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Increasing compound warm spells and droughts in the Mediterranean Basin

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ABSTRACT

The co-occurrence of warm spells and droughts can lead to detrimental socio-economic and ecological impacts, largely surpassing the impacts of either warm spells or droughts alone. We quantify changes in the number of compound warm spells and droughts from 1979 to 2018 in the Mediterranean Basin using the ERA5 data set. We analyse two types of compound events: 1) warm season compound events, which are extreme in absolute terms in the warm season from May to October and 2) year-round deseasonalised compound events, which are extreme in relative terms respective to the time of the year. The number of compound events increases significantly and especially warm spells are increasing strongly – with an annual growth rates of 3.9 (3.5) % for warm season (deseasonalised) compound events and 4.6 (4.4) % for warm spells –, whereas for droughts the change is more ambiguous depending on the applied definition. Therefore, the rise in the number of compound events is primarily driven by temperature changes and not the lack of precipitation. The months July and August show the highest increases in warm season compound events, whereas the highest increases of deseasonalised compound events occur in spring and early summer. This increase in deseasonalised compound events can potentially have a significant impact on the functioning of Mediterranean ecosystems as this is the peak phase of ecosystem productivity and a vital phenophase.

1. Introduction

1.1. Climate change in the mediterranean

The Mediterranean Basin is a region particularly prone to the effects of climate change and was characterized as one of the climate change hot-spots areas of the 21st century (Giorgi, 2006; Orlowsky and Seneviratne, 2012; Lionello and Scarascia, 2018). Temperature increases at a faster pace in the Mediterranean compared to the global average due to regional feedback mechanisms enhancing changes in extreme temperatures (Diffenbaugh et al., 2007; Orlowsky and Seneviratne, 2012). A global increase in 1.5 and 2 °C is thought to correspond to a 2.2 and 3 °C increase of the daily maximum temperature in the Mediterranean Basin, respectively (Seneviratne et al., 2016). Future warming rates in the Mediterranean are expected to be 20% higher than globally – in summer even up to 50% –and increasing inter-annual variability in the warm season is projected (Giorgi, 2006; Lionello and Scarascia, 2018). Increases in extreme events were observed in the past decades and are projected to continue in the 21st century in the Mediterranean Basin (Giannakopoulos et al., 2009; Hartmann et al., 2013; IPCC, 2019) for heat wave intensity and duration (Diffenbaugh et al., 2007; Fischer and Schär, 2010; Lionello et al., 2012; Christidis et al., 2015), as well as drought and aridity (Sousa et al., 2011; Dai, 2013; Cook et al., 2016; Samaniego et al., 2018; Spinoni et al., 2018). Heat wave intensity in the Mediterranean shows the largest growths worldwide and particularly extremely intense heat waves are becoming more frequent (Perkins-Kirkpatrick and Gibson, 2017). Soil water content also decreases in all seasons due to global warming, with the largest reductions in winter and spring (Samaniego et al., 2018).

1.2. Socio-economic and ecological relevance

Increases in hot and dry days have manifold detrimental impacts, including forest mortality (Allen et al., 2010), decreasing crop yields (World Bank, 2014; Zscheischler et al., 2017; IPCC, 2019), increasing fire risk (Ruffault et al., 2018), vegetation stress, rising energy demand, declining summer tourism (Giannakopoulos et al., 2009; van Lanen et al., 2016) and health effects (Poumadère et al., 2005; Fischer and Schär, 2010).

In addition, severe climatic changes are likely to provoke land cover

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changes and ecosystem regime shifts (Feng and Fu, 2013). Above 2 °C warming, desertification is projected to take place in the Mediterranean Basin until the end of the 21st century, rendering it inappropriate for e.g. olive cultivation (Moriondo et al., 2013; Guiot and Cramer, 2016; Fraga et al., 2020). Reduced water availability accompanied by increasing aridity elicited primarily by changes in precipitation and temperature will result in loss of Mediterranean ecosystems and their current biodiversity in the next decades (Guiot and Cramer, 2016; Cramer et al., 2018). Moreover, the increasing severity of heat and drought will lead to the loss of the function of semiarid ecosystems as carbon sink (Ciais et al., 2005; Ma et al., 2015).

Jentsch and Beierkuhnlein (2008) point out that changes in the disturbance regime associated with extreme weather events might be more harmful to ecosystem functioning than trends and shifts in mean conditions. Short-term events are likely to affect the long-term ecosystem state by shifting it to an alternate stable state (Kreyling et al., 2011). Changes in frequency and amplitude of extreme climatic events potentially result in non-linear alterations in ecosystem resilience, functionality and sensitivity (Hegerl et al., 2011). The effects of such disturbance regime shifts on ecosystem resilience and resistance are not yet well understood and therefore need to be addressed in further research (Jentsch and Beierkuhnlein, 2008; Hegerl et al., 2011; Mahony and Cannon, 2018).

1.3. Definition and importance of compound events

A dependence structure between variables increases the occurrence probability of multivariate extremes. For example, high temperatures and low precipitation are usually negatively correlated, i.e. that the probability of an extreme hot and dry summer is much higher compared to an extremely hot and wet summer (Zscheischler et al., 2018). This illustrates that univariate analyses might fall short of precisely representing the potential risks associated with compound events (AghaKouchak et al., 2014; Zscheischler and Seneviratne, 2017). In addition, the impacts of combinations of extremes can be much higher than the summed up impact of their individual components (Hegerl et al., 2011; Zscheischler et al., 2020). Many past hazard-related climatological studies focused on single drivers, while the majority of recent meteorological and climatological events with extreme impacts are compound effects by multiple drivers – often in the form of compound heat waves and droughts (Zscheischler et al., 2018; Collins et al., 2013; Sedlmeier et al., 2018). The risk of concurrent droughts and heat waves was not analysed extensively to date (AghaKouchak et al., 2014; Kong et al., 2020), although their thermodynamical relationship through soil moisture is well-known (Horton et al., 2016). Recent studies investigated concurrent droughts and heat waves e.g. in the USA (Mazdiyasni and AghaKouchak, 2015), India (Sharma and Mujumdar, 2017), Europe (Manning et al., 2019), China (Wu et al., 2019; Ye et al., 2019; Kong et al., 2020) and globally (Zscheischler and Seneviratne, 2017; Hao et al., 2018). The amplification of risks from interlinked impacts are particularly pronounced in the Mediterranean Basin (Cramer et al., 2018), e.g. increased fire risk due to heat waves and droughts (Gouveia et al., 2016). In addition, the interaction of drivers and corresponding hazards is likely to change due to climate change, leading to the occurrence of novel climatic conditions (Zscheischler et al., 2018).

Several definitions of compound events were framed in recent years (Seneviratne et al., 2012; Leonard et al., 2014; Zscheischler et al., 2018). Here, we follow the confined definition according to the workshop on correlated extremes, held in New York City from May 29–31, 2019, which defined compound/multivariate events as events occurring at the same time and in the same place (Horton and Raymond, 2018). In this study, a compound event is termed as the co-occurrence of warm spells and droughts at the same time.

We investigate two types of compound events: 1) compound events defined by the extremeness of their absolute values and 2) compound events, which are extreme in relation to the respective time of the year. We call the first category warm season compound events and the latter deseasonalised compound events. Warm season compound events are analysed only for the period May–October, whereas deseasonalised compound events are investigated year-round (for further details see section 2.3). We analyse deseasonalised compound events in addition to warm season compound events because extremes outside the warm season are rarely assessed in comparison to summertime events (Perkins, 2015). Moreover, the impact of events on agriculture and ecosystems depends on their seasonal timing and thus requires a year-round analysis. (de Boeck et al., 2011; Hegerl et al., 2011; Sippel et al., 2016; Ben-Ari et al., 2018). To assess the risks imposed by these events on the Mediterranean Basin, it is therefore crucial to incorporate also events, which might not be high in absolute values, however are considered extreme in regard of the time of the year of their occurrence (de Boeck et al., 2011). While compound warm spells and droughts have been assessed in the Mediterranean Basin before (Russo et al., 2019), this is the first paper encompassing a year-round investigation according to our knowledge.

1.4. Research questions

Within this article, the following research questions are examined. Does the number of warm season and deseasonalised compound events increase significantly in the Mediterranean Basin over the last 40 years (cf. section 3.1)? If so, how large is the increase and in which countries is it largest? Which is the major component – namely warm spells and droughts – for increases of warm season and deseasonalised compound events (cf. section 3.2)? Which months show the highest increase in the number of warm season and deseasonalised warm spells, droughts and compound events (cf. section 3.3)?

