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Changes in compound monthly precipitation and temperature extremes and their relationship with teleconnection patterns in the Mediterranean

Marc Lemus-Canovas

Climatology Group, Department of Geography, University of Barcelona, Barcelona, Spain

A R T I C L E I N F O

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A B S T R A C T

Compound extremes have increasingly become the focus of research in recent years, due to the strong impact they have upon society and ecosystems. Few studies, however, address the role of teleconnection patterns in these compound extremes, and how the former can be used to predict the latter. The present study quantifies the changes observed in the monthly frequencies of Dry-Warm, Dry-Cold, Wet-Warm and Wet-Cold concurrent extremes in the Mediterranean basin during the 1951–2020 period, and assesses the effect of different regional, continental and oceanic teleconnections upon the frequency of such concurrent extremes. Results reveal a significant increase, especially, in dry-warm months in large areas of the Mediterranean basin, mainly in summer and spring, as well as a decrease in wet-cold extremes in these seasons. On the other hand, the positive phase of the Mediterranean Oscillation (MO) has a strong capacity to drive dry-warm months in the western Mediterranean basin, as well as wet-cold extremes in the southern-east part of the Mediterranean basin. This role becomes inverted during the negative phase of this teleconnection. Furthermore, due to its subtropical linkage, the positive phase of the East Atlantic (EA) oscillation also plays an important role in accounting for the occurrence of dry-warm months in most of the Mediterranean basin, especially in the west and the north. During its negative mode, the configuration of the EA dipole favours the occurrence of wet-cold months, especially in the north and western part of the basin. The East Atlantic/Western Russia oscillation proved to be highly capable of inferring the ocurrence of dry-warm and wet-cold events in the eastern Mediterranean. The other teleconnections analysed (the North Atlantic Oscillation (NAO), the Western Mediterranean Oscillation (WeMO), and the Scandinavian (SCAND) an Polar-Eurasia (POLEUR) oscillations) played a minor role in driving these monthly concurrent extremes. The results provided by the present paper are intended to guide future research addressing the potential of teleconnection patterns to drive the temporal variability of compound extremes.

1. Introduction

Compound analysis of two or more extremes enables estimation of the real risk posed by several climate variables occurring simultaneously (Zscheischler et al. 2018), of special interest in fragile and vulnerable areas such as the Mediterranean basin (Giorgi, 2006; Cramer et al. 2018; Tuel and Eltahir, 2020; Vogel et al. 2021), within a context of anthropogenic climate change. In this sense, one of the compound extremes that has aroused considerable interest is that of droughts and heat waves, with many studies focusing on various regions of the world, such as Russo et al. (2019) for the Mediterranean; Manning et al. (2019) for Europe; or Zscheischler and Seneviratne (2017) at the global level, because these events have been shown to have major environmental and social impacts, such as crop yields losses (Ribeiro et al. 2020). Moreover, they can trigger large fires (Turco et al. 2019) or negatively affect human health (Bandyopadhyay et al. 2012). On the contrary, wet-cold extremes can have beneficial effects in spring in the mediterranean area, such as reducing the risk of fire. Nevertheless, they can also trigger crop yield losses, comparable to those occurring during dry-warm extremes (Li et al. 2019). Finally, dry-cold and wet-warm extremes have negligible ramifications in the Mediterranean area, and in general at medium and low latitudes (Mueller and Seneviratne, 2012), because no positive correlation exists between temperature and precipitation (Tencer et al. 2014).

Results from previous studies show an overall increase in dry-warm and wet-warm months at global level over the last few decades (Hao et al. 2013), thus indicating that the thermal component predominates over precipitation. This is also the case when changes in these compound extremes are analyzed at the regional level, such as in US (Mazdiyasni and AghaKouchak 2015); India (Sharma and Mujumdar, 2017); or China

E-mail address: mlemus@ub.edu.

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(Wu et al. 2019), among others. Fewer studies evaluate the impact of teleconnections and circulation patterns on compound extremes (Seneviratne et al. 2012; Kopp et al. 2017, De Luca et al. 2020b). In this sense, Hao et al., 2018, performed a global approximation of the impact of the ENSO on Dry-Warm months to estimate the likelihood of such extremes. López-Moreno et al. (2011) investigated the effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains ranges. Finally, De Luca et al. (2020b), analysed at the relationship between the NAO and the occurrence of compound precipitation and wind extremes in Europe. However, most studies focus on estimating the relationship individually, i.e. either with precipitation or with temperature. For example, in the Mediterranean area, it has been estimated that teleconnections have had a greater influence upon the distribution and frequency of precipitation and its variability (Krichak et al. 2014; Lopez-Bustins and Lemus-Canovas, 2020; Mathbout et al. 2020; Martinez-Artigas et al., 2021, among others), as well as on temperature (Ben-Gai et al. 2001; Ríos-Cornejo et al. 2015; Baltacı et al. 2018, etc.). There is currently a need for studies that analyse the impact of several teleconnections on the behaviour of compound extremes in the entire Mediterranean basin, highlighting the novel contribution of the present research. It is therefore vital to establish the teleconnections that most intensely regulate the frequency of monthly concurrent extremes, in order to promote future studies on the predictive capacity of these circulation patterns during the occurrence of compound extremes (Hao et al. 2019; De Luca et al. 2020a).

The present paper attempts (i) to characterize the frequency of dry-warm, dry-cold, wet-warm and wet-cold monthly concurrent extremes, as well as to evaluate changes therein in recent years; (ii) to identify the influence of different regional, continental and oceanic teleconnection patterns on the occurrence of dry-warm and wet-cold monthly compound extremes; (iii) and finally, to establish the empirical probability of dry-warm and wet-cold monthly compound extremes occurring by means of the different teleconnections, and to determine the dominant pattern in the Mediterranean area. Our study is intended to constitute a roadmap for future research into the relationship between the co-occurrence of extremes and the different modes of atmospheric variability provided by the teleconnection patterns.

2. Data and methods

2.1. Data

To identify Dry-Warm, Wet-Cold, Dry-Cold and Wet-Warm extremes, we used the monthly temperature and precipitation variables from the ERA-5 reanalysis dataset (Hersbach et al., 2020) for the 1951–2020 period, with a spatial resolution of 0.25°.

The use of the EOBS grid (Cornes et al. 2018) was discarded following several tests and due to the fact that there are scarce data for North Africa and little spatial continuity with regard to ensuring proper identification of events of interest, a fact already pointed out in previous articles (Manning et al. 2019; Herrera et al. 2019). The use of the ERA-5 grid was considered to be sufficient with regard to estimating spatial patterns and occurrences of compound events based on percentiles.

Additionally, the teleconnection patterns influencing compound events were divided into three groups based on the position of its dipole:

Mediterranean: Western Mediterranean Oscillation (WeMO) (Martin-Vide & Lopez-Bustins, 2006); Mediterranean Oscillation (MO) (Conte et al. 1989). Both indices were provided by the Climatic Research Unit (CRU) (https://crudata.uea.ac.uk/cru/data/pci.htm, accessed on Sep 2021).

