Climate sensitivity of Mediterranean pine growth reveals distinct east-west dipole

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Abstract

The European Mediterranean region is governed by a characteristic climate of summer drought that is likely to increase in duration and intensity under predicted climate change. However, large-scale network analyses investigating spatial aspects of pre-instrumental drought variability for this biogeographic zone are still scarce. Here, we introduce 54 mid to high-elevation tree-ring width (TRW) chronologies comprising 2186 individual measurements from pine trees (*Pinus* spp.). This compilation spans a 4000 km east-west transect from Spain to Turkey, and was subjected to quality control and standardization prior to the development of site chronologies. A principal component analysis (PCA) was applied to identify spatial growth patterns within the network's common period 1862-1976, and new composite TRW chronologies were subsequently developed and investigated. The PCA reveals a common variance of only 19.7% over the 54 pine chronologies from the same biogeographic zone. More interestingly, a dipole pattern in growth variability is found between the western (15% explained variances) and eastern (9.6%) sites, persisting back to 1330 AD. While pine growth on the Iberian Peninsula and Italy favors warm early growing seasons, summer drought is most critical for ring width formation across the eastern Mediterranean. Synoptic climate dynamics have been identified as the driving mechanism of a distinct east-west dipole in the growth variability of Mediterranean pines, which have been in operation at least for the last seven centuries.

48

49 **Keywords**

50 Climate dynamics, Dendroclimatology, Drought response, Mediterranean East-West dipole,

51 Palaeoclimatology, *Pinus* spp., Principal Component Analysis, Tree-ring width

52

53 **Running title:** East-west dipole in climate sensitivity of Mediterranean pines

54

55 **1. Introduction**

56 The European Mediterranean region represents a unique climatic zone where drought-prone
57 ecosystems have developed under strong environmental constraints including perpetual
58 summer drying and extensive settlement pressure. Projected global warming will likely have
59 an impact on the hydrological cycle in this region (IPCC, 2013). General circulation models
60 forecast a decrease in precipitation and increase in temperature, together with an increase in
61 the frequency and severity of weather extremes such as floods and heat waves (Gao and
62 Giorgi, 2008). To facilitate accurate future climate scenarios and related ecological
63 implications for this region, quantitative information about pre-industrial climate conditions,
64 derived from proxy climate records, is needed.

65 Predicting future climate scenarios for the Mediterranean region is challenging because
66 climatic fluctuations exhibit a high degree of spatial variability due to the complex interaction
67 of synoptic modes (Dükeloh and Jacobeit, 2003). This complexity is mainly governed by
68 meridional climatic differences representing the transition from the temperate zone in the
69 north to the subtropics in the south. The land-sea distribution and significant orographic
70 features also influence local climatic conditions. Numerous investigations based upon
71 instrumental climate and re-analyses data, especially for the winter season, have provided an
72 improved understanding of regional climate differences in the Mediterranean Basin. However,
73 these studies are largely restricted to the last 50 years (e.g., Xoplaki *et al.*, 2003; Sousa *et al.*,

2011) and only a limited number of annually resolved climate proxy data is available to extend this record further back in time (see Luterbacher *et al.*, 2012 for a review).

Tree-ring width (TRW) chronologies are the most prevalent of these proxy data, are characterized by a broad spatial availability, and offer the possibility to cover most of the last millennium at annual resolution. The pine genus (*Pinus* spp.) is a native, long-lived, ubiquitous component of the Mediterranean flora (Barbéro *et al.*, 1998) and enables the development of well-replicated and dense networks over large spatial and long temporal scales. Pine trees are of particular interest because they exhibit a large ecological amplitude and various adaptation strategies and form natural forest stands up to timber line in the Mediterranean Basin. So far, the majority of conducted dendroclimatological studies using Mediterranean trees have largely been restricted to either local scales (e.g. Büntgen *et al.*, 2010a; Seim *et al.*, 2012), occasionally to sub-regional scales (e.g. Richter *et al.*, 1991; Hughes *et al.*, 2001; Touchan *et al.*, 2014) or to one single species at larger scale (de Luis *et al.*, 2013). The only spatial field reconstruction for the Mediterranean was developed by Nicault *et al.* (2008) and addresses summer drought variability in a multi-species network over the past 500 years.

