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Proposal of a new method for drought analysis

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Abstract: Below-average precipitation and above-average air temperature are important factors in the occurrence and intensity of drought. In the context of global climate change, air temperature increase, as a key climatological parameter, has to be considered when calculating the drought index. We introduce a new method of drought analysis, relying on standardized values of precipitation and mean air temperatures for a certain period. The standardized value is calculated by subtracting the average value for each period from each measured value and dividing the obtained value by the standard deviation of the sample. Next, the New Drought Index (NDI) is calculated by subtracting the standardized temperature value from the standardized precipitation value. NDI values were determined for the monthly and annual precipitation time series and mean monthly and annual air temperatures measured at the stations Split-Marjan and Zagreb-Grič between 1948 and 2020. The NDI indicates that the risk of drought has intensified significantly in recent decades, which may be related to the effect of global warming.

Keywords: Drought; Air temperature; Precipitation; New Drought Index (NDI); Split-Marjan; Zagreb-Grič.

INTRODUCTION

Drought is a complex phenomenon (Van Loon, 2015; Wong et al., 2013; Yevjevich et al., 1983) that can potentially have catastrophic consequences at multiple levels, e.g., agriculture, water resources. The literature dealing with drought effects is considerable (Barker et al., 2016; Bonacci, 1993; Ferina et al., 2021; Hisdal, 2002; Li et al., 2021; Mishra and Singh, 2010; Morid et al., 2006; Palmer, 1965; Pandžić et al., 2020; Tadić et al., 2015; Van Lanen et al., 2013). In the context of climate change, the duration and intensity of drought are expected to be strongly influenced by increase in temperature (Dai, 2011). Using the Standard Weighted Average Precipitation Index, Zhao et al. (2020) pointed to the possibility that during the 21st century climate change will frequently lead to more sudden changes in droughts and floods.

The generally accepted definition of a drought relates to a deficit of water relative to the normal conditions prevailing in an area (Lloyd-Hughes, 2014). Panu and Sharma (2002) claim that droughts are perceived as extreme events in climate systems, whereas in reality, they need to be considered common occurrences. AghaKouchak et al. (2021) consider that the traditionally accepted definition of drought as a deficit of water-related variables and/or activities (e.g., precipitation, soil moisture, surface and groundwater reserves, irrigation water, etc.) caused by natural variability is incomplete because it does not consider local factors. In this paper, we consider that droughts must be defined and understood differently within the coupled human-water system. To meet this goal, it is necessary to consider the complex interrelated dynamics of natural phenomena and changes induced by human activities. A so-called anthropogenic drought should be understood as a phenomenon that combines several dimensions at different time scales. Drought is governed by a combination of natural water variability, climate change, human activities and decisions, as well as micro-climatic conditions that occur due to changes in land exploitation and water management. Anthropogenic drought in a broader context should be defined as the occurrence of drought caused or intensified by human activities.

Several concepts and methods are at hand for studying, identifying and quantifying drought. Since these approaches (hydrological, meteorological, agronomic, socio-political, etc.) treat droughts differently, they are prone to deliver contrasting results. The latter can potentially jeopardize the design and implementation of effective and timely drought mitigation actions strongly influenced by temperature increase (Dai, 2011).

Due to the complexity of the drought phenomenon, it is necessary to use objective and transparent approaches to define it. Several indices, which differ in their definition and the data needed to calculate them, are used in the literature to describe drought. Despite numerous efforts, no universal drought index has been established to date. Another term, also used in the literature, is the aridity index which represents the relationship between the mean annual potential evapotranspiration and precipitation that controls the mean annual inflows of surface and groundwater in an area (Neto et al., 2020).

The need to quantify the characteristics of drought has resulted in the development of numerous drought indices that assess this phenomenon in various ways. The characteristics of drought commonly defined are (1) duration (T); (2) strength or cumulative deficit (S); (3) deficit intensity (S/T). In addition, it is essential to define the beginning of the drought, while the end time is usually easier to determine since it mainly occurs when abundant precipitation occurs in the monitored area. Lloyd-Hughes (2014) considers it essential to include evidence of water supply, demand, and management in the monitored area to quantify and more accurately describe drought. The same author states that there are more than a hundred specialised drought indices in the related literature, which indicates the complexity of this phenomenon, but also the difficulty in defining generally acceptable and reliable indicators. The fact is that many of the parameters used in calculating drought indices are highly correlated, but they must be applied with caution when defining the concept of “drought” in the broader sense. In de-

termining a hydrological drought, the fact of a non-linear response of terrestrial processes to climatic stimuli should be considered (Van Lanen et al., 2013; Van Loon, 2015).

Although numerous studies related to the quantification of drought have been conducted so far (and are being carried out intensively even today), many doubts and uncertainties continue to prevail. The Standardized Precipitation Index (SPI) is considered as the most reliable drought index by multiple authors (Pandžić et al. 2020; Tadić et al. 2015; WMO, 2012). Based on the probability of precipitation occurring over a given period, it is developed as a spatially independent indicator of drought, considering the importance of weather intervals in analyses of water availability and use (Dragičnić et al., 2017). The fact that it exclusively uses precipitation data somewhat limits its ability to characterize the properties of various types of drought. Barker et al. (2016), using the Standardized Streamflow Index and the Standardized Precipitation Index, examined the relationships between hydrological and meteorological drought in the UK.

The Palmer Drought Index was developed for monitoring changes in soil water balance (Palmer, 1965). In the US, it is used as a standard to study meteorological drought. It depends on many factors (Pandžić et al., 2006), and it is based on the hydrological balance of precipitation water movement in the soil-plant-atmosphere system. In addition to precipitation and air temperature, data on the amount of moisture in the soil, evapotranspiration, and the rate of moisture filling in two surface soil layers bordering the atmosphere (upper up to 20 cm, and lower up to 80 cm), are required to define it. This method requires data that are rarely measured, so less reliable estimations are used. This index should determine long-term droughts lasting several months.

Given that drought is mainly caused by rainfall deficiencies and high evapotranspiration rates, Fassouli et al. (2021) have proposed a Factual Drought Index (FDI) as a composite tool, based on precipitation and potential evapotranspiration (PET).