Eurasia: East Atlantic/Western Russia pattern (EAWR) (Barnston and Livezey, 1987); Scandinavian pattern (SCAND) (Barnston and Livezey, 1987); Polar/Eurasian pattern (POLEUR) (CPC, 2021). All indices were retrived from the Climate Prediction Center (CPC) (https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml, accessed on Sep 2021).

North Atlantic: North Atlantic Oscillation (NAO) (Hurrell, 1995); East Atlantic pattern (EA) (Wallace and Gutzler, 1981). Both indices were also obtained from the CPC.

All teleconnection patterns were aggregated on a monthly basis and for the 1951–2020 period. We created the atmospheric composites associated with the teleconnection phases using monthly geopotential height at 500 hPa (Z500) and mean sea level pressure standarized anomalies (SLP), with respect to the reference period 1981–2010, using the ERA-5 dataset.

2.2. Event definition

Following previous studies defining compound extremes (Beniston, 2009; Hao et al., 2013; Wu et al. 2019), the 25th and 75th percentiles of precipitation and temperature were computed for each month and for the reference period 1981–2010. Then, we used the abovementioned thresholds defined in the reference period to estimate the exceedances over the entire study period (1951–2020). The wet extreme occurs individually for each month when precipitation is above the 75th percentile, while the dry extreme occurs when precipitation is below the 25th percentile. Similarly, the warm extreme occurs when the temperature is above the 75th percentile, while the cold extreme occurs when the temperature is below the 25th percentile. The compound extreme is therefore defined as the co-occurrence of two extremes in the same month. Note that the 75/25 percentiles employed to define extreme months involve a moderate deviation from the mean. However, the joint precipitation–temperature statistics are found to be relatively insensitive to the choice of quantile levels, producing similar patterns of changes in concurrent extremes (Hao et al., 2013). In addition, selecting a more extreme threshold (i.e. the 90/10 percentiles) would give rise to a very low co-occurrence of extremes, which would make it difficult to analyse changes in the frequency of concurrent extremes according to subperiods.

2.3. Comparison of periods and impact of teleconnections on compound extremes

We first estimated the grid-based monthly occurrence of Dry-Warm, Dry-Cold, Wet-Warm and Wet-Cold compound extremes, aggregated at seasonal level: Autumn (Sep-Oct-Nov), Winter (Dec-Jan-Feb), Spring (Mar-Apr-May), Summer (Jun-Jul-Aug); for the 1951–1985 and 1986–2020 periods, to determine whether there was an increase in events in the latter period. To estimate the significance of such differences, a two-sample *t*-test (Wilks, 2019) was performed, which indicated that the significant difference occurred at the 95% confidence level.

On assessing the impacts of the teleconnections, we only employed the Dry-Warm and Wet-Cold events, since these are more frequent in the Mediterranean area, due to the negative correlation they present between temperature and precipitation (Fig. S1). We also included the summer season in this analysis although its observed weak atmospheric circulation in the Mediterranean area during this season (Martin-Vide & Lopez-Bustins, 2006; Lemus-Canovas et al. 2019), a fact that implies that some teleconnections could play an irrelevant role during this period of the year. To estimate this relationship between teleconnection patterns and compound extremes, we first defined the dichotomous variable Y to represent the occurrence ($Y = 1$) or non-occurrence ($Y = 0$) of a compound extreme. Using the logistic regression model, we estimated this binary variable from an independent variable X, which in our case is the teleconnection index. This relationship can be expressed by the following equation (1) (Agresti, 2006):

$$logit\ (p(x)) = \alpha + \beta x \quad (1)$$

where $p(x) = \mathrm{P}(\mathrm{Y} = 1|x)$, which can be referred to as the probability of a compound extreme occurrence, given a value $\times$ of the corresponding teleconnection pattern, with α and β being the coefficients of the model. The left side of the equation is known as the logit transformation. The logit is a linking function and can be expressed as $\text{logit}(p(x)) = \ln(p(x)/(1 - p(x)))$. One can then derive from Eq. (1) that the ratio of the odds for a one-unit increase in X is $\exp(\beta)$ (or the odds ratio), defined as the probability of occurrence divided by the probability of non-occurrence (Agresti, 2006). The odds ratio represents the "constant effect" of the independent variable upon the likelihood of an outcome occurence (Hao et al., 2018). An odds ratio greater than 1 implies the higher odds of compound extreme occurrences associated with an increase in the values of the corresponding teleconnection index (and vice versa). The odds ratio can then be used to evaluate the response of the occurrence of a compound extreme to the teleconnection pattern (Hao et al., 2018).

Moreover, the probability of occurrence of a concurrent extreme was estimated by means of a specific threshold of the teleconnection indices. This probability can be calculated using the following equation (2):

$$P(Y = 1|x) = \frac{1}{1 + exp(-(\alpha + \beta x))} \quad (2)$$

For positive -negative- values of β, the probability $p(x)$ of a compound extreme occurring increases -decreases-. The thresholds of the teleconnection indices were selected from different quantiles, because the distributions of such indices reveal different kurtoses (see Fig. S2). Specifically, the 10th and 90th percentiles were used as thresholds for each index and season (Table 1). Interestingly, the probability of occurrence was estimated at seasonal scale, so that a $p(x) = 1$ indicates the unequivocal occurrence of at least 1 compound extreme month in the corresponding season, in the same way that it does not preclude the possiblity that up to 3 compound extreme months occur (as many as there are months in the season).

In order to understand the physical mechanisms triggering these extreme compound months, we mapped the Z500 and SLP standardized anomalies for the 1951–2020 with respect to the reference period 1981–2010. We computed them for each season and for the values surpassing the above mentioned two quantile thresholds (Table 1).

3. Results and discussion

3.1. Characterization and recent changes in the frequency of compound events

The frequency of compound extremes is defined as the total number of months exhibiting a co-occurrence of events within each season. In this sense, Fig. 1a shows the frequency of the 4 compound extremes for each season and during the 1951–2020 period.

As previously stated, the Dry-Cold and Wet-Warm extremes display a lower frequency than the Dry-Warm and Wet-Cold extremes, due to the negative correlation generally existing between temperature and precipitation, i.e. dry extremes occur with high temperatures and low precipitation. This, however, calls for consideration of several aspects. In winter, this correlation (Fig. S1) becomes positive on the western and south-western façades due to the fact that the polar front follows a more southerly path than in summer (Hall et al. 2015), which implies that the frequency of Wet-Warm and Dry-Cold events depends more strongly on the dynamics of this front. Something similar occurs in the southern Mediterranean basin in summer with the Dry-Cold and Wet-Warm events, which are more frequent than in the rest of the basin due to the slightly positive correlation between temperature and precipitation (Trenberth and Shea, 2005). Clearly, the Mediterranean basin is mainly affected by Dry-Warm and Wet-Cold extremes, with a north–south dichotomy, depending on the season (Fig. 1a). For example, in summer the frequency of dry extremes in the northern and eastern half of the Mediterranean basin is much higher than in the southern half, a fact also contrasted in De Luca et al. (2020a), and vice versa in winter. In spring, the number of Dry-Warm extremes is very high throughout the basin. These spatial frequency patterns of Dry-Warm extremes are transferable to the frequency of Wet-Cold extremes. Autumn presents a similar pattern to spring, but with a lesser amount of compound extremes, especially for Dry-Warm and Wet-Cold concurrences.