2. Methods

2.1. Study area

The study area is refined to the zones, which are part of the Köppen-Geiger categories Csa and Csb within the Mediterranean Basin (cf. Fig. 1). The Csa and Csb categories refer to "Warm temperate climate with dry and hot summer" and "Warm temperate climate with dry and warm summer", respectively. The Köppen-Geiger classification map was obtained from Kottek et al. (2006) and Rubel et al. (2017).

2.2. Data

Hourly 2 m air temperature, total precipitation and potential evaporation were obtained from the ERA5 reanalysis data set with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ – encompassing 2 883 pixels in total – for the 40-year period from 1979 to 2018 (Copernicus Climate Change Service, 2017; Hersbach et al., 2019). The daily maximum 2 m air temperature was extracted from hourly data. Hourly total precipitation and potential evaporation were summed up monthly.

2.3. Definition of events

The typical time scales of droughts and warm spells diverge – droughts typically are investigated on a monthly to yearly scale, whereas warm spells are observed on a daily to weekly scale (Miralles et al., 2019). Therefore, using a single time scale might not capture all relevant temporal dynamics (Le Page and Zribi, 2019) and separate time scales for both phenomena are required. We use a peak over threshold approach to define extremes. Here, we define daily maximum temperature above the 90th percentile of the daily maximum 2 m air temperature of the period 1979–2018 with a duration of at least 5 days for each pixel as the standard case for a warm spell. In addition to that, also warm spells defined by the 85-, 90-, 95th percentile and a duration of 3, 5 and 7 days (leading to nine cases of warm spells in total) are investigated for

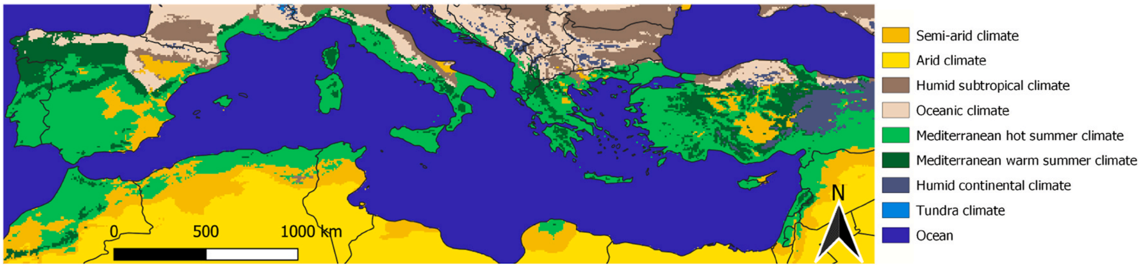

Fig. 1. Mediterranean study area for which the Köppen-Geiger climate category is "Mediterranean hot summer climate" (light green) or "Mediterranean warm summer climate" (dark green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

assessing the impact of the choice of duration and magnitude on the obtained changes in the number of events. For the definition of droughts, two indices are applied, the Standardised Precipitation Index (SPI) (McKee et al., 1993) and the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010).

For the calculation of the SPI, precipitation is summed monthly, a probability distribution function is fitted (a gamma distribution for the SPI and a log-logistic distribution for the SPEI, respectively) and transformed to a normal distribution with mean of 0 and standard deviation equal to 1, where positive values indicate wet conditions and negative values indicate dry conditions. The SPEI is calculated similarly to the SPI, but it is based on the difference of precipitation and potential evapotranspiration – not solely on precipitation as it is the case for the SPI. Both indices are calculated monthly based on the current and the two preceding months separately for each pixel. This means, that e.g. the SPI and SPEI value for the month of July always includes also precipitation data from May and June. This 3-month SPI and SPEI is abbreviated as SPI-3 and SPEI-3 hereafter, respectively. According to Szalai et al. (2000), soil moisture drought is correlated best with SPI-2 and SPI-3, thus the SPI-3 can serve as a proxy for soil moisture conditions (WMO, 2012). A drought is defined as SPI-3 < -0.8 and SPEI-3 < -0.8 respectively following the methodology of Mueller and Seneviratne (2012) and Mazdiyasni and AghaKouchak (2015).

Compound warm spells and droughts are defined as warm spells coinciding with SPI-3 droughts according to the approach by Mazdiyasni and AghaKouchak (2015). We analyse first the changes in compound events (cf. section 3.1) and then examine their individual components – namely warm spells and SPI-3 droughts (cf. section 3.2). In the latter part, also SPEI-3 droughts – which are not part of the definition of compound events – are included in addition to SPI-3 droughts to cover not only the precipitation aspect of droughts, but also the influence of potential evapotranspiration to acquire a more comprehensive characterisation of the drought regime in the Mediterranean.

Compound events are categorized in two ways regarding absolute extremes – which we refer to as warm season compound events – and extremes relative to their respective timing of the year – which we refer to as deseasonalised compound events.

Warm season compound events are defined as the joint occurrence of a warm season warm spell and a warm season SPI-3 drought. A warm season warm spell is defined as the 5-day exceedance of the 90th percentile threshold of the daily maximum temperature values of the 40-year period (Mazdiyasni and AghaKouchak, 2015). For the calculation of the warm season SPI-3 drought, the entire distribution of the respective time span from March to October is used (Note: March and April are included because they are required for the calculation of the SPI-3 in May and June. Otherwise, their values are neglected in this study.). Therefore, a warm season SPI-3 drought is a representative measure for a drought condition during the period from March to October. The process is performed similarly for SPEI-3 droughts.

Deseasonalised compound events are defined as the joint occurrence of a deseasonalised warm spell and a deseasonalised SPI-3 drought. A deseasonalised warm spell is defined as the 5- day exceedance of the 90th percentile threshold of the deviation of the daily maximum temperature from the long-term mean condition of the respective date of the year. Daily maximum temperature is deseasonalised by subtracting the mean of the respective calendar day k of the year as stated below (cf. equation (1)).

The deseasonalised temperature $T_{n\kappa}^{des}$ is defined as:

$$\forall n \in N(T_{n\kappa}^{des} = T_{n\kappa} - \overline{T}_{nk}) \quad (1)$$

where $T_{n\kappa}$ is the temperature of the given day κ and $\overline{T}_{nk}$ is the mean temperature for the given calendar day k for all pixels $n \in N$, where N denotes the set of all pixels in the Mediterranean Basin belonging to the Köppen-Geiger categories Csa and Csb. $\overline{T}_{nk}$ is calculated by averaging over all days κ with the same calendar day k (e.g. the first day of January 01.01.) within the time span 1979–2018 and subsequently smoothing the obtained curve of the mean annual temperature cycle for each pixel $n \in N$ to minimise stochastic fluctuations in the annual temperature curve.

For the calculation of the deseasonalised SPI-3 drought, the SPI is calculated based on the distribution of each month of year – and its 2 preceding months – separately, i.e. it is representative for the extremeness with respect to the given time of the year. The process is performed similarly for SPEI-3 droughts.

2.4. Challenges of the SPI and the SPEI

All drought indices have certain limitations. The applicability of the SPI in dry seasons has been questioned because in such cases, periods without rainfall are the norm and cannot be considered as a drought (Wu et al., 2007). If there are too many zero precipitation values, it is infeasible to fit a suitable gamma distribution and thus to yield normally distributed SPI values (Mishra and Singh, 2010). In addition, relatively small deviations can lead to disproportionately large changes in the SPI value in case of periods with scarce rain (WMO, 2012). In the Mediterranean Basin such periods without precipitation are common during summer time (Palutikof et al., 1994; Manning et al., 2019). This is the reason why there are particularly few droughts detected for the deseasonalised summer months. In our study, this limitation is partially alleviated by using the SPI-3 to avoid covering a period with insufficient length for rainfall occurrence.

The SPEI is highly correlated with temperature (Kong et al., 2020) and is thus to a certain degree also already an indicator for a compound event. For this reason SPEI droughts are not investigated in co-occurrence with warm spells in this study. Nevertheless, it can serve as good additional indicator to verify the analyses of warm spells and SPI droughts as it is related to both measures – directly to SPI, because it has a precipitation component and indirectly to warm spells because temperature is a driver of potential evapotranspiration.