Here, we propose a New Drought Index (NDI), relying on precipitation and air temperature data. The NDI leverages the fact that in the context of drought analysis, temperatures have an inversely proportional effect from precipitation. Higher-than-average precipitation and lower-than-average temperatures have a more favourable effect on drought mitigation and vice versa (Ljubenkov and Bonacci, 2011).

MATERIALS AND METHODS

Climatological data used

We use annual and monthly precipitation data along with mean monthly and mean annual air temperatures observed at the main meteorological stations of the State Hydrometeorological Institute (DHMZ) Zagreb-Grič (hereinafter Zagreb) and Split-Marjan (hereinafter Split) during a period of 73 years, from 1948 to 2020 (Data generously provided by DHMZ).

The distance between the meteorological stations Zagreb and Split is 259 km (Figure 1). At the meteorological station Zagreb, the climate is moderately warm and humid with warm summers (Šegota and Filipčić, 2003). According to the Köppen and Geiger (1936) climate classification, it belongs to the Cfb class. The station is at an elevation of 157 meters above sea level (m a.s.l.), and the geographical coordinates are 45° 48' 52" N and 15° 58' 19" E. The meteorological station Split has a Mediterranean climate with hot summers (Šegota and Filipčić, 2003). According to the Köppen and Geiger (1936) climate classification, it belongs to the Csa class. The station is at an elevation of 122 m above sea level, and the geographical coordinates are



Fig. 1. Map of the study area.

43° 30' 30"N and 16° 25' 35" E. Both stations are located in fast-growing cities, but since they are placed on the tops of hills, they are not exposed to strong urbanization (this is especially true for the Split station), and the impact of the urban heat island effect remains limited.

Statistical methods used

We used linear and nonlinear regression and correlation methods for the analyses of time series. For determining the statistical significance of differences between variances and mean values of successive subsets of precipitation, mean temperatures, and New Drought Indices, we used the nonparametric F-test and t-test (McGhee, 1985).

The Rescaled Adjusted Partial Sums (RAPS) method served to determine the sub-period with a statistically significant difference in average values over complete time series (1948–2020) of precipitation and temperature (Bonacci and Roje-Bonacci, 2020; Garbrecht and Fernandez, 1994). The statistical significance of the differences was determined using the F-test and the t-test. The equation for calculating RAPS is:

$$RAPS_k = \sum_{t=1}^{k} \frac{Y_t - Y_m}{S_y} \quad (1)$$

where Y_t, represents precipitation or mean temperature in a given time interval, t, Y_m, the average value of the entire analysed series, S_Y, the standard deviation, n, the number of data in a series, $k \in (1, 2\ldots, n)$, the counter of sums for the k analysed time unit in a series of the total, n.

The statistical significance of the linear trends of the series of annual and monthly precipitation, mean temperatures, and NDI, was determined using the Mann-Kendall (M-K) test (Hamed and Ramachandra, 1998; Kendall, 1975; Mann, 1945). At present, this test is considered the most reliable procedure for assessing the statistical significance of trends in the analysed time series. One of its essential advantages is that it does not require the analysed data to be adjusted to any distribution curve, i.e., the M-K test is nonparametric. Therefore, it is also most widely used in the time series analysis of climatological parameters, especially temperature and precipitation (Allen et al. 2015; Hori et al., 2017; Wang and Stephanson, 2018). We used the pyMannKendall, a python package, in this paper

(Shourov and Mahmud, 2019). Our null hypothesis was that there is no monotonic trend in the analysed time series. An alternative hypothesis was that the trend exists. In this paper, the probability value, $p<0.05$, was used as a criterion for accepting the alternative hypothesis (existence of a statistically significant linear trend).

New Drought Index (NDI)

In this paper, we introduce the New Drought Index (NDI), using precipitation and air temperature data. Both climatological parameters used to define NDI values play a key role for determining all drought characteristics such as duration, severity, intensity, as well as the beginning and end of the drought period. Potential and/or real evapotranspiration are a crucial parameter in many drought characteristics determination methods. The different methods, approaches and equations at hand give very different and, for engineering practice very often, unreliable results. Bonacci (2004) considers that evapotranspiration is the most unreliably assessed variable in the determining of the water balance, as well as of drought. Therefore, we opted in our study for using air temperature instead of real or potential evapotranspiration.

In the case of precipitation, the intensity of the abovementioned drought features is influenced by its deficit (deficit in relation to the average values of the analysis period in the monitored area), in the case of temperature, it is influenced by temperatures higher than the average of the analysis period. Ultimately, the use of temperature data for calculating the drought index is becoming more and more relevant due to global climate change and the related temperature increase.

Prior to their use in one index, both climate parameters need to be transformed into dimensionless quantities by the standardization process. We propose to determine the NDI via the following equation:

$$NDI_i = [(P_i - P_{av})/S_P] - [(T_i - T_{av})/S_T] \quad (2)$$

where:
P_i, precipitation in the year or month, i,
P_{av}, the average value of the analysed series of precipitation in the analysis period,
S_P, the standard deviation of the analysed series of precipitation in the analysis period,
T_i, the mean temperature in a year or month,
T_{av}, the average value of the analysed series of mean temperatures in the analysis period, and
S_T, the standard deviation of the analysed series of temperatures in the analysis period.

Since this paper analyses the series from 1948 to 2020, a total of 73 years or 876 months, the values of i span different data sets. When analysing annual values, $i \in (1, 2...,73)$, and when analysing monthly values from January 1948 to December 2020, $i \in (1, 2..., 876)$.

RESULTS AND DISCUSSION

Analysis of annual series of precipitation and temperatures

In the first row of Table 1, the values of average annual precipitation, P_{pr}, temperature, T_{pr}, and standard deviations, S, for Split and Zagreb in the period from 1948 to 2020 are listed. In the considered period, the average precipitation measured in Zagreb was 884.2 mm/year, 73.4 mm/year higher than in Split, which was 810.8 mm/year. The average annual temperature measured in Split was 16.36 ºC, 4.25 ºC higher than that of 12.11 ºC measured in Zagreb.

Figure 2 shows the series of annual precipitation for Split and Zagreb in the period 1948 to 2020. The figure also shows the linear regression directions, and the equations of the linear regressions, the values of the linear correlation coefficients, r, and the probability values of the M-K test, p. We noted no statistically significant trend in the series of annual precipitation at either station. Although the complete time series of precipitation at both stations do not show any trend within 73 years, subperiods have emerged with statistically significant different average values.