However, on quantifying the changes in frequencies between the 1986–2020 and 1951–1985 periods (Fig. 1b) for each grid point, the increase in Dry-Warm extremes is seen to be statistically significant in summer throughout large areas of the entire Mediterranean basin –76.6% of the study area (Fig. S3a)–, with larger increases in the northern and eastern half. In this sense, Manning et al. (2019) found that Balkan region showed the lowest return period of hot-dry events in summer, which is clearly related with the increase above-mentioned. This statistically significant increase can also be observed in spring, accounting for 61.8% of the study area. It is in these two seasons, summer and spring, that a bias is clearly observed in the distribution of the frequency anomalies between the two periods (Fig. 1c), indicating a sharp increase in their recurrence, and in a lesser extent, in winter and autumn. The opposite case has been detected for the Wet-Cold extremes, in which a clearly significant decrease in this type of concurrent extreme is quantified (Fig. 1b). This covers quite a large area in summer, i.e, 58.4% of the area, and in spring – 54.6% (Fig. S3b)–. A general pattern observed during summer Dry-Warm and Wet-Cold extremes is that the eastern part of the Mediterranean basin responds with greater statistical robustness to the significant increases and decreases in such concurrent extremes, in accordance with previous studies on precipitation in this specific area (Mathbout et al. 2018; Zittis, 2018). The Dry-Cold and Wet-Warm extremes present a decrease and an increase, respectively. However, all the changes in the set of compound extremes appear to indicate that the thermal component is what drives the increase in the frequency of warm months (e.g. Dry-Warm and Wet-Warm), whereas it causes a decrease in cold months such as the Dry-Cold and Wet-Cold ones, a phenomenon also detected in other regions such as China (Wu et al., 2019);or in Europe, in relation to Dry-Warm extremes (Manning et al., 2019;). This thermal rise leading to an increase in dry and warm extremes has also been clearly discerned in the Mediterranean basin (Vogel et al. 2021), as well as in more local regions such as the Pyrenees (Lemus-Canovas and Lopez-Bustins, 2021a).

3.2. Impact of teleconnections on Dry-Warm and Wet-Cold compound events

This section analyzes the impact of teleconnection patterns on the Dry-Warm and Wet-Cold concurrent extremes, discarding the Dry-Cold and Wet-Warm months, which are seen to be less relevant in this region at the frequency level.

Herein we first analyze the direction, using the odds ratio, of the relationship between the Dry-Warm and Wet-Cold compound extremes and the teleconnections capable of varying the frequency of these events (Fig. 2). These results reveal that for Dry-Warm and Wet-Cold extremes, the EA and MO patterns are the ones displaying the clearest significant relationship therewith; the former pattern represents 83% of the area in winter for Dry-Warm extremes and the latter one refers to 48% of the Mediterranean area for this same season and kind of extremes.

Table 1
Seasonal values of the teleconnection indices referring to the 90th and 10th quantiles. These quantiles enable the positive and negative phase of each teleconnection pattern to be characterized.

	Autumn		Winter		Spring		Summer	
	Q90	Q10	Q90	Q10	Q90	Q10	Q90	Q10
WeMO	1.3	−1.5	1.2	−1.3	1.3	−1.9	1.5	−1.7
MO	0.4	−0.6	0.4	−0.9	0.2	−0.6	0.7	0.2
EAWR	1.6	−1.3	1.1	−1.3	1.4	−1.5	1.7	−1.5
SCAND	1.4	−1.1	1.4	−1.1	1.2	−1.3	1.5	−1.2
POLEUR	1.3	−1.2	1.7	−1.5	1.2	−1.3	1.2	−1.5
NAO	1.5	−1.1	1.2	−1.7	1.2	−1.6	1.4	−1.6
EA	1.0	−1.6	1.3	−2.0	1.1	−1.5	1.2	−1.5

