPI is compared with the WAP in Lu [19]. The SPI is actually a special case of the WAP, where the a tends to be 1. Since the coefficient of the precipitation no longer decays with the number of the day, the SPI must, as always, ask for a timescale, so that the simple average of the precipitation can be calculated over the time period. The SPI is based on statistics and does not explicitly incorporate physical processes. It essentially averages the precipitation over a predefined period and compares the result with historical records, without considering the time decay of antecedent precipitation effects. By contrast, the WAP has physical meaning. The flood/drought extent of the present day relies on the precipitation of both the day and the earlier days, while the weight decays with the number of days past. Therefore, the WAP can reflect the physics that the present flood/drought

state has a memory of the earlier precipitation, although the memory decays with time, which is true in reality.

The SPI cannot be used for short-timescale (e.g., daily and weekly) monitoring. While the SPI requires a timescale to calculate the simple average of precipitation over the time period, the precipitation before the period is not considered. This can be accepted if the timescale is sufficiently long, e.g., one or several months. However, if the scale is very short, e.g., several days, this may cause a problem. Since the timescale of the SPI should be sufficiently long and a simple average is calculated for precipitation, what the SPI shows is merely the overall flood/drought situation of the period. Instead, the WAP does not require a timescale, and can be used for the day-to-day monitoring of the drought and flood state.

3. The Modification of the Model and the Derived Index for Monitoring Hydrological Drought

On the basis of meteorological drought monitoring, we can further consider hydrological drought monitoring, which has also been studied [24,25]. In the above simple physical model, as a first-order approximation, flood extent is forced by precipitation only, and evaporation is implicitly combined with other components in the dissipation term. In this section, as a second-order approximation, we further consider the forcing of the evaporation. In order to make use of evaporation data, we separate it from the dissipation term, and incorporate it in the forcing term.

In this section, as a second-order approximation, hydrological drought monitoring can be further considered through the forcing of the evaporation. In order to make use of evaporation data, it is separated from the dissipation term, and incorporate it in the forcing term.

Thus, the modified physical model becomes

$$\frac{df(t)}{dt} = -bf(t) + [P(t) - E(t)], \quad (4)$$

where E is the evaporation. The “flood extent” f is forced by the $(P - E)$.

Precipitation P increases flood extent f , while evaporation E reduces it. The heavy and persistent rainfall can make f gain a large positive value. When the effect of the precipitation decays to zero, if it continues to be clear and the evaporation becomes strong and persistent, the f may gain a large negative value. Thus, the f here can be both positive, representing flood, and negative, representing drought.

The parameterized term $-bf$, where $b > 0$, acts now as a restoring force, to make the f get back to the neutral state, i.e., to make it turn to zero. When there is precipitation and it is in flood state, the $-bf$ mainly reflects the overall effect from the water flows, including the surface runoff, the ground water flow, and the percolation. When there is no precipitation, especially when in drought state, there is no water flow. However, beneath the ground, there may be diffusions, in both the horizontal and vertical directions, due to the spatial difference in the soil moisture. The term $-bf$ then represents the overall effect from these diffusions. Note that in the flood stage, the f is large in magnitude. The large magnitude of the $-bf$ corresponds to the strong water flows. By contrast, the f in the drought stage is relatively small in magnitude. Correspondingly, the small magnitude of the $-bf$ relates to the diffusion of the moisture, which is relatively weak.

If $(P - E)$ is persistently positive, the f will keep increasing. When f is positive and is very large, the $-bf$ is negative. At this time, if $(P - E)$ becomes negative, then the $-bf$ and the $(P - E)$ will work together to make the positive f decrease. When f reaches 0, the $-bf$ becomes 0. At this time, if $(P - E)$ continues to be negative, the f will become negative, and finally reaches its largest negative value. At this moment, the $-bf$ is positive and is very large in value. If the $(P - E)$ starts to become 0 or very small in value, then the f will decrease its negative value and gradually return to the neutral position.

The physical essence of the process is that when it reaches severe drought, so that the f has a very large negative value and the $-bf$ has a large positive value, if there is no, or very small, evaporation in the later days, the $df(t)/dt$ will have the tendency to make the f go to the neutral value of 0. During this period, the local drought may have a relief tendency. This is caused by the restoring force, the $-bf$, which may converge water to the local area through the spatial gradient of the soil moisture, i.e., the horizontal transport of the moisture from the surrounding soil as well as the vertical transport of the moisture from the deep soil, the so-called “dialysis” effect. However, the loss of the moisture of the surrounding areas may lead to the expansion of the drought region. This may actually reflect the worsening of the drought event.