Using the RAPS method, graphically represented in Figure 3A, we found four sub-periods in Split (1948 to 1958; 1959 to 1982; 1983 to 1994; 1995 to 2020) and three sub-periods in Zagreb (1948 to 1958; 1959 to 1966; 1967 to 2020). Graphic representations of four subsets of Split and three subsets of Zagreb are shown in Figure 3B.

Although the annual precipitation measured at these two stations does not differ significantly, as confirmed by the high value of the linear correlation coefficient, $r = 0.581$, their behaviour during the observed 73 years is significantly different. The differences between consecutive average values of the subperiod were tested with the F-test and t-test. The probabilities, p, for consecutive subsets obtained with the t-test, are shown in Table 2.

Table 1. Values of the average annual and monthly precipitations, P_{av}, air temperatures. T_{av}. and standard deviation, S, measured at the two meteorological stations during the analysed period (Jan. 1948–Dec. 2020).

Period	SPLIT				ZAGREB			
	P_{av} (mm)	S (mm)	T_{av} (ºC)	S (ºC)	P_{av} (mm)	S (mm)	T_{av} (ºC)	S (ºC)
year	810.8	155.2	16.36	0.678	884.2	144.3	12.11	0.993
January	77.9	45.1	7.95	1.56	52.8	33.5	1.45	2.57
February	66.2	40.7	8.40	1.91	47.0	28.4	3.49	3.04
March	63.3	46.1	10.80	1.67	51.7	28.8	7.76	2.33
April	62.6	33.0	14.39	1.39	62.7	31.0	12.47	1.68
May	57.3	36.7	19.11	1.51	81.2	37.8	16.08	1.62
June	50.1	35.7	23.24	1.49	96.9	38.0	20.23	1.57
July	27.6	28.0	26.05	1.35	88.3	44.8	22.14	1.54
August	38.6	40.3	25.78	1.64	85.2	50.4	21.58	1.81
September	71.6	53.1	21.55	1.46	90.8	47.9	17.33	1.52
October	78.8	50.7	17.13	1.21	77.7	51.4	12.23	1.43
November	113.4	55.0	12.7	1.39	85.5	48.4	7.03	2.11
December	103.3	66.6	9.32	1.26	64.5	36.1	2.65	2.03

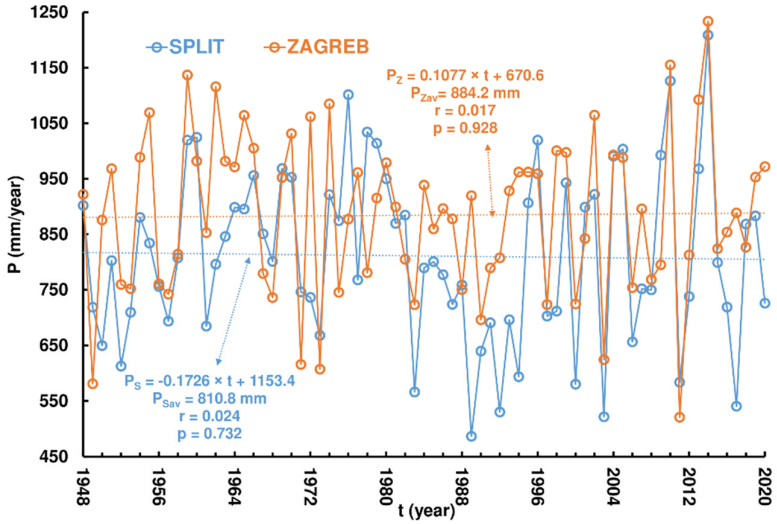


Fig. 2. Series of annual precipitation of Split and Zagreb in the period 1948 to 2020.

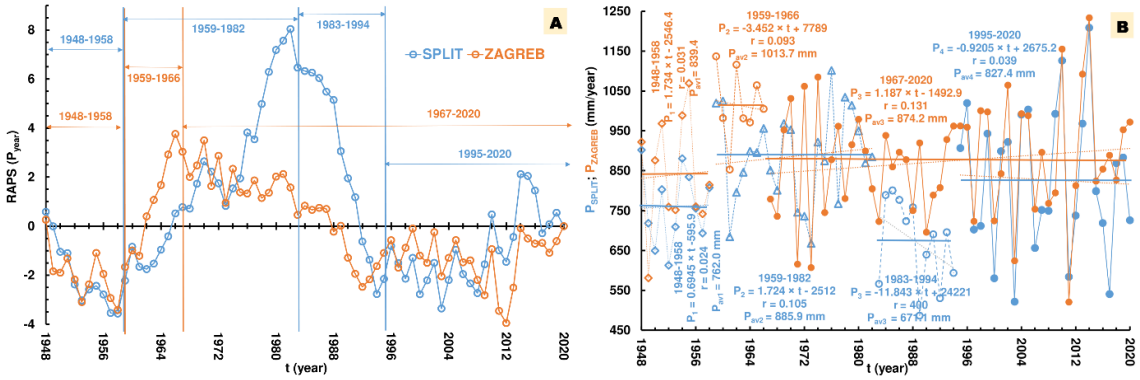


Fig. 3. Graphic representation of RAPS for the series of annual precipitation of Split and Zagreb in the period 1948 to 2020 (A) and representation of four subsets of precipitation in Split and three subsets of precipitation in Zagreb determined by RAPS method (B).

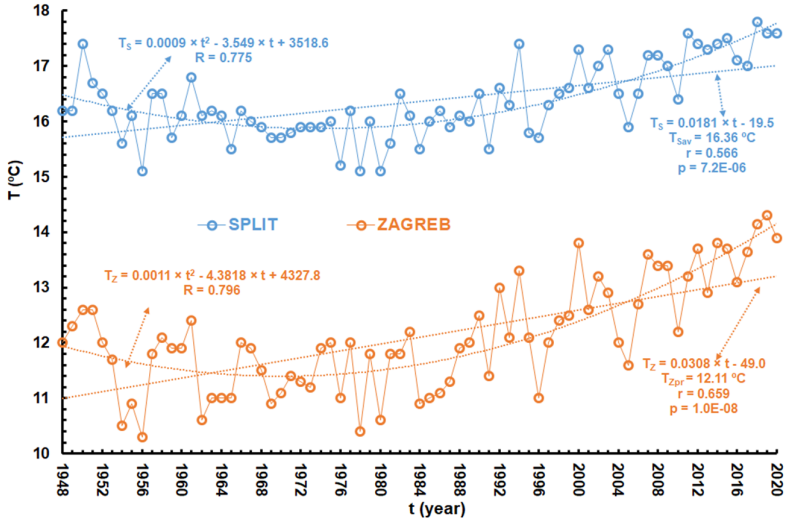


Fig. 4. Series of mean annual temperatures of Split and Zagreb in the period 1948 to 2020.