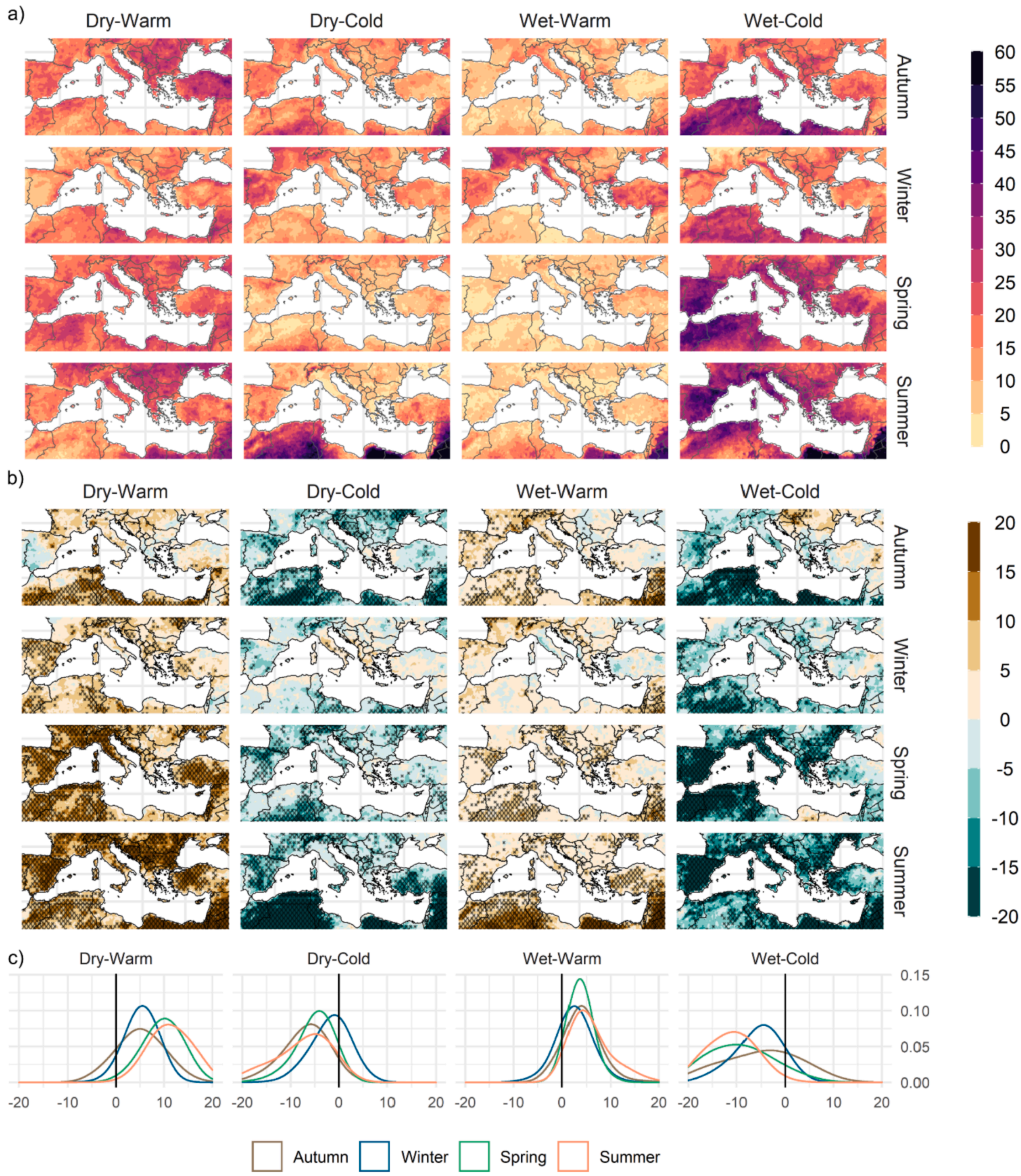

Fig. 1. (a) Frequency (months) of compound extremes relating to precipitation and temperature during the 4 seasons and for the 1951–2020 period in the Mediterranean basin; (b) Changes in the frequency (months) of compound extremes relating to precipitation and temperature for the 1986–2020 period with respect to the 1951–1985 period for the four seasons. Stippled crosses show statistically significant changes in the frequency of compound extremes. (c) Probability density functions between periods for all compound extremes and for the 4 seasons.

These results show a clear dipole in their relationship with Dry-Warm extremes, with a positive relationship between the MO values and these extremes in the whole north-western region during winter and spring (Fig. 2a, MO); this phenomenon can also last into the autumn season, but is irrelevant in summer. In contrast, this relationship is inverse –odds ratio below 1– in the southeast of the study area (Fig. 2a, MO). In its positive phase, positive anomalies of SLP and Z500 clearly dominate in the western half of the Mediterranean basin, whereas the opposite situation occurs in the eastern half, where negative anomalies of both variables dominate, mainly in winter and spring (Fig. 3, MO, Winter and Spring), due to the formation of the well-known Cyprus-low (Hochman et al., 2020).

Thus, in this positive phase, the western Mediterranean basin is affected by intrusions of dry subtropical air, which is clearly associated with an increase in the likelihood of dry and warm extremes occurring in this area during the four seasons analysed, especially in autumn and spring (Fig. 4a). On the contrary, in a large part of northern Africa, under this positive phase of the MO, an inverse relationship is quantified between its values and the co-occurrence of dry and warm months. In other words, the placement of the dipole in this positive phase favours advection of the northern component, with a high moisture contribution to the southern-eastern basin (Törnros, 2013) (Fig. 3, MO, Winter and spring). This means that under this positive MO phase, months are more likely to be cold and wet in this area, reaching probabilities of occurrence close to 20–30%, mainly along the coasts of the Southern Levant and north-eastern Africa (Fig. 4c). During the negative phase of the MO (Fig. 5), one would expect to observe an exchange of roles between the northwest and southeast regions of the basin, with the former zone more

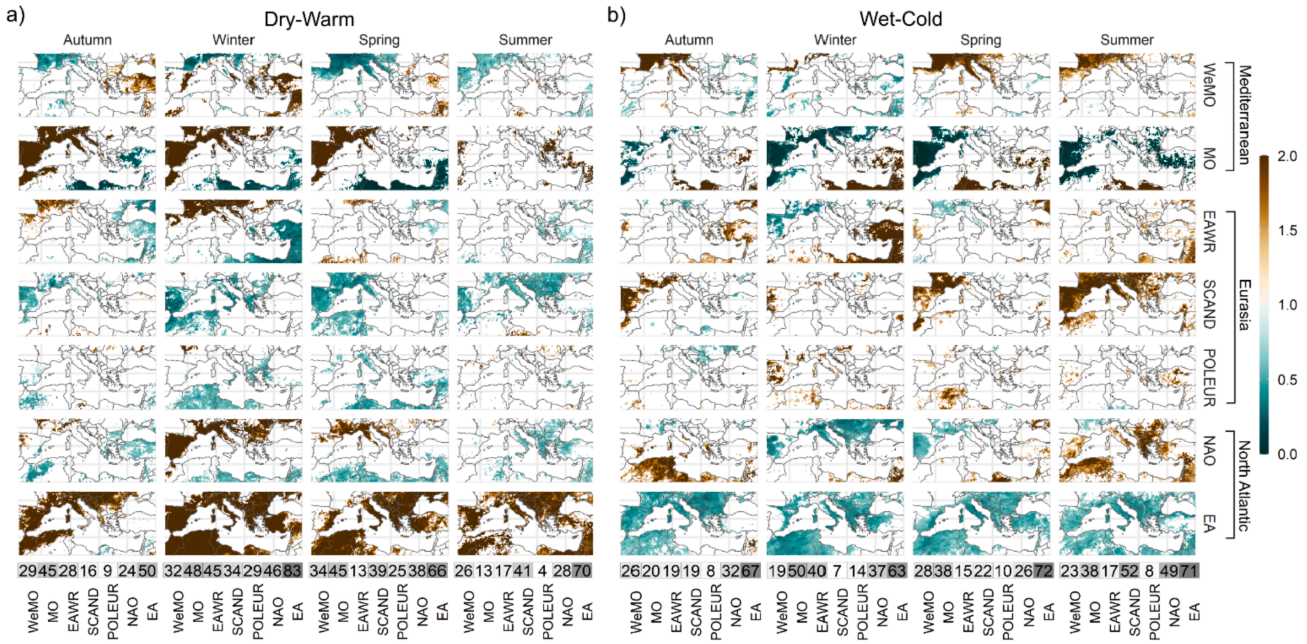

Fig. 2. The statistically significant odds ratio of the (a) Dry-Warm and (b) Wet-Cold compound extremes in autumn, winter, spring and summer seasons and in relation to the different teleconnections. An odds ratio greater than 1 implies the higher odds of compound extreme occurrences associated with an increase in the values of the corresponding teleconnection index (and vice versa). The percentage of the statistically significant area covered by each teleconnection is shown at the bottom, regardless of the direction of its relationship.

susceptible to wet-cold events. However, disposition of the low pressure during this winter phase is largely based on the cyclogenesis appearing in northern Italy, so that its disposition does favour cold advection, albeit with a continental and dry track, preventing wet-cold synergy (Fig. 5, MO, Winter). This results in a very weak influence in winter, which can also last until autumn (Fig. 2b, MO), and in the occurrence of Wet-Cold events over the northwestern Mediterranean basin. In spring, the position of the low favours a high moisture flow towards the Iberian Peninsula, together with cooler temperatures (Fig. 5, MO, spring), favouring an increase in the probability of wet and cold months occurring during this negative phase; probabilities of occurrence between 50 and 60 % (Fig. 4d) are reached in the abovementioned region. In this negative phase, northeast Africa and the eastern mediterranean basin are affected by positive anomalies in SLP and Z500, thus increasing the likelihood of Dry-Warm events arising, up to 40 % in the aforementioned regions, mainly in winter and spring (Fig. 4b). It should be noted that the empirical probabilities obtained for the summer season may not be linked to the internal variability of the MO teleconnection pattern, since in this season, the SLP and Z500 dipole disappears completely (Fig. 3 and Fig. 5, MO, Summer).