With Equation (4), similarly, through integration, discretization, and truncation procedures, the f of the present day can be obtained. Based on this derived f , the index for monitoring the hydrological drought is defined as the Weighted Average of Precipitation minus Evaporation (WAPE), which can be expressed as

$$WAPE = (1 - a) \sum_{n=0}^N a^n (P_n - E_n) \quad (5)$$

where E_n is the evaporation n days prior to the present day 0. Similarly, for general use, it is also suggested to take the parameter a as 0.9, and the N as 44 days.

4. A Schematic Comparison of the Indexes for Meteorological and Hydrological Droughts

Figure 1a provides a schematic of the daily variation in precipitation and evaporation over a year, which is specially designed with the purpose to consider all the possible combinations of precipitation (P) and evaporation (E). The configuration of the two quantities is generally reasonable, and the sub-periods of the process may possibly occur in reality. Assume that the P and E prior to Day 1 are both zero. The annual process is as follows. From day 11 to day 60 (denoted as AB), there appears a moderate precipitation, with 50 units per day. From day 61 to day 100 (BC), it is cloudy, and there is no evaporation. From day 101 to day 150 (CD), it becomes clear, and evaporation increases gradually, from 0 to 40 units. From day 151 to day 200 (DE), there is heavy precipitation, with 100 units per day. From day 201 to day 250 (FG), corresponding to the variation from cloudy weather to clear weather, evaporation increases gradually, from 0 to 40 units. Then, from day 251 to day 280 (GH), because of the sunshine and the wet soil, evaporation is strong and maintains 40 units per day. From day 281 to day 320 (HI), evaporation is small, with 10 units per day. From day 321 to day 345 (IJ) and then to the end of the year, it is cloudy and the soil contains little moisture; correspondingly there is no evaporation during the

period. We also assume that before day 10 (A), in a 45-day period, there is neither precipitation nor evaporation.