Furthermore, estimations of potential evaporation can vary depending on the applied method (Zhao et al., 2013). Potential evaporation of a vegetated land surface, which may be partially water-limited, cannot be measured routinely for large regions. Therefore, several approaches exist for its calculation or estimation, e.g. physically-based (i.e. based on the energy budget of the land surface) ones like the Penman-Monteith equation and temperature-based estimation approaches like the Thornthwaite and the Hargreaves equation (Thornthwaite, 1948; Monteith, 1965; Hargreaves, 1975; Zhao et al., 2013). Potential evaporation values from ERA5 are based on surface energy balance calculations (such as the Penman-Monteith equation) with the vegetation parameters set for well watered agricultural land (Copernicus Climate Change Service, 2017). The Penman-Monteith equation is energy-balance-based and requires air temperature, relative air humidity, net radiation and wind speed as input atmospheric variables and estimates for water conductance through the vegetation cover (Allen et al., 1998; Bonan, 2016). It usually yields rather realistic estimations of evapotranspiration with a high spatial and temporal resolution. However, due to its comprehensive data requirements its usage is limited in many regions (Donohue et al., 2010). In such cases the application of the empirical Hargreaves equation can be recommended, which was designed for simplicity and is based solely on temperature (Allen et al., 1998; Hargreaves and Allen, 2003). Another widely applied method in cases of data scarcity is the Thornthwaite equation (Garcia et al., 2004).

2.5. Detection of temporal change

The number of compound events are aggregated yearly and divided by the number of pixels to obtain the average yearly number of compound events per pixel. Using this aggregation, autocorrelation is reduced. Trend detection is performed using the non-parametric Mann-Kendall test for the aggregated time series from 1979 to 2018. A modified version of the Mann-Kendall Test was used to account for temporal autocorrelation based on the Hamed and Rao (1998) variance correction approach. Additionally, we corrected for multiple testing using the Benjamini and Hochberg (1995) correction.

Moreover, the 40-year time span from 1979 to 2018 is divided into two 20-year periods to analyse changes over time. The percentage change in the number of events between both time spans 1979–1998 and 1999–2018 is investigated by calculating the proportion of compound events E_{prop} from the total number of compound events that occurred in each 20-year period as stated in equation (2), where N_{79-98}, N_{99-18}, N_{79-18} are events occurring in the time spans 1979–1998, 1999–2018 and 1979–2018, respectively.

$$E_{prop} = \frac{N_{99-18} - N_{79-98}}{N_{79-18}} \tag{2}$$

Furthermore, the two-sample Cramér-von-Mises test and the two-sample Kolmogorov-Smirnov test are applied for comparing the differences in the distributions of compound events between the two time spans 1979–1998 and 1999–2018. These tests evaluate the distance between the cumulative distribution functions of the two time spans 1979–1998 and 1999–2018. The tests indicate, whether the two sample distributions stem from the same population based on the rejection of the null hypothesis indicated by the significance level of the p-value. A p-value < 0.05 (5% significance level) is considered to be significant for the Mann-Kendall test, Cramér-von-Mises test and the Kolmogorov-Smirnov test. In addition, we apply a change vector analysis to compare the relative increases of warm spells in relation to droughts between the time periods 1979–1998 and 1999–2018. The change vector analysis is a visualisation technique often used for display of temporal changes in two spectral bands in satellite imagery (Malila, 1980; Johnson and Kasischke, 1998). A more detailed explanation of this visualisation tool is given in section 3.2 and Fig. 9.

The analysis was carried out using R version 3.6.1 and Python version 3.7.3. The R package 'SPEI' was applied for calculating SPI-3 and SPEI-3 (Beguería and Vicente-Serrano, 2017) and the R package 'RStoolbox' was used to perform the change vector analysis (Leutner et al., 2019).

3. Results

3.1. Temporal changes in compound events over the period 1979–2018

The development over time of compound events from 1979 to 2018 shows a significant increase for both warm season and deseasonalised compound events (cf. Fig. 2). According to the slope of the fitted regression, the number of events rises from 0.27 (0.29) events per year in 1979 to 1.22 (1.16) in 2018 with an average standard deviation of 0.99 (1.06) for warm season (deseasonalised) compound events. The average annual growth rate is 3.9% (3.5%) for warm season (deseasonalised) compound events. These trends are statistically significant (cf. Table 1). Extreme hot and dry years such as 2003, 2012 and 2017 show notable peaks in the number of warm season compound events. Another striking feature is the high number of deseasonalised compound events in the years 2014–2017, which all rank among the highest six years within the entire 40-year period.

The average yearly number of warm season (deseasonalised) compound events per pixel in the entire period 1979–2018 is 0.72 (0.72), with an average event number of 0.46 (0.48) in the first period from 1979 to 1998 and 0.98 (0.96) in the second period from 1999 to 2018 (cf. Fig. 3). The boxplots and the empirical cumulative distribution functions of the average yearly number of events per pixel deviate strongly between the two time periods for both warm season and deseasonalised compound events (cf. Figs. 3 and 4). Particularly in the upper tail of the distribution of warm season compound events the divergence is highly pronounced (cf. left panel in Fig. 4), indicating that especially the years with the highest number of extreme events are getting more frequent. This increase in the upper tail – i.e. increase in years with substantially high numbers of events and/or particularly long events – can also be seen in Fig. 3 in the large extension of the right whisker of warm season compound event in the period 1999–2018.

The spatial patterns of changes in event number are mostly consistent for warm season compound events compared to deseasonalised compound events (cf. Fig. 5). The number of compound events has increased substantially in the years 1999–2018 compared to 1979–1998 in most areas of the Mediterranean Basin. For warm season (deseasonalised) compound events, 86.7% (91.1%) of all pixels have a higher number of events in the time period from 1999 to 2018 compared to 1979–1998 with the increases being most pronounced in Morocco, south-eastern Spain and western Turkey. There are only few pixels, where the number of (warm season/deseasonalised) compound events has not changed (4.4%/2.0%) or decreased (8.9%/6.9%) from the first to the second period, notably in southern Turkey and the north-eastern region of the Iberian Peninsula.

The highest increases over the 40-year period have occurred in the Western Balkan countries (Albania, Bosnia and Herzegovina, Croatia, Montenegro and North Macedonia) for warm season compound events (cf. Fig. 6), followed by Italy, Morocco, France and Spain. Libya is the only country showing decreases over time. Interestingly, on the other hand, Libya has the second highest increases regarding deseasonalised compound events – only superseded by Syria –, which is in contrast to the temporal decrease for warm season compound events. However, we consider this contrast between warm season and deseasonalised compound events insignificant, because the Mediterranean region in Libya is fairly small and the strong increase in deseasonalised compound events is mainly driven by a few events in the last decade (cf. Fig. A11). The

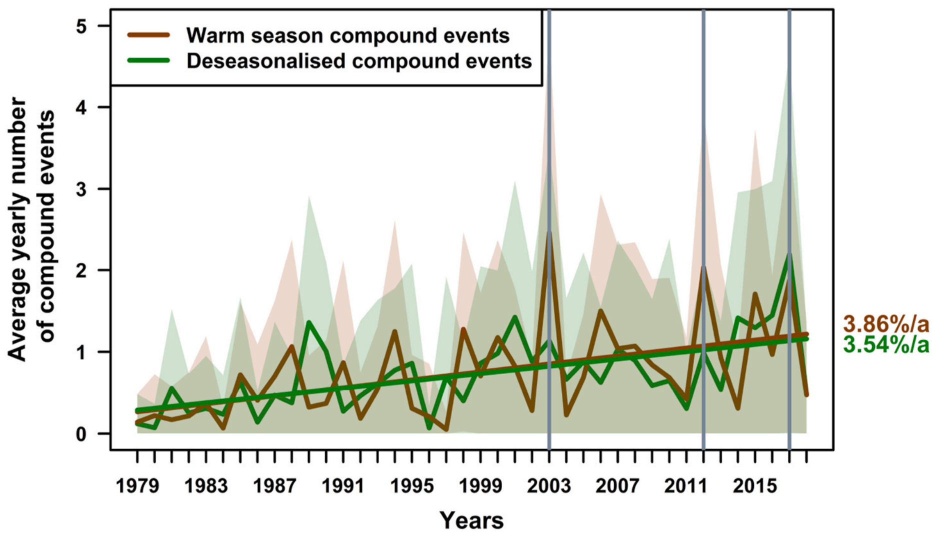

Fig. 2. Number of warm season (brown) and deseasonalised (green) compound events in the Mediterranean averaged yearly over all pixels for the 40-year period 1979–2018. The standard deviation is displayed as shaded area in the respective colour. The average annual growth rate in percentage is stated adjacent to the regression lines for warm season (brown) and deseasonalised (green) compound events. The three years with the highest number of warm season compound events (2003, 2012 and 2017) are marked by grey vertical lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

First column: Mann-Kendall (MK) trend detection for the number of compound events, SPI-3 and SPEI-3 droughts and warm spells averaged yearly over all pixels in the Mediterranean over the period 1979–2018. Second and third column: Statistical analysis of changes in event distributions for the periods from 1979 to 1998 and 1999–2018 for compound events, SPI-3 and SPEI-3 droughts and warm spells averaged yearly over all pixels in the Mediterranean using the Cramér-von-Mises test (CvM) and the Kolmogorov-Smirnov test (KS). Significant p-values are depicted bold. Forth column: Average annual growth rate (AAGR) in percentage.