The EA shows a positive relationship with this type of Dry-Warm extreme practically throughout the area, with very widespread coverage in winter, as already mentioned, but this relationship is also positive in summer, spring and autumn (Fig. 2a, EA). In all seasons, during the positive phase of the EA, the high SW-NE zonality promotes the intrusion of subtropical ridges into the western Mediterranean; these ridges even reach the northern part of the eastern Mediterranean (Fig. 3, EA, Winter). Remarkably, although the EA and NAO dipoles present a similar structure, the EA possesses a strong subtropical link associated with modulations in the intensity and location of the subtropical ridge, while the positive phase of the NAO gives rise to a dry –but not warmer– environment; thus, the positive phase of the NAO exerts less influence on the occurrence of dry and warm extremes because the air mass originates at a more northerly latitude than in the positive EA (Fig. 3, NAO, Winter). This means that there is a 30% likelihood of a Dry-Warm month occurring during the positive phase of the EA in the eastern part of North Africa and the Iberian Peninsula, in the southern half of Italy and in the Balkan area, especially during winter, spring and summer (Fig. 4a). Precisely, some authors identified a strong relationship between a postive EA phase and negative precipitation anomalies and positive temperature anomalies in the northern part of the Mediterranean (Toreti et al., 2010a, Toreti et al., 2010b; Rust et al., 2015).

The negative phase of the EA is weakly related to the occurrence of dry-warm months in the Mediterranean basin, since under this phase, neutral or negative anomalies predominate (Fig. 5, EA). This negative phase, on the contrary, strongly influences the occurrence of Wet-Cold months (Fig. 2b, EA). The negative phase of the EA is characterised by an anticyclonic block in the western area of the British Isles in autumn, this gets stronger in winter and in the following seasons, becoming more intense in the North Atlantic. This implies that the European Atlantic coast, including the northwestern part of the Iberian Peninsula, presents drier weather (Sousa et al., 2017), whilst the western and northern half of the Mediterranean is favoured by a wetter and colder weather regime, with a 40–50% probability of a Wet-Cold month occurring in the Balkan area. This teleconnection pattern plays a less important role in the eastern end of the Mediterranean basin.

As mentioned above, the NAO has a strong link with the EA, but its dipole exhibits a more northerly position, transferring wet weather into the northern half of the basin (Philandras et al., 2011), as well as into the north of Morocco (Ahmed et al., 2016) during its negative phase, mainly during winter. The negative phase of the NAO also implies lower-than-average temperatures (López-Moreno et al., 2011), a fact which to some extent influences the occurrence of Wet-Cold months throughout the northern half of the basin (Fig. 2b NAO), albeit without providing very high probabilities of occurrence (Fig. 4d). Logically, its positive phase –more pronounced in autumn and winter– (Fig. 3,NAO), restricts the position of the polar jet towards northern latitudes, implying dry and warm conditions throughout the northern part of the Mediterranean (Fig. 4a); however, there is a lower probability of a Dry-Warm month occurring (Fig. 4a), because the air mass is not linked to a subtropical origin as in the case of the EA. Nonetheless, in autumn and under this positive phase, slightly negative geopotential height anomalies at 500 hPa with some cyclonic airflow can be observed over northern Algeria and Morocco (Fig. 3, NAO). This reveals a greater likelihood of Wet-Cold

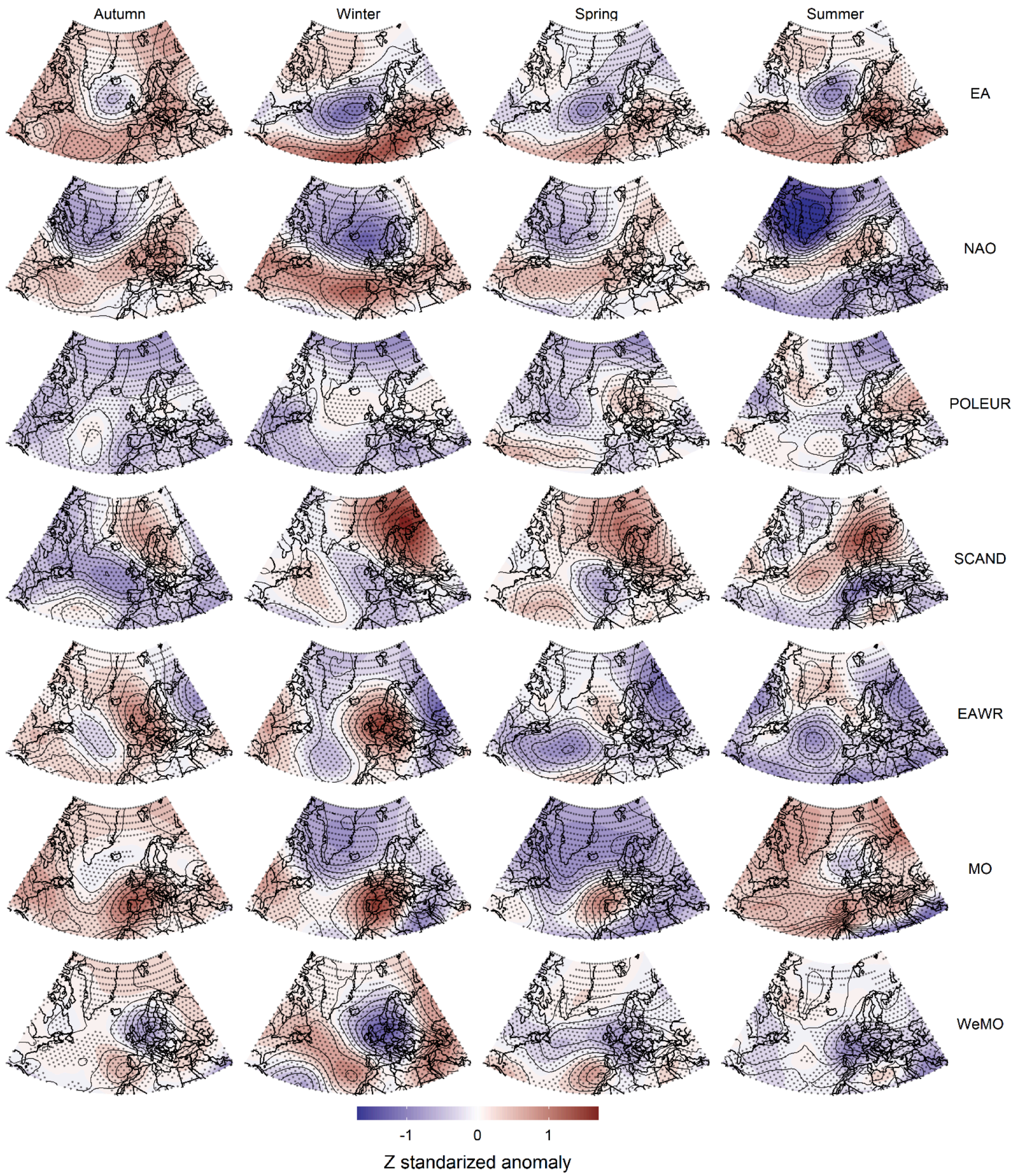

Fig. 3. Composites of mean standardized monthly anomalies (1951–2020) of geopotential height at 500 hPa (Z500) for the positive phase of each teleconnection pattern (Q90) with respect to the 1981–2010 climatology (shaded areas) as well as mean sea level pressure (SLP) anomalies (black contour lines) within the North Atlantic sector in autumn (left), winter (middle) and spring (right). Stippling indicates statistically significant anomalies at the 95% confidence level (two-sided *t*-test).