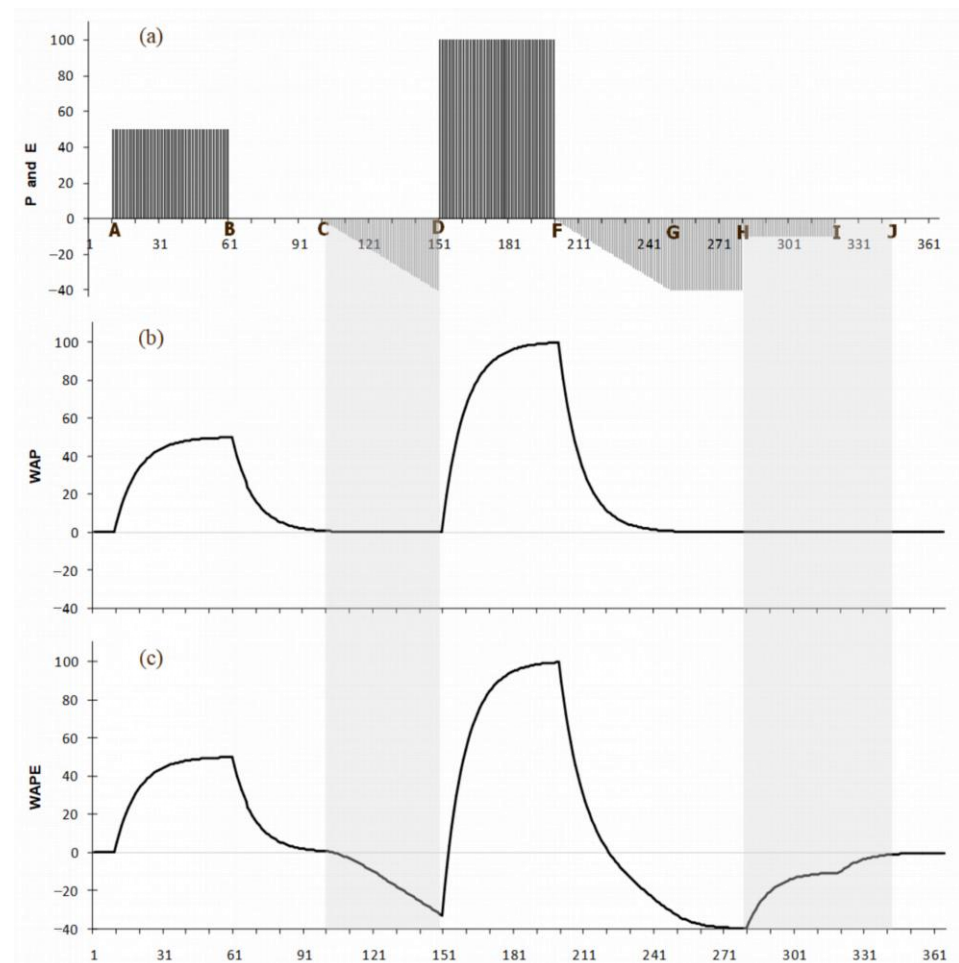


Figure 1. The specially designed daily P (black) and daily E (gray) processes (a), and the calculated daily WAP (b) and daily WAPE (c). The four quantities are in same unit, and an appropriate unit can be given. Eight periods are marked in (a) with letters. Two periods are highlighted in light gray for all three plots.

The calculation of the WAP index uses precipitation only. Figure 1b presents the obtained day-to-day variation in the WAP. With the moderate precipitation during period AB, the index increases from 0 to a large value, close to 50 units, the averaged precipitation intensity of the period. This indicates that the moderate precipitation leads to a change from a drought state to a relatively flood state. During period BC, the effect of the precipitation of these earlier days decays gradually and finally it goes back to the drought state. During period CD, although there is evaporation, the meteorological drought/flood extent is not influenced, and it remains the drought state. With the heavy precipitation during period DF, it varies greatly from the drought state to a very strong flood state. In the later periods, the evaporation does not influence the meteorological drought/flood state. With the decay of the earlier heavy precipitation, during period FG, it returns to the drought state.

The WAPE is consistent with the WAP in the capability of separating the flood and drought situations, based on the day-to-day variations. The result of the WAPE can improve the result of the WAP in the severe drought portion of the day-to-day variation in the flood extent, which is more reasonable in reality. During the period when there is no precipitation, and the contribution of the earlier precipitation has decayed, if there comes

strong evaporation, the drought tends to be aggravated. During the period when the local drought is very severe, if evaporation becomes small, the drought might be mitigated, because of the restoring effect exerted by the horizontal and vertical gradients in the soil moisture. When evaporation E is not taken into account, the probability density function distribution of precipitation P is skewed (figure omitted), and precipitation is greater than or equal to 0, so the WAP value is greater than or equal to 0. According to the principle of water balance, after considering evaporation, the difference between precipitation and evaporation $P - E$ should be a nearly normal distribution, so the WAPE index can be positive or negative. A WAPE of less than 0 indicates that the region is developing towards drought, and a smaller WAPE value indicates a more severe drought.

Figure 1c shows the results of the WAPE, which are quite different from the results of the WAP index, especially the two drought periods that are highlighted in gray, including period CD and period HJ. Due to the absence of precipitation and evaporation in the early stage, the evolution of WAPE in period AB is consistent with that of WAP. There is no effect of evaporation in period BC, so the attenuation curve of precipitation in WAPE is the same as that of WAP. At point C, both values are 0, indicating that the influence of precipitation disappears at this time. However, in the subsequent period CD, the values of WAPE tend to differ, indicating that when the influence of precipitation in the earlier period decays to zero, the influence of evaporation becomes prominent. Unlike WAP, which shows meteorological drought, WAPE can further show hydrological drought. During period CD, WAPE keeps decreasing and develops gradually into a large negative value, representing the intensification of drought under the influence of evaporation. After reaching the extreme value of drought at point D, WAPE begins to increase due to the influence of heavy rainfall during period DE. Different from WAP, which increases from 0 at point D, WAPE can more accurately describe the transition between drought and flood, between points D and F. During period FG, the influence of the previous precipitation decays and the state changes from flood to drought, under the influence from evaporation. Due to the persistent strong evaporation during period GH, the drought becomes most severe at point H. In this stage (point H), because of the very large negative value of f , there is a large positive value of $-bf$, the restoring force. Then, over period HJ, which has small or no evaporation, due to the restoring effect, the severe drought is relieved gradually from point H to point J.

In sum, compared to the WAP, the WAPE can reasonably describe the following two processes. One takes place during the period when there is no precipitation, and the contribution of the earlier precipitation has decayed; if there is strong evaporation, the drought tends to be aggravated. The other takes place during the period when the local drought is very severe; if evaporation becomes small, the drought might be locally mitigated, because of the restoring effect exerted by the horizontal and vertical gradients in the soil moisture. These two processes exist in reality.