	p-value			AAGR
	MK	CvM	KS	
Compound events				
warm season	$\mathbf{1.47 \cdot 10^{-3}}$	$\mathbf{3.00 \cdot 10^{-3}}$	$\mathbf{1.23 \cdot 10^{-2}}$	3.86%
deseasonalised	$\mathbf{1.53 \cdot 10^{-4}}$	$\mathbf{\leq 2.2 \cdot 10^{-16}}$	$\mathbf{3.97 \cdot 10^{-3}}$	3.54%
Droughts				
SPI-3, warm season	$7.71 \cdot 10^{-1}$	$6.83 \cdot 10^{-1}$	$8.32 \cdot 10^{-1}$	$-1.92 \cdot 10^{-1}$%
SPI-3, deseasonalised	$8.00 \cdot 10^{-1}$	$9.85 \cdot 10^{-1}$	$9.83 \cdot 10^{-1}$	$-4.55 \cdot 10^{-2}$%
SPEI-3, warm season	$\mathbf{3.45 \cdot 10^{-3}}$	$\mathbf{3.00 \cdot 10^{-3}}$	$\mathbf{2.71 \cdot 10^{-4}}$	$6.28 \cdot 10^{-1}$%
SPEI-3, deseasonalised	$\mathbf{5.90 \cdot 10^{-3}}$	$\mathbf{1.80 \cdot 10^{-2}}$	$8.11 \cdot 10^{-2}$	1.58%
Warm spells				
warm season	$\mathbf{5.22 \cdot 10^{-6}}$	$\mathbf{\leq 2.2 \cdot 10^{-16}}$	$\mathbf{5.57 \cdot 10^{-5}}$	4.57%
deseasonalised	$\mathbf{7.02 \cdot 10^{-9}}$	$\mathbf{\leq 2.2 \cdot 10^{-16}}$	$\mathbf{9.55 \cdot 10^{-6}}$	4.38%

only country with a significant trend for both warm season and deseasonalised compound events is Turkey indicated by an asterisk in Fig. 6. Additionally, for warm season compound events, a significant trend occurs in Israel and Palestinian territories (Palest. ter.), Italy, Morocco and Spain, as well as in France, Syria and Tunisia for deseasonalised compound events. The peak of 2003 compound event in the Western Mediterranean stands out clearly in France, Italy, Tunisia and the Western Balkan, whereas the most pronounced event in the Eastern Mediterranean occurs in 2010, clearly observable in Cyprus, Israel and Palestinian territories, Lebanon and Syria (cf. Fig. A11).

3.2. Investigation of the drought and the warm spell component of compound events

There is a significant trend from 1979 to 2018 for the number of compound events, warm spells and SPEI-3 droughts for both warm season and deseasonalised compound events (cf. Table 1). Only SPI-3 droughts show no significant trend. Likewise, the distribution of events differs significantly between 1979 - 1998 and 1999–2018 for the number of compound events, warm spells and SPEI-3 droughts for both warm season and deseasonalised compound events – except for deaseasonalised compound events according to the Kolmogorov-Smirnov test –, but not for SPI-3 droughts. The average number of events increases from 0.40 (0.62) events per year in 1979 to 2.39 (3.44) events per year in 2018 for warm season (deseasonalised) warm spells according to the fitted linear regression. For SPEI-3 droughts, the average number of events rises from 2.02 (1.94) to 2.59 (3.63), respectively. For SPI-3 droughts, none of the tests shows any significance, i.e. there are no indications of changes over time.

Compound events are increasing – indicated by an annual growth

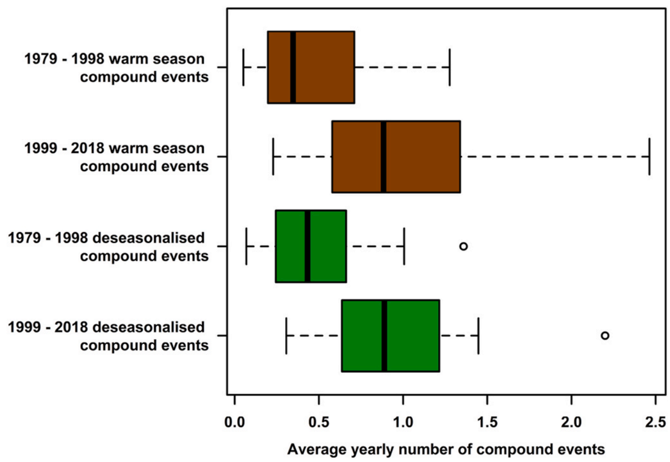

Fig. 3. Boxplots of the number of warm season (brown) and deseasonalised (green) compound events in the Mediterranean for the time periods 1979–1998 and 1999–2018 averaged yearly over all pixels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

rate of 3.9 (3.5) % for warm season (deseasonalised) compound events –, but to a lesser degree than warm spells alone – indicated by an annual growth rate of 4.6 (4.4) % for warm season (deseasonalised) warm spells (cf. Table 1). SPI-3 droughts on the other hand show no notable increases. Therefore, the changes in compound events can likely be mostly attributed to increases in warm spells alone. However, in contrast to SPI-3 droughts, SPEI-3 droughts are increasing substantially. This means while precipitation is not showing large changes, potential evapotranspiration is increasing because of the higher frequency of warm spells.

Finally, it should be noted that, the choice of duration and magnitude in the definition of warm spells affects the obtained annual growth rates in the number of events substantially. Notably, the higher the chosen definition for the respective warm spell duration and magnitude is, the higher are the changes in number of compound events over time (cf. Fig. 7), ranging from an annual growth rate of 2.4% (2.2%) for the 3-day duration and 85th percentile to 7.4% (5.8%) for the 7-day and 95th percentile for warm season (deaseasonalised) compound events. Interestingly, for the most extreme events defined by 7-days durations above the 95th percentile, in many regions these events occur only in the time period from 1999 to 2018. This indicates that novel climatic conditions are emerging; producing extremes with a magnitude and duration, which did not occur in earlier times.

Increases of deseasonalised and warm season warm spells are highly consistent (cf. Fig. 8). Except for Portugal and Galicia, warm spells increase throughout the entire Mediterranean. SPI-3 droughts decrease in many regions, especially in southern Italy, Albania, Greece and western and southern Turkey. SPEI-3 droughts show also decreases at some locations in these regions, however to a lesser degree. In general, SPEI-3 droughts slightly increase throughout the Mediterranean, but not as pronounced as warm spells.

Fig. 9 shows how droughts and warm spells change in relation to each other in space between the first (1979–1998) and second period (1999–2018), qualitatively and quantitatively. The direction of change given by the angle indicates how both components are changing over time, e.g. if both warm spells and SPI-3 droughts are increasing (cyan colouring), mostly SPI-3 droughts are increasing, while warm spells are stagnant (green colouring) or mostly warm spells are increasing with stagnant SPI-3 droughts (dark blue colouring). For warm season compound events the average angle of all pixels is 82.5°, i.e. the prevailing case in the Mediterranean Basin are increasing warm spells with stagnant SPI-3 droughts over time (indicated by dark blue colouring) or sometimes even with decreasing SPI-3 droughts, e.g. in Cyprus, southern Turkey and southern Italy (purple colouring). By contrast, in the Iberian Peninsula and the Maghreb states often also SPI-3 droughts are increasing (cyan colouring) and sometimes only droughts are increasing, whereas warm spells remain stagnant (green colouring). Decreases and stagnation in warm spells are rare, but occur e.g. in southern Turkey and Portugal (yellow, orange, red and rose colouring).