Here, we evaluate the growth-climate response of a substantial collection of 54 pine TRW site chronologies from mid- to high-elevations in the Mediterranean Basin. Regional growth patterns were identified using Principal Component Analysis (PCA) for the common period 1862-1976. New composite TRW chronologies were developed for three main and five sub-regions that were compared, assessed, and discussed with respect to possible causes for regional pine growth variability, prevailing synoptic climate forcing, and the potential for future drought reconstructions.

2. Data and methods

2.1 Network establishment

We compiled a network of 2186 TRW series from 54 pine sites across the Mediterranean region (**Figure 1** and Table S1, Supporting Information). Only chronologies spanning more than 200 years, with an inter-series correlation (R_{bar}) above 0.45, were considered (Table S1, Supporting Information). In total, 13 TRW chronologies were contributed by the authors, 39 TRW chronologies were selected from the ITRDB (International Tree-Ring Data Bank, <http://www.ncdc.noaa.gov/paleo/treering.html>, Grissino-Mayer and Fritts, 1997), and two chronologies, one from Greece and one from Italy, were kindly provided by P.I. Kuniholm and L. Todaro, respectively. The genus composition in this pine network includes *P. halepensis* var. *brutia* Hen., *P. heldreichii* Christ plus *P. heldreichii* var. *leucodermis* Ant., *P. mugo* Turra, *P. nigra* Arn., *P. sylvestris* L., and *P. mugo* spp. *uncinata* (Ramond) Domin.

Cross-dating of all TRW series was first visually checked and then statistically verified using the program COFECHA (Holmes, 1983). To preserve growth variation on inter-annual to multi-decadal time-scales, age-related growth trends were removed from all individual TRW series using 150-year cubic smoothing splines (150yr SPL) after power transformation (PT) (Cook and Peters, 1997), via the application of the program ARSTAN (Cook and Krusic, 2010). TRW chronologies were truncated at a minimum of five series. The robustness of the chronologies was evaluated by the Expressed Population Signal (EPS; Wigley *et al.*, 1984), which was calculated over 50-year periods with 25 years of overlap.

2.2 Instrumental data

A high-resolution ($0.5^\circ \times 0.5^\circ$) monthly resolved dataset of gridded climate indices (CRU TS3.1; Mitchell and Jones, 2005) was used to assess the climate sensitivity of the individual site chronologies. Temperature, precipitation and drought (scPDSI; van der Schrier, 2006) anomalies, with respect to their 1961-1990 averages, were calculated for the period 1901-2002 for each grid point closest to the TRW sites (Figure 1a). In a later step, the climate variables from individual grid points were averaged in correspondence with the outcome of

the PCA (see chapter 2.3). In our correlation analysis we used 31 grid boxes of temperature and precipitation data, and 30 grid boxes of scPDSI data because the latter were only available north of 35°N. The grand means of all Rbar values of annual temperature, precipitation, and scPDSI data across the network are 0.57 ($p < 0.001$), 0.21 ($p < 0.05$), and 0.26 ($p < 0.05$) respectively, indicating comparable temperature but heterogeneous moisture conditions across the region. Pearson's correlation coefficients were calculated between TRW records and means of monthly temperature, scPDSI, and sums of monthly precipitation, using an 18-month window from previous year's May to current October. Spatial correlations with CRU TS3.1 data were calculated and plotted using the KNMI Climate Explorer (<http://climexp.knmi.nl>; van Oldenborgh and Burgers, 2005; Trouet and van Oldenborgh, 2013).