5. Some Real Examples of Monitoring Meteorological and Hydrological Droughts at Daily Scale

In this section, we present case studies to illustrate the behavior of the WAP and WAPE indices and to demonstrate the physical reasonableness of the WAPE in capturing drought aggravation and mitigation processes. The purpose of these case studies is not to conduct a comprehensive validation of the indices against all available hydrological observations—which would require extensive ground-based soil moisture and streamflow data across multiple regions and time periods—but rather to show, through real-world examples, how the explicit inclusion of evaporation in the physical model leads to more

reasonable representations of drought evolution during dry periods. The consistency between the WAPE results and the physically expected processes (drought aggravation under strong evaporation and drought relief under weakened evaporation due to the restoring force) provides qualitative support for the validity of the modified model. Quantitative validation against in situ soil moisture and river runoff observations is planned as a future step.

As a real data example, Figure 2 can display the major features illustrated in Figure 1. It presents the daily precipitation and evaporation as well as the calculated daily WAP and WAPE of 1994 in Beijing. After explicitly considering evaporation, the process of drought aggravation and relief can be clearly seen in the two gray areas in the figure. The WAP index in the first period is basically 0, which describes the continuation of the drought from the perspective of meteorological drought, but it is impossible to determine how the drought worsens after it is formed. The WAPE curve continues to decrease during this period, which means that after the occurrence of drought, the impact of evaporation becomes more prominent, and the gradual aggravation of the drought can be seen from a hydrological perspective.

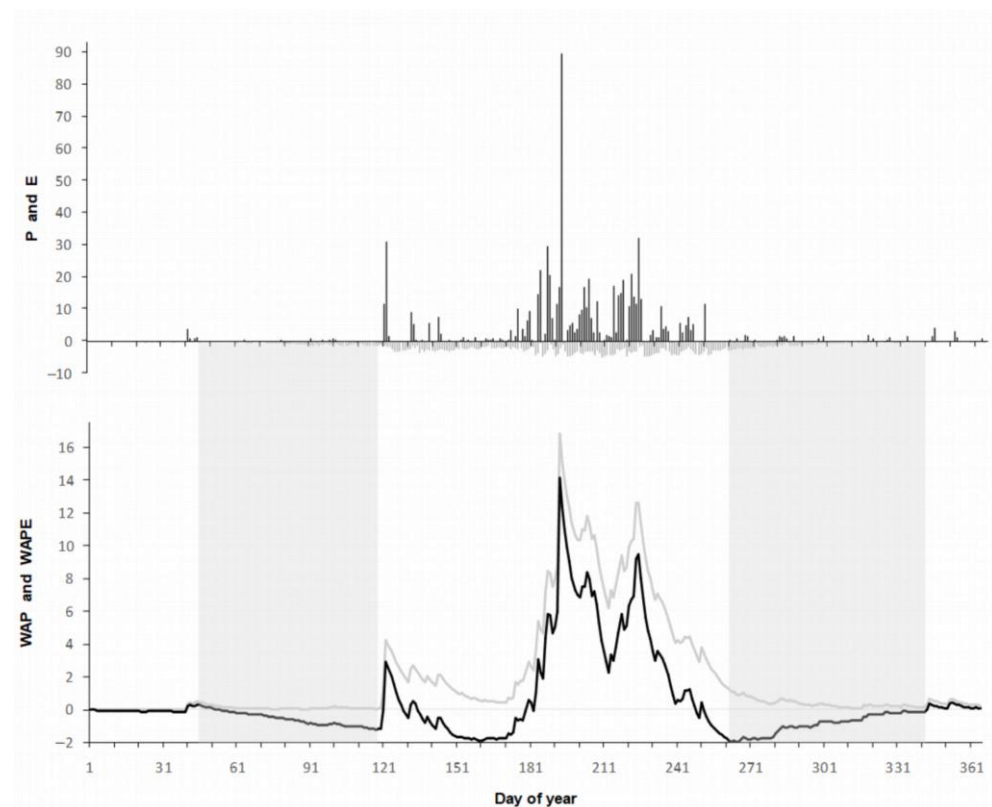


Figure 2. The daily precipitation P (positive) and evaporation E (negative) of 1994 (**upper panel**) in Beijing, represented with grid point (40°N , 116°E), from the dataset of ERA5 reanalysis, and the calculated WAP (gray) and WAPE (black) with the data of this year and the prior year (**bottom panel**). Units for the four quantities are all mm/day.

In the second period, there is a big difference in the degree of drought shown by WAP and WAPE. First, at the beginning of this period, the influence of the previous heavy precipitation gradually weakened, and the WAP index had not yet decayed to 0, while the WAPE index had reached the extreme negative value at this time, that is, the drought was the most severe at this time. Second, the WAP value during this period is gradually decreasing and is basically 0 in the second half of the period, that is, from the perspective of

meteorological drought, the drought is getting worse. As for the value of WAPE, the negative value gradually decreases and tends to be close to 0. That is, the drought went from being the most severe to gradually easing.