For deseasonalised compound events primarily the warm spells increase, whereas SPI-3 droughts remain constant, illustrated by an average angle of all pixels of 86.5°(indicated by dark blue colouring in the lower left panel in Fig. 9). In Morocco, eastern Turkey and Libya, both droughts and warm spells are increasing (cyan colouring). Moreover, regions with decreasing SPI-3 droughts and increasing warm spells are prominent in southwestern Spain, southern Italy and Greece (purple colouring). A remarkable different behaviour is detectable near the Atlantic Coast of the Iberian Peninsula, where many pixels with increasing SPI-3 droughts are located (indicated by cyan, green and yellow colouring). Northwestern Iberia was also identified as a region with increasing moisture availability during the 20th century by Sousa et al. (2011). However, the magnitude of the change is often not very

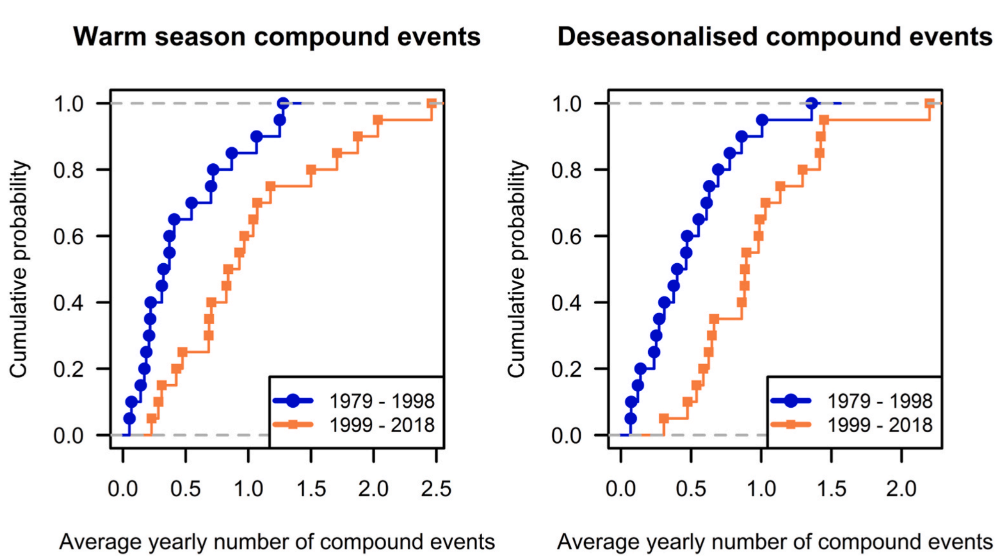

Fig. 4. Event frequency specified by the empirical cumulative distribution functions of the number of warm season (left panel) and deseasonalised (right panel) compound events in the Mediterranean averaged yearly over all pixels for both time periods 1979–1998 (green) and 1999–2018 (brown). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

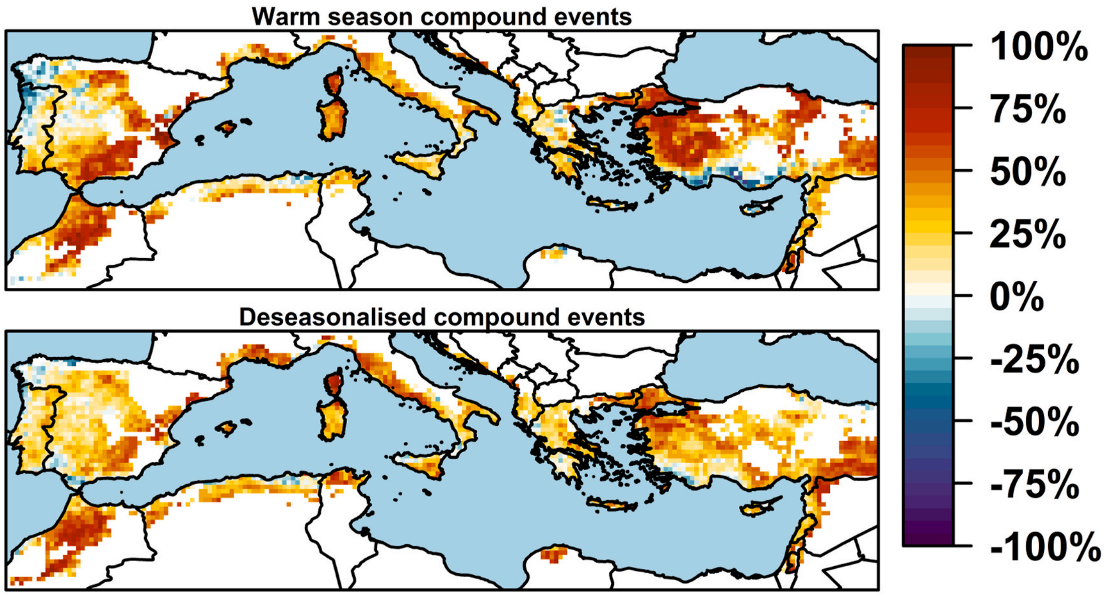

Fig. 5. Regional change detection of compound events between the two periods 1979–1998 and 1999–2018 showing the proportion of compound events from the total number of compound events that occurred in each 20-year period for warm season (upper panel) and deseasonalised (lower panel) compound events in the Mediterranean. The percentage is given by the difference between both periods divided by the entire time span 1979–2018 (cf. equation (2)). A value of 100% indicates all events occurred in the period 1999–2018, a value of −100% indicates all events occurred in the period 1979–1998 and a value of 0% indicates an equal number of events in both periods.

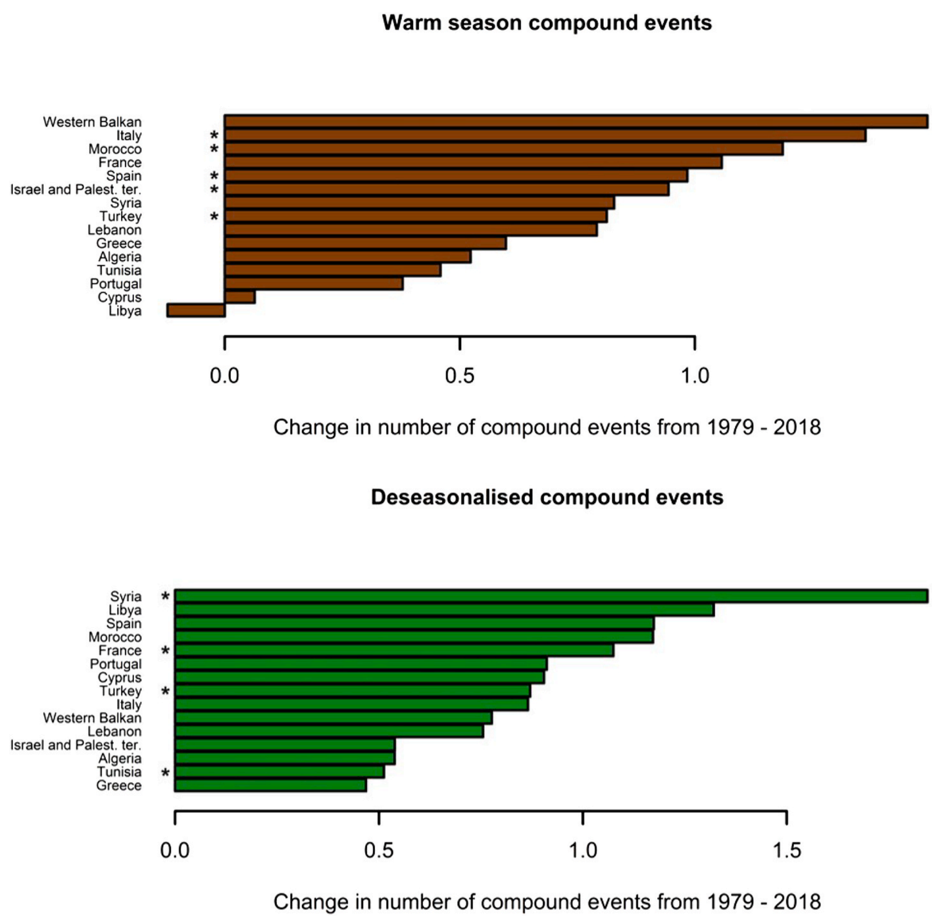

Fig. 6. Absolute change in the number of warm season (upper panel) and deseasonalised (lower panel) compound events over the 40-year-period 1979–2018 for each country. Note that only the regions located within the study area (cf. Fig. 1) of the respective countries are incorporated. Significant trends based on the Mann-Kendall test are marked with an asterisk. The corresponding time series are shown in Fig. A11.

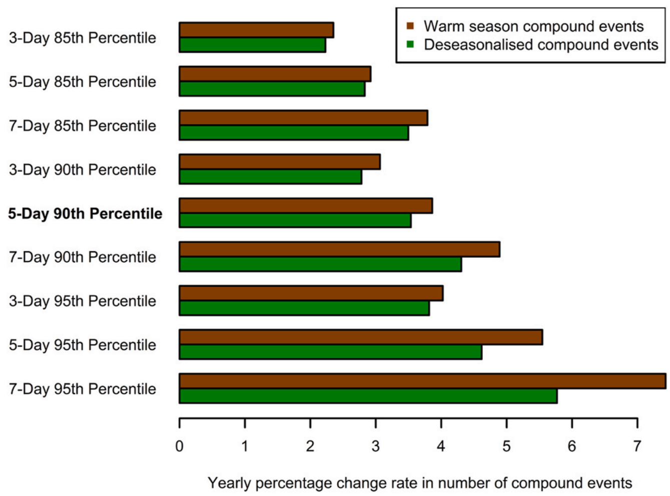

Fig. 7. Comparison of the effect of different warm spell lengths and magnitudes on change rates of compound events in the Mediterranean: Percentage change in the number of warm season (brown) and deseasonalised (green) compound events averaged yearly over all pixels from 1979 to 2018 for nine warm spell definitions using all nine combinations of the three warm spell durations (3, 5 and 7 days) and three warm spell intensities (85th, 90th and 95th percentile). The 5-Day 90th percentile is the standard case used in this article and is highlighted in bold. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

pronounced, so the behaviour of the warm spells has to be carefully interpreted here.