Figure 4 shows the mean annual temperatures series of Split and Zagreb in the period 1948 to 2020. The linear regression lines, the linear regression equations, the values of the linear correlation coefficients, *r*, and the probability values of M-K test, *p*, are provided in the figure, as well as the second-order curves and their equation and values of the nonlinear (parabolic) correlation index, *R*. At both stations, linear growth trends are statistically significant. However, it should be noted that the

Table 2. Matrix of the average annual precipitation, P_{av}, in the sub-periods defined by the RAPS method and the probability of the t-test, p, between consecutive sub-periods.

Station	Sub-period	P_{av} (mm)	p (t-test)
SPLIT	1948–1958	762.0	3.4E–03
	1959–1982	885.9	5.3E–06
	1983–1994	671.1	8.7E–03
	1995–2020	827.4	
ZAGREB	1948–1958	839.4	7.0E–03
	1959–1966	1013.7	9.7E–03
	1967–2020	874.2	

Table 3. Matrix of the average annual air temperature, T_{av}, in the sub-periods defined by the RAPS and the probability of the t-test, p, between consecutive sub-periods.

Station	Sub-period	T_{av} (°C)	p (t-test)
SPLIT	1948–1997	16.04	5.9E–12
	1998–2020	17.06	
ZAGREB	1948–1991	11.53	1.4E–12
	1992–2020	12.97	

second-order curves adjust much better to the analysed series and that the squares index values of the nonlinear correlation are significantly higher than those of the linear correlation coefficients. It is visually noticeable that the sharp rise in temperatures began in the last decades of the twentieth century. Similar time series temperature behaviour was observed throughout the Western Balkans (Bonacci, 2010; 2012), as well as in several other locations on the planet (Kim et al., 2015; Kothawale and Kumar, 2005; Levi, 2008; Li, 2010; Pandžić et al., 2020).

The graphical representation of RAPS mean annual temperatures (Figure 5A) shows that at the Split station the sudden rise in temperatures began in 1998, while at the Zagreb station it began six years earlier in 1992. Graphical representations of the two subsets of Split and Zagreb are shown in Figure 5B. It is important to notice that at both stations in recent years the M-K test indicates statistically significant (ongoing) growth trends. The probabilities, p, for consecutive subsets obtained with the t-test, are shown in Table 3. The value of the square linear correlation coefficient between the mean annual temperatures at the two observed stations is high and amounts to, $r = 0.906$.

Analysis of the monthly series of precipitation and temperatures

Table 1 lists the average monthly precipitation values, P_{pr}, temperature, T_{pr}, and standard deviations, S, for Split and Zagreb, between 1948 and 2020. To clearly highlight the differences in precipitation regimes at the two stations over twelve months, the average monthly values and their differences, $\Delta P_i = P_{i.SPLIT} - P_{iZAGREB}$, are shown in Figure 6A.

Although the annual precipitation amounts differ only by 10%, the differences in the precipitation regime during the year are significant and considerably affect the potential drought regimes in these two locations. In Split, heavy precipitation occurs in the cold period of the year. The maximum occurs in November and the minimum in July. In Zagreb, heavy precipitation occurs from May to November, with a maximum in June and a minimum in February. From November to March, the average monthly precipitation in Zagreb is lower than in Split, while from May to September, it is higher. In April and October, they are practically the same.

The regime of average values of mean monthly temperatures during the year at both stations is very similar. Figure 6B shows the average monthly values and their differences, $\Delta T_i = T_{i.SPLIT} - T_{iZAGREB}$. The maximum occurs in July and the minimum in January. The largest differences occur in December and amount to $\Delta T_{12} = 6.66$ °C, while the minimal occur in April when the difference is $\Delta T_4 = 1.93$ °C.

Table 4 lists the values of the linear correlation coefficients, r, and the results of the M-K test, p, for the series of monthly precipitation and mean monthly temperatures at both stations for the period 1948 to 2020. The results for series with a statistically insignificant downward trend ($p>0.05$) are marked in blue. The results for series with a statistically significant upward trend ($p<0.05$) are marked in bold red, while the results for series with a statistically insignificant increase trend ($p>0.05$) are marked in black characters. For the monthly precipitation series, we have found downward trends (marked in blue) and upward trends (marked in black) – nearly all of them being statistically insignificant. For mean monthly temperatures series, we identified a completely different pattern. All monthly series at both stations show an upward trend. In most months, especially during the summer period, these upward trends are also statistically significant.

Analysis of annual values of NDI

The bar chart shown in Figure 7A reveals the series of the New Drought Index, NDI_i, $i \in (1, 2...,73)$, defined on the basis of 73 annual values of precipitation and mean annual temperatures of Split and Zagreb for the period 1948 to 2020. The second-order curves, their equations, and indices of nonlinear correlation, R, are also given. The subperiods in which the F-test and t-test yield consecutive average NDI values with a