There is such an obvious difference mainly because evaporation and precipitation affect the development of drought and flood in a region at the same time. The general development trend of droughts and floods is mainly determined based on the intensity of precipitation and evaporation. When precipitation weakens but evaporation remains strong, drought continues to develop and reach its maximum intensity. Subsequently, the evaporation weakens and the restoring term is greater than the evaporation term, making the WAPE index develop towards a stable state. This is caused by the dialysis of water in the surrounding and deep soil. The results obtained by the WAP index, which does not consider the impact of evaporation, are completely different.

A severe drought affected Southwest China and lasted for three seasons, from fall 2009 to spring 2010. Lu et al. [26] investigated the anomalies of the atmospheric circulation during the drought, and pointed out that while there is a lack of water vapor input into the atmosphere, the high temperature during the drought also plays an important role in the formation of the severe drought.

Figure 3 shows the daily precipitation and evaporation as well as the calculated daily WAP and WAPE of 2010 in Kunming. In the first 140 days of the year (marked gray), both indices fluctuated under the influence of precipitation, affected by several weak precipitation events. The value of the WAP index, which does not consider evaporation, only increases rapidly when there is precipitation, and then slowly drops to a small value close to 0. The entire period presents several mitigations in the drought process. The WAPE index is basically negative throughout the entire period, which means that from the perspective of hydrological drought, this period is overall in a drought state. Even during several periods of weak precipitation, the drought only eases, or briefly turns to a water-logged state. This suggests that the intensity of the precipitation cannot sufficiently alleviate the strong evaporation. Under the influence from evaporation, along with runoff and infiltration, this area is still dry.

During the spring of 2011, the middle and lower reaches of the Yangtze River basin suffered a once-in-50-years drought. Lu et al. [27] revealed that although there was cold air invading the basin during the drought, led by the deeper-than-normal trough over East Asia, the Western Pacific subtropical high was much weaker than normal and retreated to the east, which made monsoonal moist air difficult to transport from lower latitudes to the region.

Figure 4 displays the daily precipitation and evaporation, as well as the WAP and WAPE, of 2011 in Nanjing. During the spring drought of this year, precipitation days were few and precipitation intensity was weak. From the perspective of meteorological drought, the WAP index shows that spring persisted in a dry state, and WAP maintains small values. However, it cannot further reflect the development tendency of drought aggravation. During the period, there was strong evaporation. After adding the influence of evaporation, the WAPE index can effectively reveal the drought tendency during the period. Subsequently, with the heavy rainfall, both indices changed to indicating floods.

The monitoring with WAPE shows that in the fall of this year, there was also a drought that lasted for one and half months. The WAP curve lags behind WAPE in reflecting the development of drought. When WAPE drops to a negative value, although WAP has been reduced due to the attenuation of the influence of previous precipitation, it still has a large value. Compared with WAP, the value of WAPE decreased greatly in August due to strong evaporation. During September and October, due to almost no precipitation and still strong evaporation, the value of WAPE dropped greatly again and became negative.