Quantitatively, the increase for both warm season and deseasonalised compound events is highest in western Turkey and Andalusia, whereas the smallest changes occur at the Atlantic coast of the Iberian Peninsula and southern Turkey (cf. right panels in Fig. 9). This shows that within Turkey, there is a substantial gradient in the change of the number of compound events on a relatively small spatial scale.

3.3. Monthly assessment of compound events, warm spells and droughts

The absolute number of warm season compound events increased from 1979 to 2018 by 0.19 events per pixel in July and 0.69 in August, whereas the other months showed virtually no changes (cf. Fig. 10). According to Conte et al. (2002), two thirds of all heat waves happen within July and August, which explains why these are also the months where compound events are predominantly increasing. However, the number of deseasonalised compound events increases most in February, May and June by 0.11, 0.11 and 0.17 events per pixel from 1979 to 2018, respectively, whereas July, August and September have rather small increases by only $3.8{\cdot}10^{-1}$, $6.2{\cdot}10^{-1}$ and $1.8{\cdot}10^{-1}$ events per pixel, respectively (cf. Fig. 10).

Both deseasonalised and warm season warm spells have increased over the 40-years time period in all months (cf. Fig. 10 and Table 1). Warm season warm spells particularly increased in July and August – with the maximum increase in August of 1.10 in the number of events from 1979 to 2018, whereas deseasonalised warm spells increased most in the months from April to June – with a maximum increase of 0.44 in April. SPI-3 and SPEI-3 droughts show varying behaviours. Warm season (desasonalised) SPI-3 droughts show decreases in a third of the months, especially in autumn with a minimum of −0.13 in September (−0.14 in October). Warm season SPEI-3 droughts have a maximum of 0.29 in July – and are much smaller in all other months. Deseasonalised SPEI-3 droughts increase in all months except March and November, where the difference is approximately zero, with maximum increases during the summer months – up to an increase of 0.34 events in August.

4. Discussion

4.1. Changes in the number of warm spells, droughts and compound events

The increases in the number of compound events confirms the findings by Manning et al. (2019), who found an increasing number in dry and hot events in Europe for the period 1950–2013, which is primarily driven by increases in temperature. Especially warm spells have been increasing strongly, whereas SPEI droughts have been increasing – presumably because of increases in the potential evapotranspiration – to a lesser degree and SPI droughts are generally constant over time. This indicates that the rise in the number of compound events is primarily driven by temperature changes and not lack of precipitation. A notable exception are the findings of Gudmundsson and Seneviratne (2015), who state there are few significant changes in southern Europe over the 30-year period 1961–1990 based on an analysis of SPI droughts. Notably, the detection of changes in the number of droughts in the Mediterranean Basin is dependent on the choice of drought index and

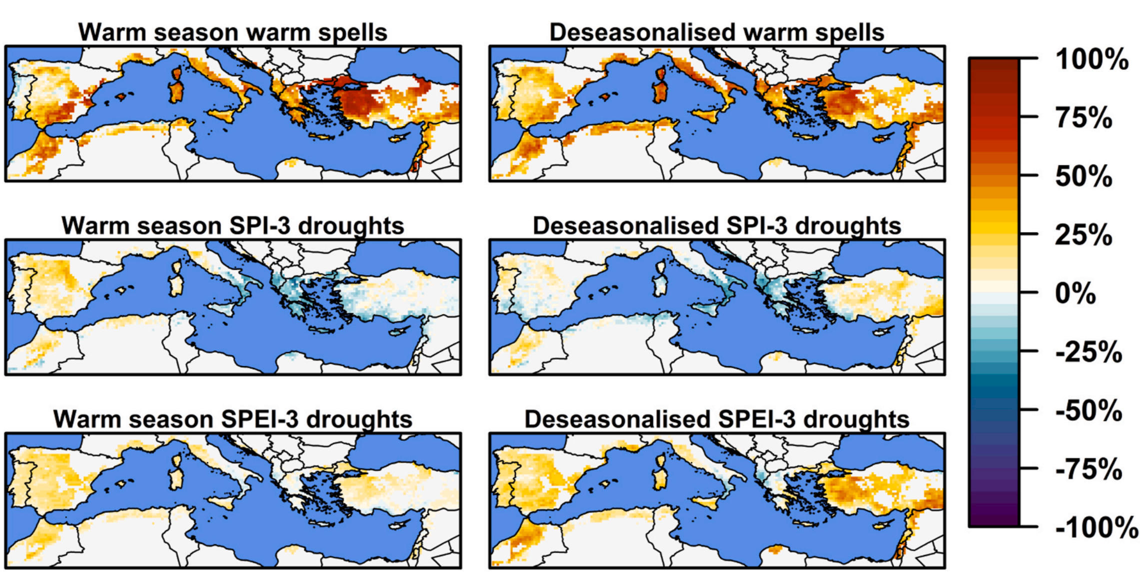

Fig. 8. Same as Fig. 5 for warm season (left column) and deseasonalised (right column) warm spells (upper panels), SPI-3 (central panels) and SPEI-3 (lower panels) droughts in the Mediterranean.