2.3 Spatial analyses

We applied a PCA (Peters *et al.*, 1981) including 54 TRW site chronologies in order to identify systematic growth patterns inherent to the pine network over 1862-1976 common period. All principal components (PCs) with eigenvalues greater than one were retained for further analysis. The first PC was used to determine the primary climatic driver of common variance. Loadings along the second and third PC axes served as the basis for regional subdivision resulting in three main groups. This procedure was repeated using chronologies categorized by PC2 and PC3, which resulted in five additional subgroups (all labeled with respect to the PCA outcome as seen in Figure 3a). Composite chronologies were developed for the eight network groupings by averaging the individual TRW series of all sites in a group. Hierarchical cluster analysis (Ludwig and Reynolds, 1988) over the same common period was conducted to verify the PCA outcome (Figure S1, Supporting Information).

Potential differences and similarities in the temporal variability of the two main groups were investigated on the basis of 20-year high- and low-pass filtered composite TRW records.

Additionally, extreme years in year-to-year variability were defined as years when the absolute value of the high-pass filtered TRW records exceeded the 1.5 standard deviation. To evaluate the spatial decay in intra- and inter-species signal strength, correlations were computed as a function of distance between all sites in the network (54 TRW and 31 climatic grid points) for the 1862-1976 (TRW) and 1901-1976 (climate) periods. The same approach was used for temperature and precipitation grid point data for winter (previous year December to current year February, DJF) and summer (June to August, JJA). Finally, factors influencing tree growth were analyzed using cross-correlations including climatic and geographic aspects, as well as species and site chronology characteristics.

3. Results

3.1 Network characteristics and regionalization

The maximum and minimum length of the chronologies after truncation $n(i) < 5$ series is 1041 years (968-2008; Lura, Albania) and 142 years (1862-2003; Scotida Forest, Greece), (Figure 2 and Table S1, Supporting Information). The mean segment length (MSL) of all chronologies is 345 years after truncation. The number of samples per site varies from 11 (Troodos Mountain, Cyprus) to 200 (Gerber, Spain) with a mean of 41 (see Table S1, Supporting Information). The first 6 PCs (eigenvalue >1) of the entire network explain 62% of the total common variance (Figure 3). Similar results were obtained for the pre-whitened residuals (not shown), but we used standardized residuals throughout the experiment. The first PC alone (herein referred to as Med.) explains 19.7% of the common variance over the entire pine network. The network can be divided in three geographically distinct regions based on PC2 (representing 15% of the total variance): sites in the western Mediterranean region (Med. West) have negative loadings on PC2 (-0.57 to -0.09; Figure 3), whereas sites in the eastern Mediterranean region (Med. East) have positive loadings (0.15 - 0.66). Sites in Italy have PC2 loadings close to zero (-0.08 - 0.08) contributing to a third geographical group.