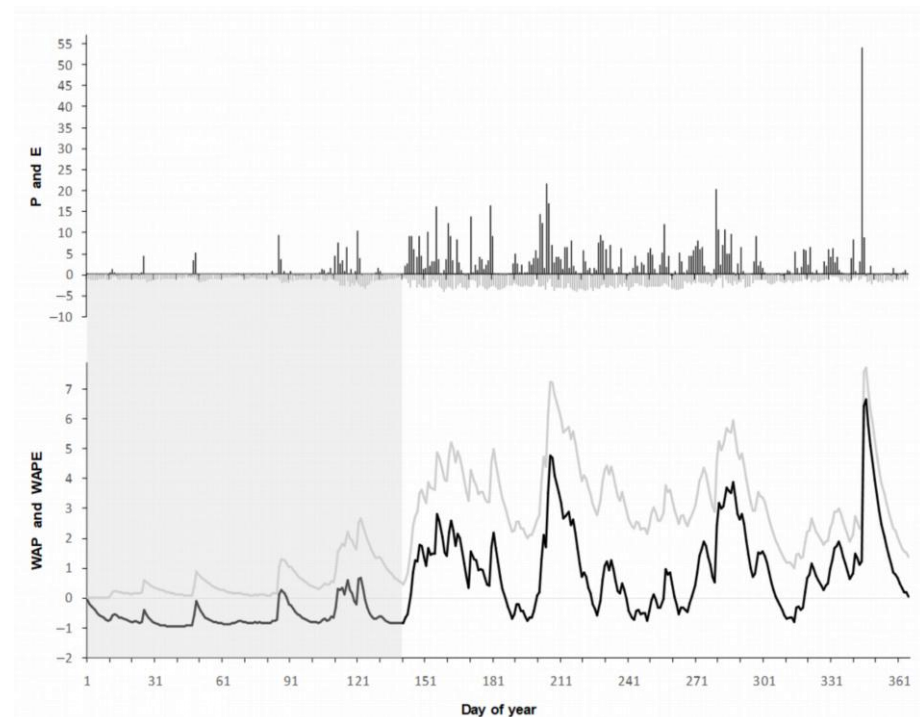


Figure 3. As in Figure 2, except for 2010 in Kunming, represented with grid point (25°N, 103°E).

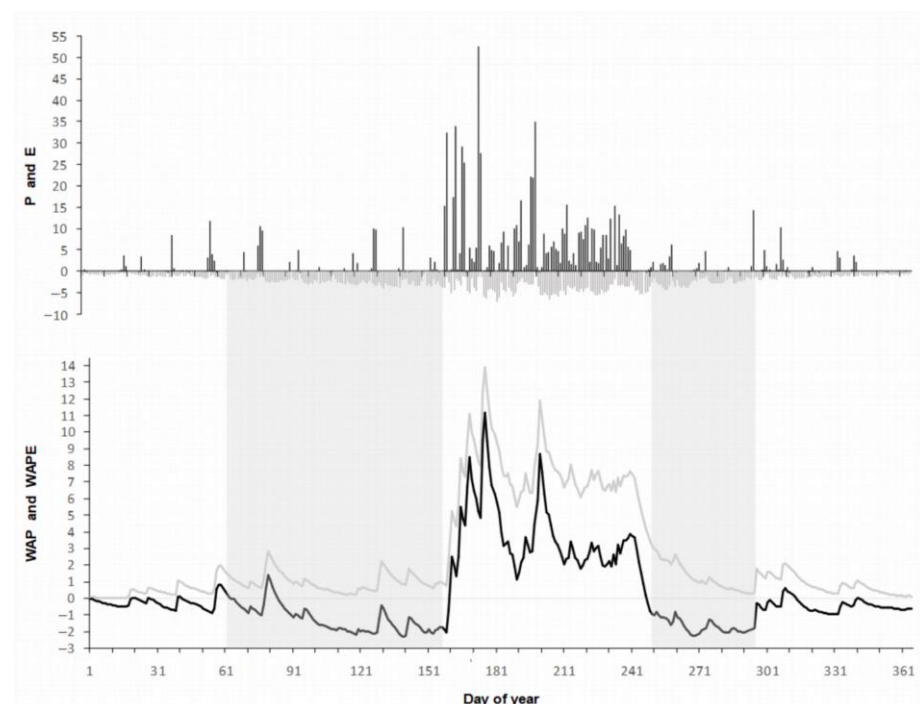


Figure 4. As in Figure 2, except for 2011 in Nanjing, represented with grid point (32°N, 118°E).

6. Summary and Discussion

Climate monitoring is an important task in climate service departments. A large variety of methods have been developed to monitor floods, droughts, monsoons, and other climate phenomena and extreme events. However, many of the methods were proposed empirically and they are somewhat subjective. We hope that physical equations and mathematical modeling will be used as much as possible. An example of this consideration is the EIDR method, developed by Lu et al. [23], which focuses on the monitoring and detection of extreme weather and climate events. They proposed a simple mathematical

model, which contains two essential constraints, and derived a baseline relation that could reasonably and reliably detect the lasting duration, the affected area, and the averaged intensity of an extreme event.

Drought was previously regarded as a long-timescale (from one month to several years) phenomenon. However, present climate services do require that drought be monitored at a shorter (daily or weekly) timescale. Lu [19] suggested, as a breakthrough idea, that the flood/drought extent, no matter how it is defined, should be treated as a state quantity, like pressure and temperature, and needs to possess an instantaneous value for each moment. Based upon this understanding, a simple physical model was proposed. It considers the change in the flood/drought extent. As a first-order approximation, the forcing of the change is from precipitation only. With the physical model, the WAP index was derived for monitoring meteorological drought.