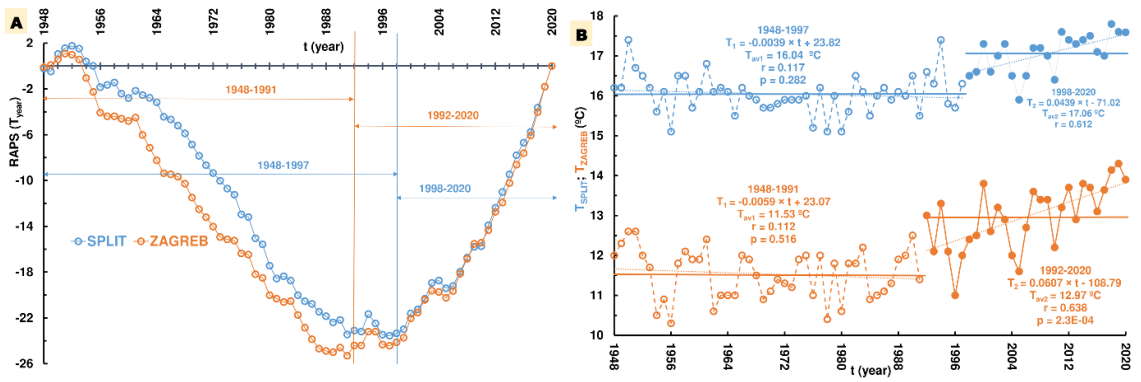


Fig. 5. Graphic representation of RAPS for the series of mean annual temperatures of Split and Zagreb in the period 1948 to 2020 (A) and representation of two subsets of mean annual temperatures of Split and Zagreb determined by RAPS method (B).

Table 4. Values of the coefficient of linear correlations, *r*, and the probability of the M-K test, *p*, for the monthly time series of precipitations and air temperatures, measured at the two analysed stations during the analysed period (1948-2020).

Month	Precipitation				Air temperature			
	SPLIT		ZAGREB		SPLIT		ZAGREB	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
January	0.085	0.363	0.161	0.105	0.130	0.282	**0.307**	**9.5E-03**
February	0.065	0.801	0.140	0.561	0.163	0.277	0.258	0.072
March	0.044	0.587	0.022	0.973	**0.284**	**0.029**	**0.360**	**4.9E-03**
April	0.027	0.753	0.085	0.440	**0.300**	**0.007**	**0.374**	**6.8E-04**
May	0.076	0.336	0.098	0.443	**0.256**	**0.017**	**0.342**	**1.7E-03**
June	0.071	0.179	0.107	0.353	**0.446**	**1.3E-04**	**0.498**	**1.7E-05**
July	0.042	0.238	0.091	0.644	**0.478**	**5.6E-05**	**0.534**	**9.2E-07**
August	0.083	0.127	0.003	0.932	**0.421**	**3.2E-04**	**0.490**	**1.9E-05**
September	0.072	0.376	0.259	0.114	0.062	0.658	0.118	0.548
October	0.050	0.775	0.201	0.096	0.191	0.117	**0.283**	**0.019**
November	0.017	0.797	0.033	0.992	**0.246**	**0.048**	**0.235**	**0.045**
December	0.095	0.338	0.011	0.890	0.066	0.472	**0.233**	**0.022**

blue numbers designate statistically insignificant decreasing trends
red bold numbers designate statistically significant increasing trends
red numbers designate statistically insignificant increasing trends

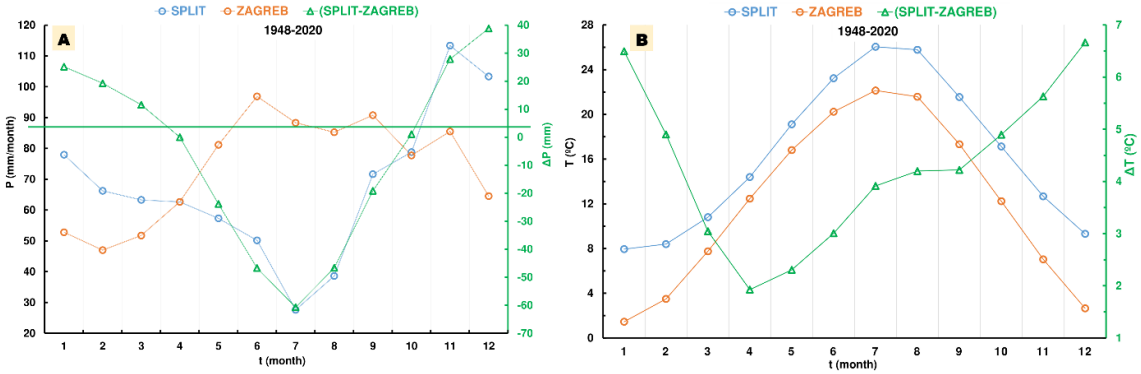


Fig. 6. (A) Average monthly values of precipitation at the observed stations during the period 1948 to 2020, and the differences between them, $\Delta P_i = P_{i.SPLIT} - P_{iZAGREB}$; (B) Average monthly values of temperatures at the observed stations during the period 1948 to 2020, and the differences between them, $\Delta T_i = T_{i.SPLIT} - T_{iZAGREB}$.

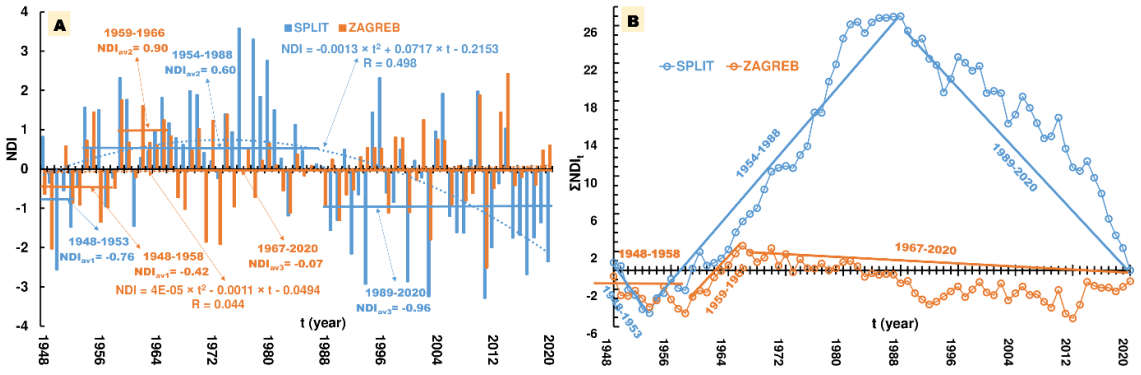


Fig. 7. Representation of the series (A) of the NDI_i, $i \in (1, 2 ..., 73)$, and the sums (B) of the New Drought Indices, ΣNDI_i, $i \in (1, 2 ..., 73)$, defined according to the annual values of precipitation and mean annual temperatures of Split and Zagreb in the period 1948 to 2020.

statistically significant difference is also shown. In Figure 7B, a graphical representation of the sum of ΣNDI_i, $i \in (1, 2..., 73)$ is used to determine the sub-period. Table 5 presents the matrix of average values of annual New Drought Indices, NDI_{av}, in the sub-periods depicted in Figure 7B and the results of the t-test, *p*, between successive sub-periods. When the year is considered a unit of analysis, it can be assumed that the occurrence of drought near Split began in 1988 and was intense. This finding is evident from the slope of the direction illustrated in Figure 7B for the sub-period 1989 to 2020. In the case of Zagreb, the NDI shows the occurrence of a milder drought in the period 1967 to 2020. Moreover, it seems that in the sub-period 2012 to 2020, the drought ceased, and a wet sub-period appeared. Note that this finding could not be corroborated by testing.