178 The Med West group consists of 32 site chronologies and the first three axes of a separate
 179 PCA of these 32 chronologies cumulatively explain 51.5% of their total variance. The first
 180 axis explains 29.5% common variance and all series have positive scores ranging from 0.3
 181 (Pic d'Anie, France) to 0.8 (Guadarrama, Loma de Noruego, Spain). The Med. West group
 182 can be subdivided based on PC2 (13.7%) representing chronologies from central Spain (Med.
 183 W1, 18 chronologies) and from the Pyrenees (Med. W2, 10 chronologies; Figure 3).
 184 The first three PCs of the Med. East (22 chronologies) explain a slightly higher amount of
 185 total common variance (63.6%) with the first axis explaining 39.7% common variance and
 186 positively loading scores ranging from 0.4 (Kozlu Pinari, Turkey) to 0.8 (Kirazli, Aligalani,
 187 Atalani, Turkey). Based on PC2 (15.8% common variance), two subgroups can be
 188 distinguished: Turkey and Cyprus (Med. E1) and the Southern Balkans (Med. E2).
 189 Based on the PC analyses, regional composite TRW chronologies were developed by
 190 aggregating the corresponding individual TRW series. All relevant statistics for the three
 191 regional groups and the five regional subgroups are shown in Table 1. Hierarchical cluster
 192 analysis revealed similar results by splitting the TRW network in 5 sub-groups including an
 193 individual Italian group (Figure S1, Supporting Information).
 194 The temporal coherency analysis between the detrended composite TRW chronologies Med.
 195 West and Med. East revealed limited common variability ($r = 0.1$, $p > 0.1$) over the well-
 196 replicated ($n > 800$ series) and robust 1330-2008 period (Figures 4a and 4b). This low
 197 coherence is confirmed in both the low and high frequency domains over three 338/339-year
 198 long correlation periods (1330-1669, 1500-1838 and 1669-2008) (Figure 4).
 199 Moreover, out of 42/46 positive/negative extreme years for West and 55/46 positive/negative
 200 extremes for East, only nine positive (1411, 1452, 1499, 1541, 1590, 1846, 1885, 1914, 1959)
 201 and five negative (1602, 1725, 1806, 1880, 1909) extreme years are in common. An
 202 association between the extreme years calculated for the West and East group is not evident at
 203 the 95% significance level ($P = 0.384$). The 14 common extreme years are also extremes in

the Med. chronology (PC1). From the total of 49/50 positive/negative extreme years for this chronology, 10/12 positive/negative extreme years are unique for the Mediterranean as a whole.

3.2 Spatial characteristics

Correlations of the 54 TRW chronologies as a function of species and distance, for the common period 1862-1976, are shown in Figure S2 (Supporting Information). The total number of pairs used in the intra-species curve is 583 and for the inter-species is 2239.

The highest positive intra-species correlation is $r = 0.58$ ($p < 0.001$) for neighboring sites, i.e., 65 chronology pairs within a range of 50 km (Figure S2a, Supporting Information). This association remains significant for up to 1500 km with a mean correlation coefficient of $r = 0.38$ ($p < 0.001$) despite the decreasing number of correlation pairs (average $n = 15$). Inter-species correlation results are similar to those for the same species despite higher replication levels (Figure S2b, Supporting Information). The highest positive correlation found is $r = 0.41$ in the first 50 km with a replication of 38 chronology pairs. Between 1700 and 3400 km the correlation coefficients settle around zero increasing slightly afterwards. The correlation decay length for both the inter- and intra-species results can be expressed using a second degree polynomial fit, with higher explained variance for the intra-species assembly ($R^2 = 0.56$, $p < 0.01$) than for the inter-species one ($R^2 = 0.23$, $p < 0.05$).

The corresponding climate data offer 930 correlation combinations over the 1901-1976 period for temperature means and precipitation sums, and 870 for scPDSI indices, for the winter (DJF) and summer (JJA) season (Figure S3, Supporting Information). The DJF and JJA temperatures (Figures S3a and S3b, Supporting Information) remained positively correlated over a longer distance and appear more homogeneous ($R^2 = 0.96 - 0.97$) than precipitation for the same two seasons ($R^2 = 0.62 - 0.66$) (Figures S3c and S3d, Supporting Information). Correlations between DJF temperatures are highly significant ($p < 0.001$) up to 2600 km and

JJA temperatures up to 1500 km. Precipitation sums for DJF and JJA exceed the 99.9% significance level up to the 600 km and 350 km range, respectively. The scPDSI correlations, between grid points dispersed over 4000 km, display similar patterns as found with precipitation (Figures S3e and S3f, Supporting Information).

3.3 Growth-climate responses

The growth-climate response for the Med. region, as a whole, shows significant negative correlations to summer temperature (May to September: $r = -0.31$, $p < 0.01$) and maximum positive correlations to June/July precipitation with $r = 0.4$ ($p < 0.01$) (Figure 5). Correlations with scPDSI were highest for July to September ($r = 0.23$; $p < 0.05$).