The WAP can monitor drought at a daily scale; however, the SPI cannot. The SPI is actually a special case of the WAP, when the parameter α tends to be 1. Because of this, the weight of the precipitation does not decay with time. Thus, precipitation is treated equally for all days. This is the reason why the SPI always needs a timescale. Moreover, the timescale cannot be short, and needs to be one month or longer, since the rainfalls before the period of the scale are not included in the calculation of the SPI. Through calculating a simple average of the precipitation over the long period, the SPI merely presents the general drought/flood situation of a long period. Also, SPI is simply a statistical method, with no physics involved. By contrast, WAP has physical meaning. It is derived from a physical model, which is reasonable, though simple.

The goal of this study is to carry out further development of the method. Through modifying the simple physical model, we derive the WAPE index that can be used to monitor hydrological drought at a daily scale. The purpose of the modification is to better reflect the change in the soil moisture. In the monitoring with WAP, when the effect of the earlier precipitation has decayed, in the subsequent period of time, it will keep the “very dry” state. However, from the viewpoint of hydrological drought, soil can be wet in the early time during the period, and then becomes very dry in the later time. We thus focus on the “dry period” of the WAP, through discerning the change in the soil moisture during the period.

For the modification of the model into a second-order approximation, we introduce evaporation explicitly into the model, and use data of both precipitation and evaporation. The change in the flood/drought extent is forced by the $(P - E)$. With this modified model, we derived the WAPE index to monitor hydrological drought at a daily scale. The WAP and WAPE are consistent in the capability of separating flood and drought, based on day-to-day variations. The advantage of the WAPE is that, compared with WAP, it can capture the further change in the drought severity during drought periods, corresponding to the changes in the soil moisture.

In sum, the WAPE can reasonably describe the following two processes. One takes place during the period when there is no precipitation and the contribution of earlier precipitation has decayed; if there is strong evaporation, drought tends to be aggravated. The other takes place during the period when the local drought is very severe; if evaporation becomes small, drought might be locally mitigated because of the restoring force exerted by the horizontal and vertical gradients in soil moisture. These two processes are reasonable in physics, and may exist in reality.

For monitoring drought, we perform investigations step by step, from the simple situation to the more realistic. In our future work, as a third-order approximation, we may further modify the model, and derive a new index for monitoring ecological drought. Through incorporating the transpiration of vegetation in the model, the derived index may also monitor ecological drought at a daily scale. Expectedly, this may be helpful for

studying the “flash drought” issue. In addition to the methodological extensions mentioned above, a critical next step is to conduct quantitative validation of the WAPE index against independent hydrological observations. Specifically, the WAPE-derived drought severity should be compared with in situ soil moisture measurements from agrometeorological stations and with streamflow records from gauging stations across different climate zones in China. Such validation will not only strengthen the credibility of the WAPE index but also help to determine region-specific optimal values of the parameter for different surface and soil conditions. This quantitative evaluation is beyond the scope of the present study, which focuses on the physical derivation of the index and its qualitative behavior, but it represents an essential direction for our ongoing and future research.

Author Contributions: Conceptualization, D.Y. and E.L.; Methodology, D.Y. and E.L.; Software, D.Y.; Data curation, D.Y.; Writing—original draft, D.Y.; Writing—review and editing, D.Y. and E.L.; Funding acquisition, E.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Qinghai Institute of Technology “Kunlun Elite” Research Project (Grant 2025-QLGKLYCZX-008 and Grant 2026-QLGKLYCZX-019) and the National Natural Science Foundation of China (Grant 42475034).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The data of the ERA5 reanalysis used in this study are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), which are available at the website <https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets> (accessed on 1 June 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Chen, H.P.; Sun, J.Q. Changes in drought characteristics over China using the standardized precipitation evapotranspiration index. *J. Clim.* **2015**, *28*, 5430–5447.
2. Wang, H.J.; He, S.P. The north China/northeastern Asia severe summer drought in 2014. *J. Clim.* **2015**, *28*, 6667–6681.
3. Zhang, L.X.; Zhou, T.J. Drought over East Asia: A review. *J. Clim.* **2015**, *28*, 3375–3399.
4. Qiang, H.; Chen, Z.S.; Tang, C.Y.; Li, S.F. Monitoring the spatio-temporal process of severe droughts in the Pearl River Basin. *Adv. Earth. Sci.* **2019**, *34*, 1050–1059.
5. Quiring, S.M. Developing objective operational definitions for monitoring drought. *J. Appl. Meteorol. Sci.* **2009**, *48*, 1217–1229.
6. Hayes, M.; Svoboda, M.; Wall, N.; Widhalm, M. The Lincoln declaration on drought indices: Universal meteorological drought index recommended. *Bull. Am. Meteorol. Soc.* **2011**, *92*, 485–488.
7. Steinemann, A.; Iacobellis, S.F.; Cayan, D.R. Developing and evaluating drought indicators for decision-making. *J. Hydrometeorol.* **2015**, *16*, 1793–1803.
8. Quiring, S.M. Monitoring drought: An evaluation of meteorological drought indices. *Geogr. Compass* **2009**, *3*, 64–88.
9. Palmer, W.C. *Meteorological Drought. Research Paper No. 45*; Superintendent of Documents, U.S. Government Printing Office, Washington, DC, USA, 1965; p. 58.
10. Mo, K.C.; Chelliah, M. The modified Palmer drought severity index based on the NCEP North American Regional Reanalysis. *J. Appl. Meteorol. Climatol.* **2006**, *45*, 1362–1375.
11. Lu, E.; Cai, W.Y.; Jiang, Z.H.; Zhang, Q.; Zhang, C.J.; Higgins, R.W.; Halpert, M.S. The day-to-day monitoring of the 2011 severe drought in China. *Clim. Dyn.* **2014**, *43*, 1–9.
12. Otter, J.A.; Svoboda, M.; Hunt, E.D.; Ford, T.W.; Anderson, M.C.; Hain, C.; Basara, J.B. Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bull. Am. Meteorol. Soc.* **2018**, *99*, 911–919.
13. Sreeparvathy, V.; Debdut, S.; Mishra, A. A review of advances in flash drought research: Challenges and future directions. *Earth’s Futur.* **2025**, *13*, e2025EF006603.