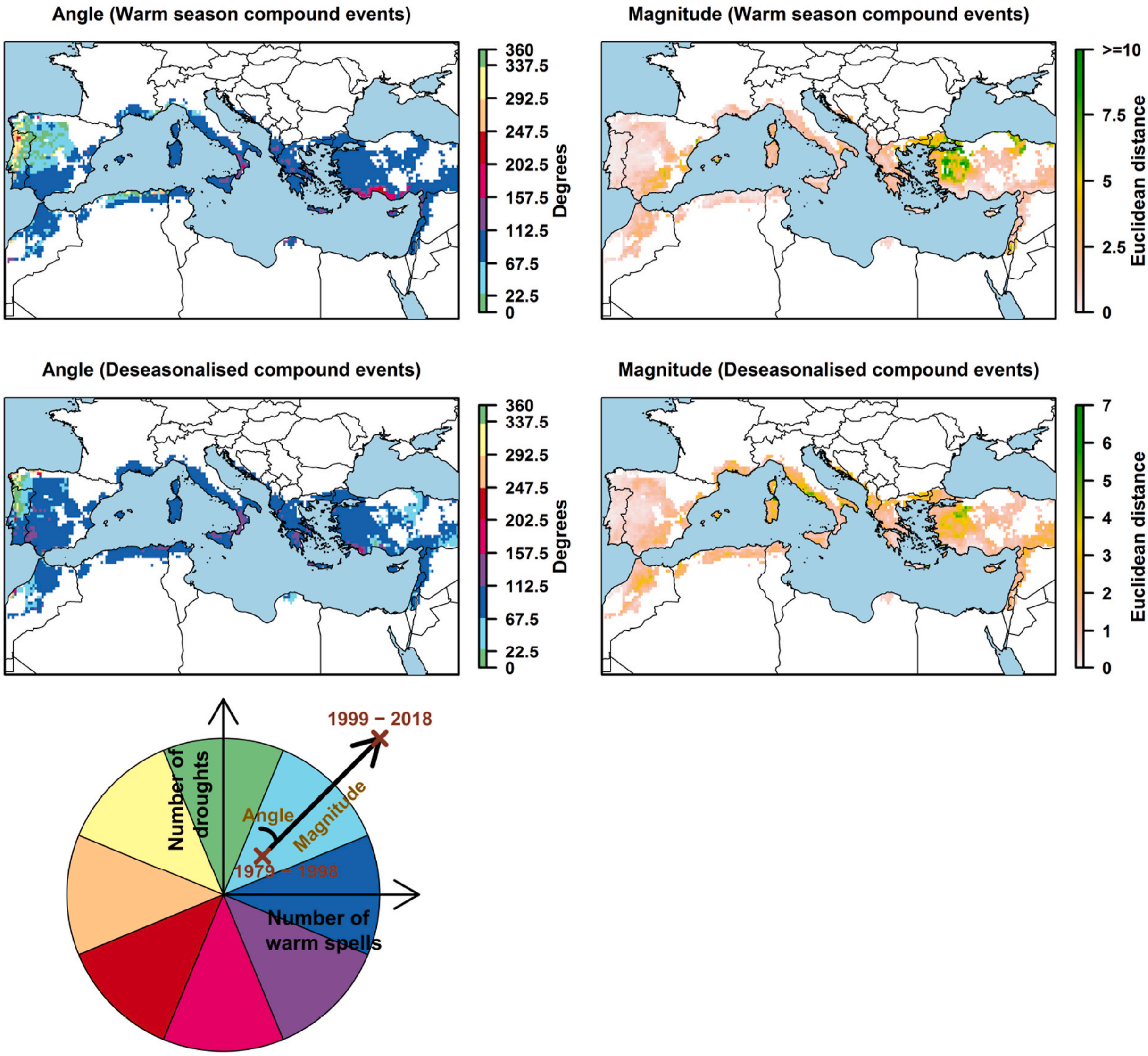

Fig. 9. Detection of change in the number of warm spells and SPI-3 droughts in the Mediterranean between the time periods 1979–1998 and 1999–2018 using a change vector analysis: A change vector is defined by two points given by the number of warm spells and the number of SPI-3 droughts in the period from a) 1979–1998 and b) 1999–2018. The angle (left column) and the magnitude (right column) of the change vector are displayed, where the angle is defined by the vector and the y-axis – the y-axis displays the number of droughts in this case – and the magnitude is given by the length of the vector, i.e. the Euclidean distance between both points. Warm spells and SPI-3 droughts are normalised by division through the number of droughts and warm spells in the first period (1979–1998), respectively. The colouring of the angular plot divides the angles into eight 45°sections (see schematic illustration of the change vector analysis with an exemplary vector at the bottom of the plot).

the reference time period (Spinoni et al., 2017). Therefore, the non-significant trends for SPI droughts in this study have to be interpreted with caution.

The increase rate of warm spells depends on the choice of percentile used for defining the warm spell magnitude in the Mediterranean, with larger increases at higher percentiles. The most extreme compound events - i.e. those with the highest heat wave duration and magnitude – occur primarily in the period from 1999 to 2018, which indicates the emergence of novel unprecedented climatic conditions in the Mediterranean in recent decades. This is consistent with previous findings indicating that temperatures at the hot tail, i.e. the highest percentiles, increase much faster than mean temperature, up to 6 °C for 1.5 °C mean warming due to surface moisture and atmospheric feedbacks in the Mediterranean Basin, (Diffenbaugh et al., 2007; Fischer and Schär, 2010; Mueller and Seneviratne, 2012; Orlowsky and Seneviratne, 2012; Lewis et al., 2019).

4.2. Discrepancy between SPI and SPEI droughts

Lack of precipitation and high evapotranspiration rates are the general drivers of Mediterranean droughts (Sousa et al., 2011; Spinoni et al., 2017). In contrast to SPI droughts, SPEI droughts are increasing substantially (cf. Fig. 10 and Table 1), indicating that while precipitation is not showing large changes, potential evapotranspiration is increasing. This is in line with Vicente-Serrano et al. (2020) who link increasing drought severity in the Mediterranean primarily to increasing atmospheric evaporative demand rather than precipitation deficits. Therefore, the Mediterranean is likely getting drier in spite of unchanged precipitation patterns. The SPEI is particularly suitable to detect the warming impact by climate change (Vicente-Serrano et al., 2010), whereas the SPI cannot show such warming-induced changes in droughts as it is based solely on precipitation (Dubrovsky et al., 2009). This leads to the conclusion that, while compound events are strongly

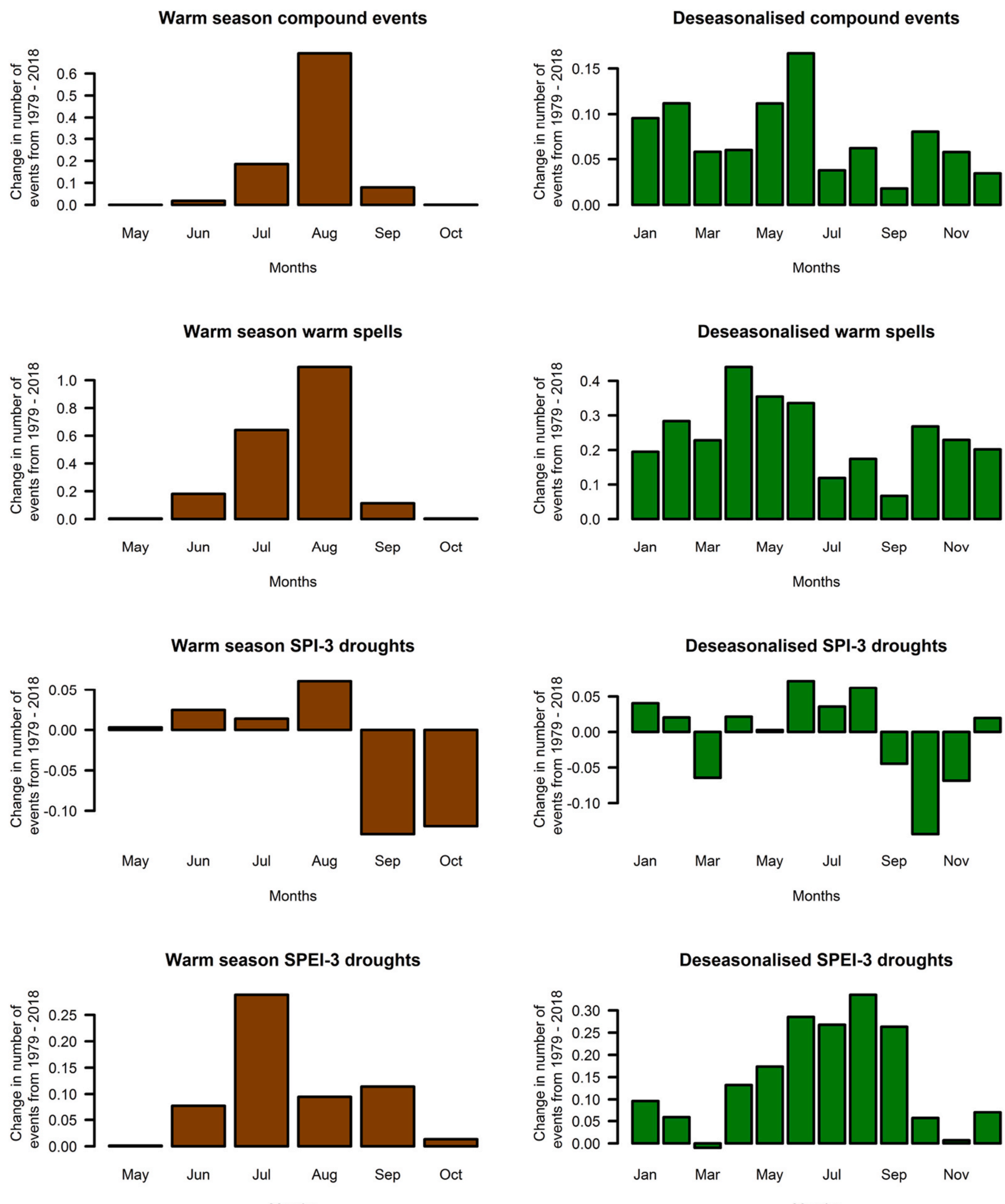

Fig. 10. Absolute change in the number of warm season (left column) and deseasonalised (right column) events in the Mediterranean averaged yearly over all pixels over the 40-year-period 1979–2018 for each month for compound events (first line), warm spells (second line), SPI-3 droughts (third line), SPEI-3 drought (fourth line).

increasing in the Mediterranean, the increases of compound events calculated by the definition based on the SPI used here is presumably underestimating the drought component. Future research should aim for adequately incorporating the water balance and land-atmosphere feedbacks by using direct measurements of soil moisture droughts and actual evapotranspiration, e.g. based on remote sensing (Sharma and Mujumdar, 2017; Toulios et al., 2020). However, such an approach can be presumably only be undertaken reliably for the last two to three decades due to the scarce spatio-temporal satellite coverage before (Dorigo et al., 2017). Furthermore, remote sensing only retrieves surface soil moisture, but users are often requiring deeper reaching root-zone soil moisture (Albergel et al., 2008; Dorigo et al., 2017).

Increases in SPEI-3 droughts are highly relevant, as heat waves jointly with increasing evapotranspiration can lead to a drier climate state, potentially leading to desertification in the Mediterranean Basin with drastic impacts on its ecosystems (Conte et al., 2002; Gao and Giorgi, 2008; Guiot and Cramer, 2016; Samaniego et al., 2018). The Mediterranean biome will extend northwards in future due to global warming (Seneviratne et al., 2006; Feng and Fu, 2013), potentially leading to similar exacerbations in the number of compound events in those regions.