Table 5. Matrix of the average annual New Drought Index, NDI_{av}, in the sub-periods defined in Figure 7B and the probability of the t-test, p, between consecutive sub-periods.

Station	Sub-period	NDI_{av}	p (t-test)
SPLIT	1948–1953	–0.758	2.4E–03
	1954–1988	0.901	6.9E–05
	1989–2020	–0.844	
ZAGREB	1948–1958	–0.416	4.9E–03
	1959–1966	0.897	9.7E–03
	1967–2020	–0.070	

Table 6. Matrix of the average monthly New Drought Index, NDI_{av}, in the sub-periods defined in Figure 8 and the probability of the t-test, p, between consecutive sub-periods.

Station	Sub-period	NDI_{av}	p (t-test)
SPLIT	I 1948 – IX 1952	–0.424	9.3E–05
	X 1952 – VI 1987	0.385	1.1E–03
	VII 1987 – VII 1999	–0.073	8.5E–03
	VIII 1999 – XII 2020	–0.490	
ZAGREB	I 1948 – IX 1952	–0.366	5.0E–08
	X 1952 – VIII 1987	0.434	3.3E–04
	IX 1987 – II 1999	–0.076	6.4E–03
	III 1999 – XII 2020	–0.580	

Table 7. Values of the coefficient of linear correlations, r, and the probability of the M-K test, p, for every monthly time series of the New Drought Index, NDI_i, $i \in (1,2,3,\ldots, 73)$, measured at the two analysed stations during the analysis period (1948–2020).

Month		SPLIT	ZAGREB
January	r	0.159	**0.332**
	p	0.232	**0.003**
February	r	0.069	0.081
	p	0.764	0.577
March	r	0.153	0.217
	p	0.207	0.102
April	r	0.173	**0.288**
	p	0.136	**0.004**
May	r	0.103	**0.254**
	p	0.348	**0.044**
June	r	**0.310**	**0.374**
	p	**0.008**	**1.6E-04**
July	r	**0.320**	**0.374**
	p	**1.9E-04**	**0.002**
August	r	**0.285**	**0.288**
	p	**0.003**	**0.007**
September	r	0.006	0.084
	p	0.928	0.735
October	r	0.094	0.539
	p	0.449	0.943
November	r	0.192	0.195
	p	0.172	0.076
December	r	0.076	0.268
	p	0.438	0.079

blue numbers designate statistically insignificant decreasing trends
red bold numbers designate statistically significant increasing trends
red numbers designate statistically insignificant increasing trends

Analysis of NDI monthly values

To study the occurrence of drought and changes between dry and wet sub-periods and because of the seasonality of each climate regime, a month, as a relatively short unit of time is better suited for reliably characterizing the occurrence of drought. Figure 8 shows the sums of monthly NDI, ΣNDI_i, $i \in (1, 2..., 876)$, from January 1948 to December 2020. Similar behaviour of the time series sum is observed at both stations regardless of their difference in climatic characteristics. In both cases, we identified four sub-periods. Table 6 shows the average values of the annual New Drought Indices, NDI_{av}, in the sub-periods defined in Figure 7 and the t-test results, p, between successive sub-periods. The long-term decrease in the total value of NDIs at the Split station began in August 1999, while at the Zagreb station it started five months earlier, in March 1999. During the last period, there were occasional wet sub-periods, but the general trend indicates that drought prevails at both stations and will probably continue if air temperatures continue to rise, as expected due to global warming, and if precipitation remains the same.

Next, we investigated the behaviour of the NDI time series for each month during the period 1948 to 2020. Our analysis spans the monthly behaviour of the NDI during the monitored 73-year period.

Figure 9 shows the series of New Drought Indices, NDI_i, $i \in (1, 2..., 73)$, defined according to the monthly values of precipitation and average annual temperatures of Split and Zagreb in January for the period 1948 to 2020. In Figure 10, the sums of the New Drought Indices, ΣNDI_i, $i \in (1, 2..., 73)$, are shown for each month individually, in the period 1948 to 2020.

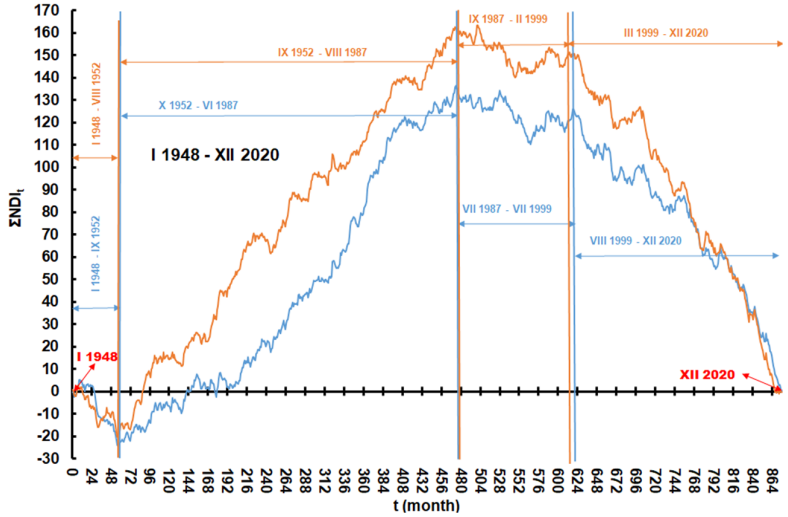


Fig. 8. Representation of the sums of the New Drought Indices, ΣNDI_i, $i \in (1, 2..., 876)$, according to the monthly values of precipitation and mean annual temperatures of Split and Zagreb in the period January 1948 to December 2020.