14. Qing, Y.; Wang, S.; Ancell, B.C.; Yang, Z.L. Accelerating flash droughts induced by the joint influence of soil moisture depletion and atmospheric aridity. *Nat. Commun.* **2022**, *13*, 1139.
15. Wang, L.Y.; Yuan, X. Two types of flash drought and their connections with seasonal drought. *Adv. Atmos. Sci.* **2018**, *35*, 1478–1490.
16. Ma, F.; Li, H. Temperature is surpassing precipitation as the dominant driver of flash drought acceleration under climate warming. *Geophys. Res. Lett.* **2026**, *53*, e2025GL118457.
17. Ma, F.; Yuan, X. Earlier flash drought onset driven by spring vegetation greening and warming. *Geophys. Res. Lett.* **2026**, *53*, e2026GL122625.
18. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J. Clim.* **2010**, *23*, 1696–1718.
19. Lu, E. Determining the start, duration, and strength of flood and drought with daily precipitation: Rationale. *Geophys. Res. Lett.* **2009**, *36*. <https://doi.org/10.1029/2009GL038817>.
20. Liang, C.; Shen, S. Climatic features of the drought in the Yangtze River Basin and regions to its south disclosed by WAP index. *J. Nanjing Univ. Nat. Sci.* **2010**, *2*, 166–174.
21. Zhao, Y.; Weng, Z.H.; Chen, H.; Yang, J.W. Analysis of the evolution of drought, flood, and drought-flood abrupt alternation events under climate change using the daily SWAP index. *Water* **2020**, *12*, 1969.
22. Liu, B.; Liu, Y.B.; Wang, W.P.; Li, C.L. Meteorological Drought Events and Their Evolution from 1960 to 2015 Using the Daily SWAP Index in Chongqing, China. *Water* **2021**, *13*, 1887.
23. Lu, E.; Zhao, W.; Zou, X.K.; Ye, D.X.; Zhao, C.Y.; Zhang, Q. Temporal-spatial monitoring of an extreme precipitation event: Determining simultaneously the time period it lasts and the geographic region it affects. *J. Clim.* **2017**, *30*, 6123–6132.
24. Karl, T. Atlas of monthly Palmer hydrological drought indices (1931–1983) for the contiguous United States; National Climatic Data Center: Asheville, NC, USA, 1985.
25. Guttman, N.B. A sensitivity analysis of the palmer hydrologic drought index 1. *J. Am. Water Resour. Assoc.* **1991**, *27*, 797–807.
26. Lu, E.; Luo, Y.L.; Zhang, R.H.; Liu, L.P. Regional atmospheric anomalies responsible for the 2009–2010 severe drought in China. *J. Geophys. Res. Atmos.* **2011**, *116*, D21.
27. Lu, E.; Liu, S.Y.; Luo, Y.L.; Zhao, W.; Li, H.; Chen, H.X.; Zeng, Y.T.; Liu, P.; Wang, X.; Higgins, R.W.; et al. The atmospheric anomalies associated with the drought over the Yangtze River basin during spring 2011. *J. Geophys. Res. Atmos.* **2014**, *119*, 5881–5894.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.