4.3. Timing of events

The rate of change in number of events differs between warm season and deseasonalised compound events. The months July and August show the highest increases in warm season compound events by far, whereas the highest change rates of deseasonalised compound events occur in spring and early summer and are relatively low from July to September. It has been noted that the onset of droughts is starting earlier in the year, shifting towards spring (Beniston et al., 2007; Giannakopoulos et al., 2009; Trenberth et al., 2014; Samaniego et al., 2018). Spinoni et al. (2017, 2018) found that changes in the number of drought frequency and severity differed substantially depending on the season and are highest in spring and summer in the Mediterranean Basin. This increase in deseasonalised compound events in spring is potentially very relevant for Mediterranean ecosystems and agriculture as this is the peak phase of ecosystem productivity and a vital phenophase. This is in line with findings by Samaniego et al. (2018), stating plant development is affected negatively due to decreasing soil moisture availability during the growing season in Europe. This shows the importance of incorporating deseasonalised compound events, because these patterns are not visible for warm season compound events and might be missed if only warm season compound events are investigated. Compound warm spells and droughts may occur earlier in the year than they used to in the past, which potentially explains the high rate of change in spring and early summer compared to the relatively low rate of change in late summer for deseasonalised compound events. This shift could be due to earlier depletion of water resources in the ecosystems (e.g. soil moisture) caused by increased temperatures and the associated ecosystem productivity and evapotranspiration in springtime (Buermann et al., 2018; Bastos et al., 2020). Mediterranean winter and spring droughts are linked to the occurrence of subsequent summer heat anomalies in the Mediterranean and central Europe (Vautard et al., 2007; Russo et al., 2019). For example, the increased evapotranspiration in spring contributed roughly as much as evapotranspiration in summer to the summer heat wave and drought in 2018 (Bastos et al., 2020). This soil moisture deficit can in turn fortify the development of heat waves due to lack of evaporative cooling (Lian et al., 2020). So far, the evidence supporting this mechanism is scarce (Lian et al., 2020) and this study contributes to add to evidence supporting this hypothesis. Drought impacts also depend on seasonality. However, seasonal differences were rarely analysed for Europe up to this point (Spinoni et al., 2017, 2018).

Further research is crucial for a better understanding of the effect of weather extremes on transpiration rates in European ecosystems (Teuling et al., 2010), as the effects of warm spells and droughts on vegetation dynamics are not one-sided and vegetation dynamics in turn also influence magnitude and duration of warm spells and droughts (Lemordant et al., 2016).

5. Conclusion

Our research supports prior findings that increases in the number of compound events in the Mediterranean Basin in the last four decades are mostly driven by temperature changes. A continuing and regular combined monitoring of the changes in warm spells and droughts and their future development is crucial to provide the necessary data and information base for an adequate risk management. Such a risk management might include adaptation of crop choice, sowing schedules, and irrigation options. The interdependence between warm spells and droughts and the associated feedback mechanisms for warm spells and droughts are still under debate and the question if droughts primarily drive warm spells or vice versa is nontrivial (Sheffield et al., 2012). In this respect, the onset and development of compound warm spells and droughts is still not well understood and it remains unclear how these events and their interactions will be altered by climate change (Sheffield and Wood, 2008; Miralles et al., 2019) and thus how these compound events will evolve in future. A better insight into these intertwined mechanisms and feedbacks of such compound events might be derived from detailed coupled local or regional meteorological and soil-hydrological modelling experiments, where energy fluxes and water storages can be modelled and analysed under observed boundary conditions, such as conducted e.g. by Niu et al. (2014) and Senatore et al. (2015). Such modelling experiments, however, require data from comprehensive on-site measurements campaigns for meteorological and soil-hydrological variables to enable a model validation of both energy and water fluxes.

Increases in deseasonalised compound warm spells and droughts might have major implications for Mediterranean ecosystems and agriculture. An earlier onset of compound events in the year is likely to affect the growing season length and ecosystem productivity and in turn evapotranspiration rates. This might lead to unforeseen changes in the complex land-atmosphere feedbacks in this region. This highlights the importance of incorporating deseasonalised compound events, because these patterns are not visible for warm season compound events and might be missed if only warm season compound events are investigated.

CRediT authorship contribution statement

Johannes Vogel: Conceptualization, Software, Formal analysis, Writing - review & editing, Visualization. **Eva Paton:** Conceptualization, Writing - review & editing, Supervision. **Valentin Aich:** Writing - review & editing. **Axel Bronstert:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AppendixA

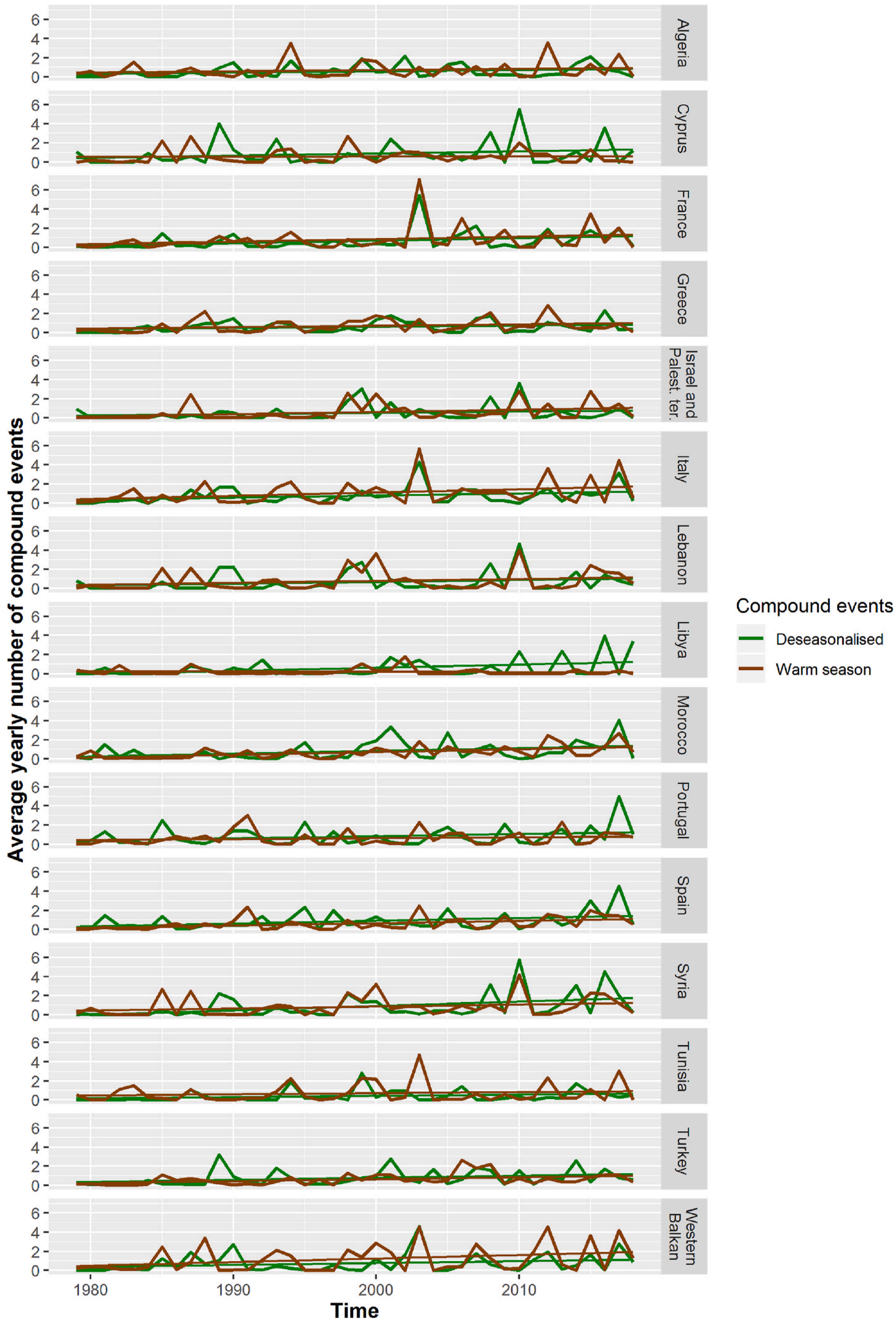

Fig. A.11. Number of warm season (brown) and deseasonalised (green) compound events for each country averaged yearly over all pixels for the 40-year period 1979–2018. Note that only the regions located within the study area (cf. Fig. 1) of the respective countries are incorporated.

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