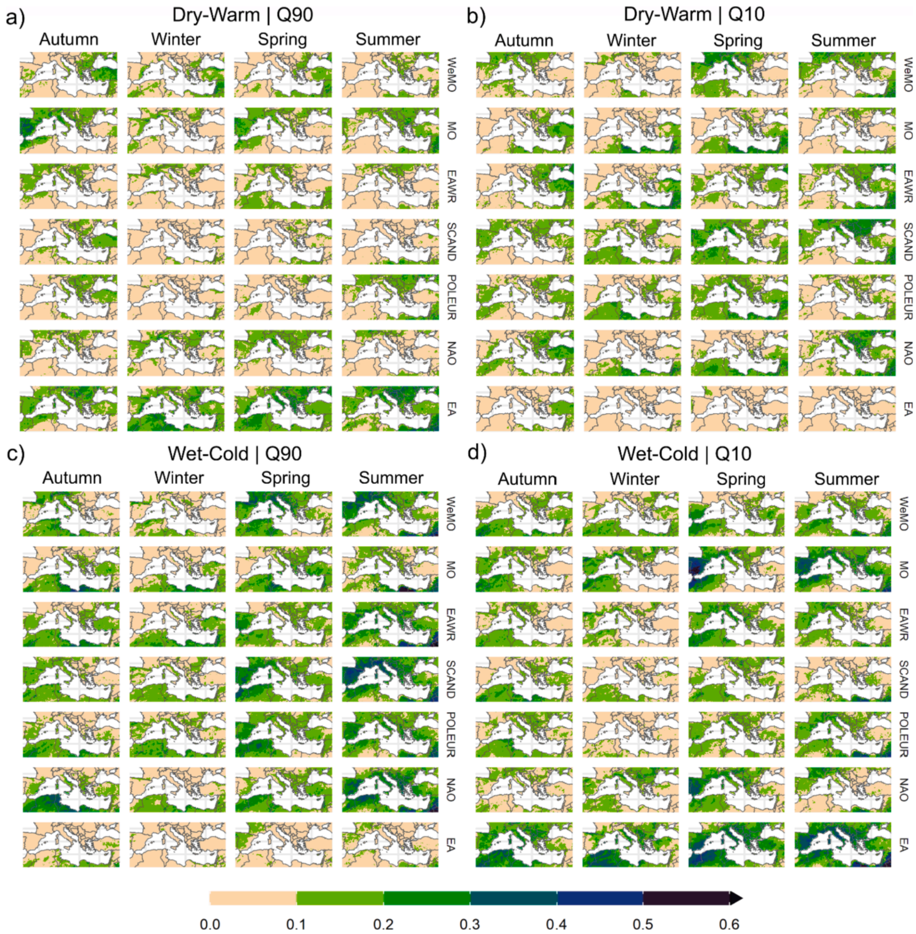

Fig. 4. Empirical probabilities of occurrence of (a, b) Dry-Warm and (c, d) Wet-Cold compound events for autumn, winter, spring, and summer based on the 90th (a, c) and 10th (b, d) quantiles of each teleconnection index for the 1951–2020 period. Note that a probability value of 1 implies the certain occurrence of at least 1 compound extreme during the corresponding season, but does not preclude the possiblity that up to 3 compound extreme months occur (as many as there are months in the season).

events in these two regions under the positive phase of the NAO, which is consistent with the positive relationship between precipitation and the NAO detected in the eastern Atlas druing november by Ahmed et al. (2016). In summer, the NAO pattern is very weakened, with a lower pressure gradient than in the rest of the seasons. In fact, in the summer version of the NAO (Folland et al. 2009), its positive phase implies high pressure and Dry-Warm weather in northern Europe (UK and Scandinavia). In contrast, throughout the Mediterranean basin, the probability of occurrence of wet-cold extremes increases markedly, reaching probabilities of 50% in many coastal locations in the northern and southern half of the basin (Fig. 4c). On the other hand, in the negative phase of the summer NAO, the synoptic configuration favours intrusions of warm and dry air, mainly in the eastern half of the Mediterranean basin, showing a pattern very similar to the positive phase of the EA (Fig. 4b).

We found that the EAWR is a significant modulator of the co-occurrence of Dry-Warm and Wet-Cold months along the eastern façade of the Mediterranean basin (Fig. 2a, EAWR). In this sense, as its maximum influence is in late autumn and winter, the positive phase of the EAWR generates a strong central-European and Scandinavian anticyclonic block, as a result of the northward expansion of the Azores high pressure centre (Fig. 3, EAWR). Such an atmospheric configuration brings northerly cold air, together with a large amount of moisture from the Black Sea, towards the easternmost Mediterranean (Krichak and Alpert, 2005; Ionita, 2014; Baltacı et al., 2018). From spring onwards, the global geopotential height anomalies related to the EAWR show a significant decrease in intensity, thus weakening its dipole, especially in this positive phase. Precisely, the positive phase in winter makes Wet-Cold months up to 30–40 % more likely to occur on the easternmost Mediterranean coastline (Fig. 4c). Its negative phase triggers the opposite situation; negative Z500 and SLP anomalies are established in central Europe, whereas in eastern Europe and Russia, the anomalies become positive (Fig. 5, EAWR), causing higher temperatures and drier weather than usual in the eastern Mediterranean area, with a probability of over 30 % of Dry-Warm extremes occurring in winter (Fig. 4b).