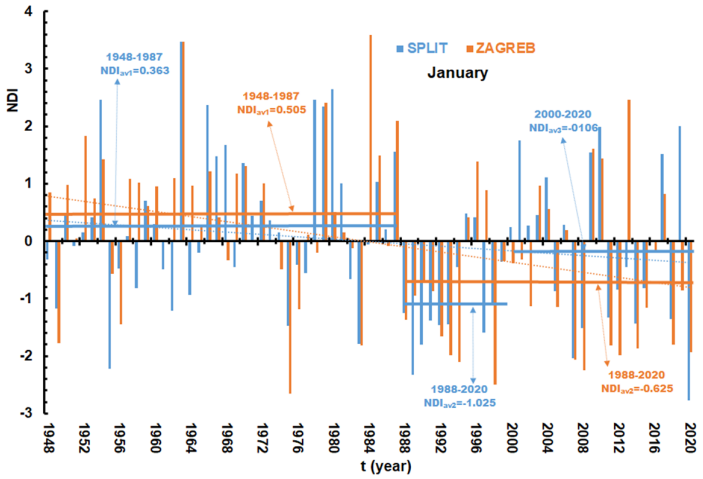


Fig. 9. Representation of the series of the New Drought Indices, NDI_i, $i \in (1, 2..., 73)$, defined according to the monthly values of precipitation and mean annual temperatures of Split and Zagreb in January in the period 1948 to 2020.

Table 8. Matrix of the average monthly New Drought Index, NDI_{av}, for Split and Zagreb station for each individual month, in the sub-periods defined in Figures 10, and the probability of the t-test, p, between consecutive sub-periods.

Station		**SPLIT**			**ZAGREB**	
Month	**Sub-period**	NIS_{av}	p **(t-test)**	**Sub-period**	NIS_{av}	p **(t-test)**
January	1948–1987 1988–1999 2000–2020	0.363 –1.025 –0.106	0.0012 0.049	1948–1987 1988–2020	0.505 –0.625	0.0004
February	1948–1980 1981–1988 1989–2002 2003–2020	–0.033 1.436 –0.937 0.151	0.008 0.0003 0.023	1948–1980 1981–1988 1989–2002 2003–2020	0.0038 1.317 –1.042 0.192	0.0148 0.0002 0.0268
March	1948–1988 1989–2020	0.385 –0.494	0.0164	1948–1988 1898–2020	0.405 –0.519	0.0111
April	1948–1955 1956–2005 2006–2020	–1.011 0.481 –1.065	0.007 0.0004	1948–1953 1954–2006 2007–2020	–1.035 0.523 –1.538	0.014 3.7E–06
May	1948–1999 2000–2009 2010–2020	0.227 –1.393 0.191	0.007 0.029	1948–1991 1992–2012 2013–2020	0.463 –1.047 0.205	0.009 0.043
June	1948–1995 1996–2020	0.483 –0.927	0.0004	1948–1995 1996–2020	0.560 –1.076	0.0004
July	1948–1952 1953–1986 1987–2020	–0.679 0.807 –0.707	0.027 4.5E–05	1948–1981 1982–2005 2006–2020	0.752 –0.170 –1.372	0.027 4.5E–05
August	1948–1962 1963–1984 1985–2006 2007–2020	–0.292 1.285 –0.128 –1.504	0.003 0.009 0.005	1948–1962 1963–1989 1990–2020	–0.185 0.921 –0.713	0.007 0.0002
September	1948–1966 1967–1978 1979–1995 1996–2003 2004–2020	–0.571 0.866 –0.675 1.639 –0.450	0.033 0.004 0.021 0.001	1948–2020	0.0003	
October	1948–1964 1965-1969 1970–1982 1983–1987 1988–1992 1993–2020	0.093 –1.256 0.899 –0.697 1.195 –0.338	0.013 0.035 0.014 0.002 0.034	1948–1964 1965–1969 1970–1994 1995-2020	0.003 -1.438 0.678 -0.378	0.015 0.006 0.019
November	1948–2010 2011–2020	0.180 –1.131	0.004	1948–1993 1994–2020	0.315 –0.535	0.0096
December	1948–1960 1961–2012 2013–2020	–0.491 0.249 –0.818	0.012 0.005	1948–1961 1962–1970 1971–1975 1976–1982 1983–1991 1992–2002 2003–2012 2013–2020	–0.066 1.491 –0.919 0.838 –0.770 0.539 –0.225 –1.314	0.007 0.001 0.009 0.003 0.0004 0.042 0.0005