Although the WeMO is of certain relevance in the northern part of the study area, it plays a secondary role. This teleconnection pattern, by definition limited to controlling atmospheric variability in the western half of the Mediterranean basin (Martin-Vide and Lopez-Bustins, 2006), is most pronounced between mid-autumn and early spring, when both the positive and negative anomalies of SLP and the Z500 associated with this dipole are most pronounced. Its positive phase, characterised by a slight northerly movement of the Azores high pressure centre, favours inflows of air from the north and northwest in central Europe, as well as in the central and northern Mediterranean area (Fig. 3, WeMO). In addition, this phase favours cyclogenesis in the Gulf of Genoa, which eventually brings precipitation to northern Italy and nearby areas (Trigo et al., 2002). This positive phase implies a probability of up to 50% of Wet-Cold months occurring in central France and northern Italy (Fig. 4c), especially during spring and summer. In the negative phase of the WeMO (Fig. 5, WeMO),there is an area of low pressure in the SW of the Iberian Peninsula during the cold period of the year, which practically disappears in summer. In contrast, in central Europe and southern Scandinavia, positive anomalies of SLP and Z500 prevails. This pattern is the cause of torrential rainfall events in different parts of the eastern Iberian Peninsula (Lopez-Bustins et al. 2020; Insua-Costa et al. 2021; Lemus-Canovas et al. 2021b), due to the maritime path of the air flow. Despite the highs amounts of precipitation in this area, the Mediterranean origin of the air mass does not imply the occurrence of cold extremes in the eastern Iberia. Only in areas of southern Iberia –during spring–, and northern Morocco –between autumn and spring–,

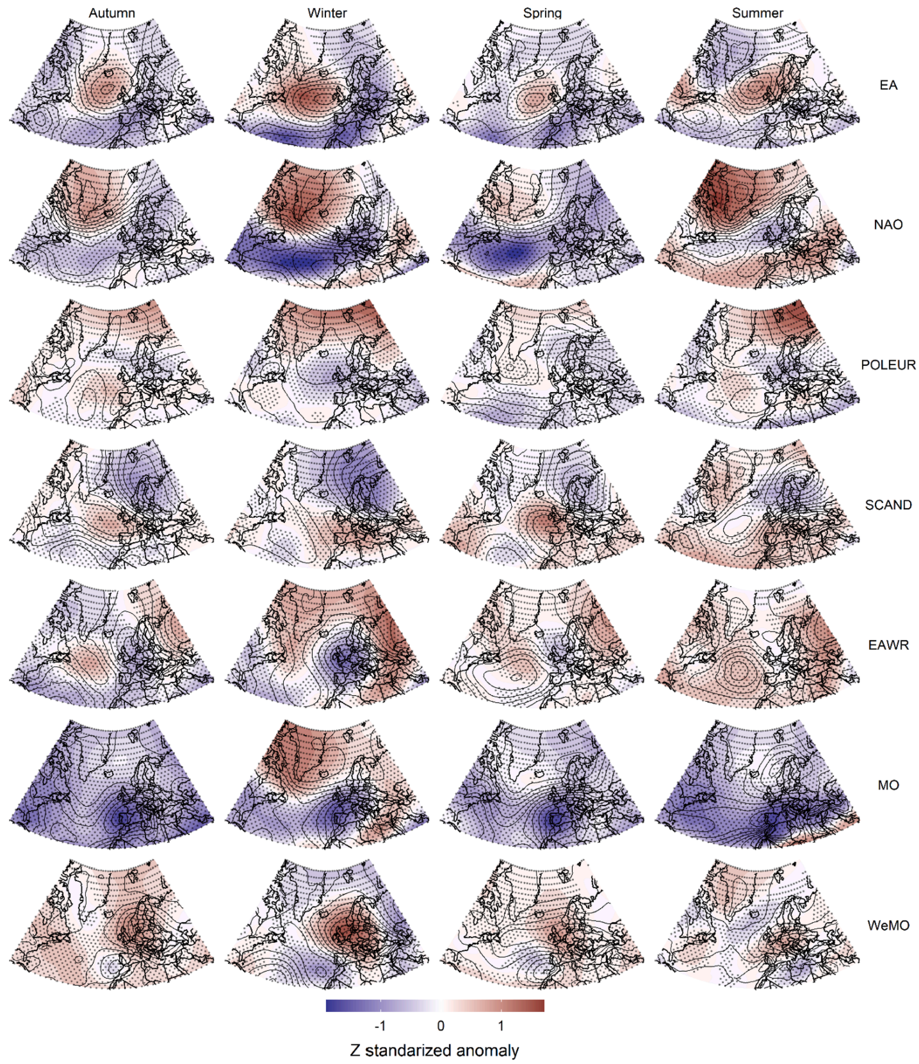

Fig. 5. Same as Fig. 3, but for the negative phase of the teleconnection patterns (Q10).

probabilities of occurrence of around 20–30% of Wet-Cold extremes are observed.

The POLEUR and SCAND teleconnections play quite an insignificant role in the modulation of concurrence extremes in the Mediterranean area. In the case of SCAND, it still has a certain influence upon the variability of precipitation in the Mediterranean; it is characterised, in its positive phase, by an anticyclonic anomaly over Fennoscandia and western Russia, as well as by negative pressure anomalies around the Iberian Peninsula (Fig. 3, SCAND), a dipole that remain fairly stable throughout the 4 seasons. Its positive phase enhances Mediterranean cyclogenesis and causes above-average precipitation in the north-western part of the Mediterranean; it presents its precipitation maxima over the Iberian Peninsula and the central-northern Mediterranean region (Krichak et al., 2014); in addition, it involves slightly below-average temperatures (Rust et al., 2015) in these areas, revealing a notable influence on the co-occurrence of Wet-Cold months (Fig. 2b, SCAND), especially during spring and summer, with a relevant impacton the co-occurrence probability, reaching the 50% in the western half of the basin (Fig. 4c).

Fig. 6 provides a synthetic analysis showing for each compound extreme the teleconnection pattern that implies the strongest likelihood of such an extreme occurring, along with the maximum probability value. This indicates that the MO is presented as a teleconnection capable of predicting the occurrence of Dry-Warm and Wet-Cold months throughout much of the north-western façade, especially on the Iberian Peninsula, where a strong influence of this teleconnection upon precipitation has already been observed (Martinez-Artigas et al., 2021). For this area, the MO plays an important role in driving dry-warm months during the autumn, and Wet-Cold extremes during the spring, exceeding probabilites of occurrence of 0.6. Additionaly, the MO also regulates the occurrence of this kind of compound extremes in the south-eastern Mediterranean during the three seasons, and implying probability values of occurrence reaching 0.4–0.5.