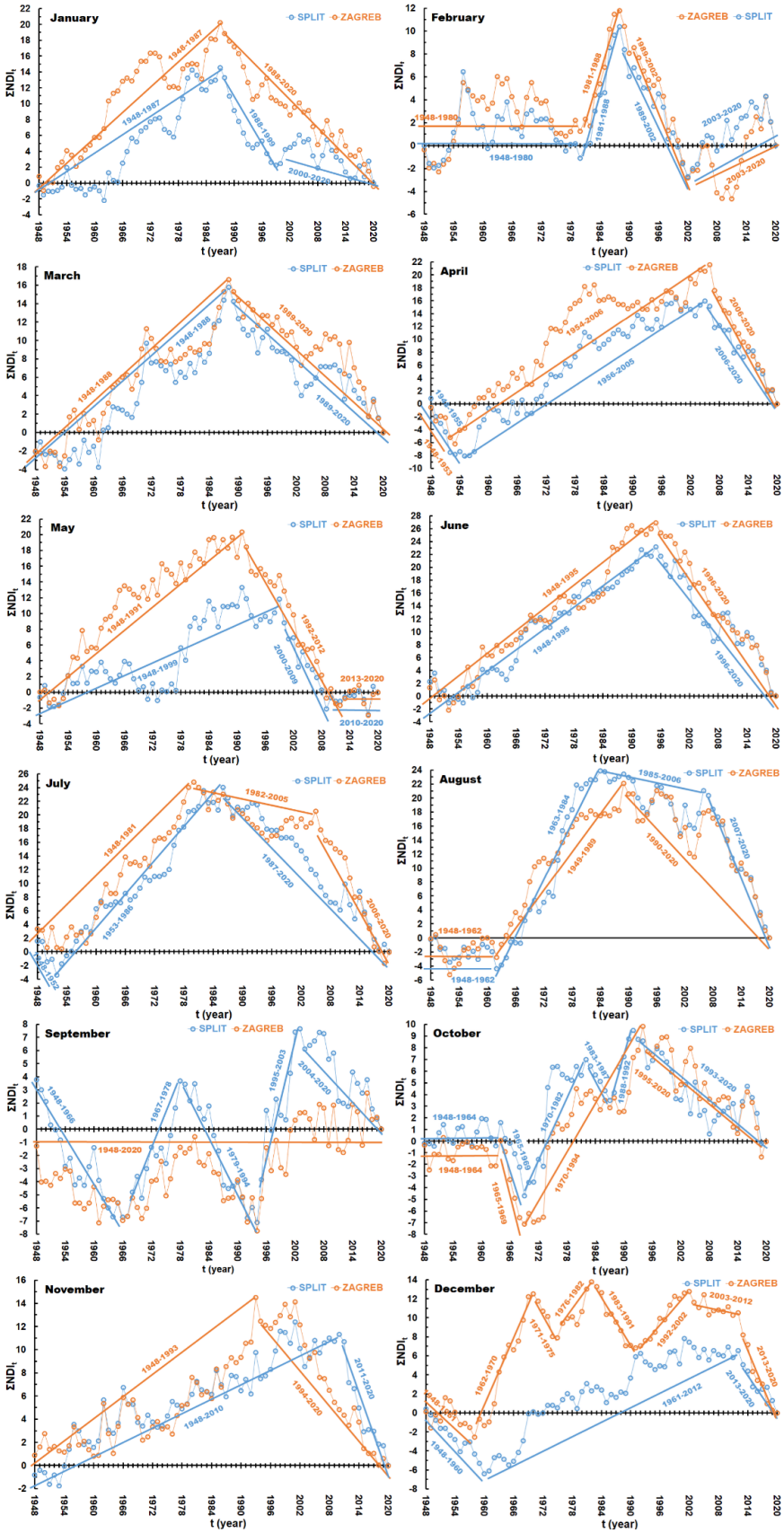


Fig. 10. Representation of the sums of the New Drought Indices, Σ*NDI$_i$*, *i* ∈(1, 2..., 73), defined according to the monthly values of precipitation and mean annual temperatures of Split and Zagreb in the 12 months in the period 1948 to 2020.

Table 7 lists the values of the linear correlation coefficients, r, and the results of the M-K test, p, for the series of individual monthly New Drought Indices, NDI_{av}, at both stations for the period 1948 to 2020. We found downward trends for all months, except September. Statistically significant downward trends are more frequent at the Zagreb station and occur for six months, in January and from April to August. At the Split station, statistically significant downward trends were determined only from June to August. The NDI indicates that drought is more pronounced during the warm period of the year.

Table 8 lists the average values of the monthly New Drought Indices, NDI_{av}, for each month in the sub-periods specified in Figure 10 and the t-test results, p, between successive sub-periods. From the data listed in Table 8, and the graphs in Figure 10, we found the NDI to behave differently during sub-periods within the overall observed 73-year period. Note that we also found evidence for cases of similar behaviours of monthly NDIs in both stations. Overall, they differ most in September, when at the Zagreb station, there is almost no statistically significant difference between wet and dry sub-periods, while at the Split station, as many as five such sub-periods do interchange.

CONCLUSIONS

We live in a time when the world is plagued by droughts, and it is almost certain that the situation will worsen in the near future. Numerous methods and a growing number of articles and books show that both science and daily practice are far from understanding and effectively combating this pervasive planetary disaster. Although many institutions and individuals are addressing the problem of drought, there is still a need and challenge to develop objective methods and efficient techniques to assess the intensity of droughts and predict their onset and end (Panu and Sharma, 2002). Drought monitoring and the development of drought early warning systems are fundamental for effectively fighting this increasing threat (AghaKouchak et al., 2021; Barker et al., 2016; Thompson, 2021).

Drought monitoring and early warning systems based on different drought indices could be crucial in mitigating and preventing their consequences. It is necessary to bring the results of drought research closer to practice, i.e., to end-users, to create the conditions for an effective fight against this increasingly dangerous threat. Although drought can generally be considered a natural phenomenon, there are several anthropogenic (e.g., excessive water demand, deforestation, land degradation, insufficient potable water supply, irrigation, etc.) and combined causes, at least some of which may be partly caused by global warming and climate change. The effect of global warming will continue to affect the intensification of drought in many areas in the near future. It needs to be noted that in each location, even in the vicinity of each other and with similar climatic properties, drought might lead to different consequences. For example, local water shortages may go unnoticed because water transfers from one location to another. Other shortages can be chronic in communities that always require more water than is available, even in wet periods (e.g., in case of water pollution). All the above and many other reasons not mentioned here call for a better conceptualization of the drought issue (Slette et al., 2019; Thompson, 2021).

In this context, the complementarity to existing indices and the main advantages of the proposed NDI are: (1) a readily availability of air temperatures and precipitations; (2) a large number of climatological stations, which monitor air temperature and precipitation all over the world; (3) long lasting time series of these two climatological parameters.

The purpose of this paper is to present to researchers, engineers, and practitioners a new, original, and practical approach based on the calculation of a simple drought index. The new and original NDI presented in this paper can serve as a new and meaningful drought metric and contribute to a better understanding and explanation of this phenomenon. The research presented in this paper is a contribution geared towards solving this complex contemporary issue and is part of the analysis of drought processes rather than a proposal for a new and reliable index.

Certainly, it is also necessary to continue the research efforts to overcome the existing dilemmas related to the identification and quantification of the phenomenon of drought. Our paper aims to make such contributions by combining two crucial parameters for drought formation: precipitation and temperature. We are confident that this method, when presented to relevant audiences, will be accepted by them as a tool of choice. Its value will be demonstrated in its application under different climatological and environmental circumstances. This is a process that will require the participation of many experts from around the world.

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Conflicts of Interest. The authors declare no conflict of interest.

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