As previously stated, the EA also plays a vital role in the occurrence of Dry-Warm months in the northeastern mediterranean during the four seasons, particularly in the area covered by Balkan peninsula and the Carpathians. The EA also partially modulates the occurrence of Wet-Cold extremes in the above mentioned regions, extending its influence to the south-western mediterranean, especially in winter and spring. Nonetheless, the probability values of ocurrence are not very high for the Balkan peninsula, only presenting a probability of around 0.3 during autumn. In contrast, in the areas influenced by the EA pattern in the Italian peninsula, eastern Iberia, northern Morocco, northern Algeria and northern Tunisia, the probabilities of occurrence for these Wet-Cold extremes reach practically 0.5. After the EA, the EAWR shows a stronger influence in the eastern Mediterranean, partially enabling the occurrence of dry-warm and Wet-Cold months to be modulated during winter, and producing probabilities of around 0.4 in both types of concurrent extremes. The remaining teleconnection patterns play a secondary role. For example, the influence of the NAO is very restricted to the ocurrence

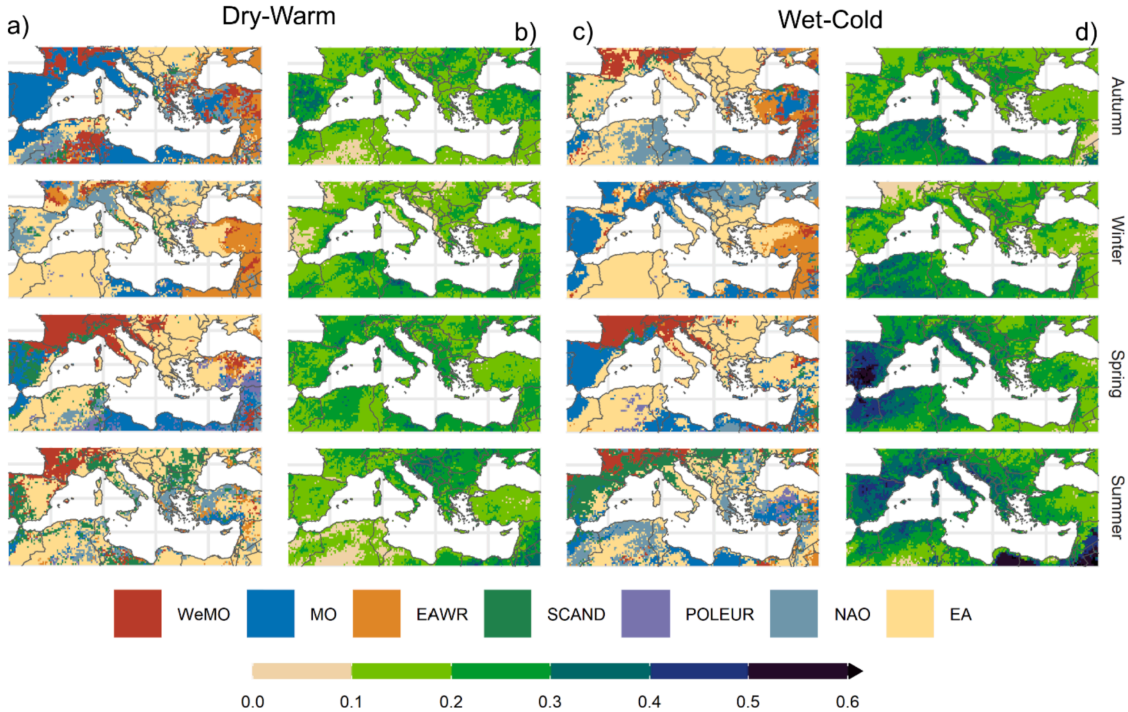

Fig. 6. Dominant teleconnection patterns for the occurrence of (a) Dry-Warm and (c) Wet-Cold extremes for autumn (first row), winter (second row), spring (third row), and summer (fourth row), regardless of the sign of the teleconnection. The maximum empirical probability for (b) Dry-Warm and (d) Wet-Cold events is also shown.

of Wet-Cold extremes in the south-central mediterranean during autumn, and in some areas of the south-western Mediterranean during summer. On the other hand, the WeMO exerts a certain degree of influence in the centre-north of the Mediterranean region during autumn and spring in the concurrence of Wet-Cold months, reaching probabilities of around 0.3–05. The SCAND has a greater influence in the occurrence of Wet-Cold extremes during summer north-western part of the Mediterranean basing, reaching probabilities arround 0.4–05. Finally, the atmospheric variability by the POLEUR teleconnection is of residual relevance with regard to accounting for the occurrence of these compound extremes.

4. Study limitations

This study is, of course, not free of limitations which are discussed next. The first limitation relates to the selection of the threshold for defining the joint temperature and precipitation extremes. The selection of the 25th and 75th percentile used in this work only represents a slight deviation from the mean, although it does allow to account a certain number of concurrences. Often the 10th and 90th percentiles are used to define extreme thresholds (i.e., Manning et al. 2019; Tavakol et al. 2020), however the downside is is that the number of co-occurring extremes for these thresholds may be very low if the time series are short.

Another important limitation of this work is related to the study period. The influence of teleconnections in driving the probability of occurrence of a concurrent extreme may vary depending on the selection of the time period. These teleconnections suffer variations with periods more linked to positive or negative phases (Visbeck et al. 2001; Mellado-Cano et al. 2019). Thus, the selection of the study period may have some influence on the probability occurrence of these extreme events. However, in this work we used the longest period available (1951–2020) of the ERA-5 dataset, to get the most robust results possible and avoiding major uncertainties.

Related to the above, it would be of notable interest, for a future work, to use atmospheric general circulation models (AGCMs), to test whether all teleconnections used in this work are robust to internal atmospheric variability, as Brands (2017) performed for the ENSO pattern. In this way, for each model of the ensemble we could compute robustly the probability of co-occurrence of extremes, and also quantifying the uncertainty of such probabilities.

5. Conclusions

We studied the changes observed in the 4 possible types of compound extremes derived from temperature and precipitation, as well as the impact of different teleconnections thereupon over the 1951–2020 period.

The main results indicate an increase in the frequency of those compound extremes related to the increase of temperature, such as Dry-Warm extremes, mainly in summer and spring, throughout much of the Mediterranean basin; or, in a lesser extent, the Wet-Warm extremes. On the contrary, the frequency of Wet-Cold and Dry-Cold extremes exhibits a decrease throughout most of the Mediterranean in these two seasons.

As for the impact of these teleconnections on the frequency of Dry-Warm and Wet-Cold compound extremes (the most frequent ones in the Mediterranean area), results show that the MO plays a significant role in driving Dry-Warm and Wet-Cold extremes between autumn and spring over large areas of the north-western and south-eastern Mediterranean basin, as a consequence of the diposition of the centres of its dipole. Specifically, we observed that the postive phase of the MO partially drives the variability of Dry-Warm months, as opposed to the negtive phase, which modulates Wet-Cold months in the above mentioned areas. The EA was also seen to strongly influence the occurrence of this kind of concurrent extremes. In this case, this pattern was closely related to Dry-Warm months during its positive phase due to its linkage to the dynamics of the subtropical ridges in the Atlantic ocean. In this sense, the positive phase of the EA constitutes an important driver of Dry-Warm extremes in most of the north-eastern Mediterranean basin, and also of Wet-Cold months during the negative phase of this pattern. Similar to the EA, but presenting an eastward displacement of its dipoles, we found that the EAWR is a significant driver of Dry-Warm and Wet-Cold months in the easternmost part of the Mediterranean basin. However, the southern half of the basin displays the weakest response to the influence of these teleconnections. The EA, MO and EAWR teleconnections represent the three most important ones in this area. Finally, the remaining teleconnections analysed, the NAO, the WeMO, the SCAND and the POLEUR, exert a much weaker influence upon the concurrence of Dry-Warm and Wet-Cold extremes.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.127580.

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