The climatic response of the Med. West and Med. East composite TRW chronologies differ strongly. The Med. West shows a generally weaker climate response than Med. East on both spatial and temporal scales (Figures 6 and 7). Med. East correlates positively with scPDSI (from June with $r = 0.28$ up to $r = 0.38$ for October, $p < 0.01$), whereas scPDSI correlations with Med. West are negative (June-October: $r = -0.12$, insignificant). Moreover, the seasonality of the climate response to scPDSI differs between the regions: summer (JJA: $r = 0.35$, $p < 0.01$) for Med. East versus spring (MAM: $r = -0.21$, $p < 0.05$) for Med. West. The distinct drought signal in the eastern TRW chronologies is supported by positive correlations with summer (JJA) precipitation ($r = 0.43$, $p < 0.01$) and negative correlations with summer temperatures ($r = -0.34$, $p < 0.01$). Although the growth response to JJA precipitation totals is significant over the entire 20th century, there is still a decrease in the obtained growth-climate relationship that occurred during the mid-1950s (Figure 6b).

Correlations between precipitation and temperature, and the western chronologies, were rarely significant (Figures 5 and 6). JJA temperatures produced strong negative correlations for Med. and Med. E in the eastern Mediterranean Basin, with extension towards Greenland,

whereas Med. W shows positive correlations across northern Spain and the Pyrenees stretching towards west – and central Europe (Figure 7a). Subgroups Med. W1 (central Spain) and Med. W2 (Pyrenees) reveal statistically insignificant growth-climate response patterns for precipitation and only Med. W2 shows a significantly positive association with temperature in May ($r = 0.28$; $p < 0.05$). Both subgroups yield significant negative correlations to scPDSI in the spring and summer season (April-July: $r = -0.22$, $p < 0.05$). This can be explained by favored tree growth under warm spring and summer conditions, especially for Med. W2 (Figure S4, Supporting Information). Italy forms a separate cluster based on the first PCA (Figure 3a), its correlation results correspond to those for the western Mediterranean. Most notable are the significant negative correlations with spring and summer scPDSI, reaching a maximum in April ($r = -0.24$, $p < 0.05$) (Figure S4, Supporting Information). Spatial field correlations for the JJA season, however, show significant ($p < 0.05$) positive associations with JJA temperature across the broader Mediterranean Basin and Europe (Figure S5, Supporting Information). Composite TRW chronologies Med. E1 (Turkey plus Cyprus) and Med. E2 (southern Balkans) show negative associations with summer temperatures of the previous as well as the current year, and positive associations with precipitation over the same time period (Figure S4, Supporting Information). The strongest correlations for Med. E1 were found with precipitation in May-August ($r = 0.44$, $p < 0.01$). Conditions limiting tree growth are thus found during hot and dry summers (May to August), represented by positive but weak correlations with scPDSI, that increase with decreasing latitude from $r = 0.11$ ($p > 0.1$) for Med. E2 to $r = 0.29$ for Med. E1 ($p < 0.01$). Spatial correlations for the JJA season are strongly significant for both sub-groups in the eastern Mediterranean and extend towards to south-eastern tip of Greenland, a pattern more distinct for Med. E1 than for Med. E2 (Figure S5, Supporting Information).

Overall, our results show that tree growth is controlled by a combination of temperature and precipitation variations in summer, expressed as a dipole growth response between the western and eastern Mediterranean. These differences are also visible at the composite TRW chronology level and at different frequencies (Figure 4).

4. Discussion

4.1 Temporal and spatial variability within the network

We found that the first PC axis explains close to 20% of the variance across the whole Mediterranean TRW network and indicates a common growth pattern across the Mediterranean. At lower hierarchical orders, the PCA yielded a strict division between the eastern and the western Mediterranean, but the position of the central Mediterranean, represented by Italy, remains unclear. Our results show a time-stable discrepancy between West and East Mediterranean sites over the last 700 years (1330-2008) at different temporal resolutions (Figure 4), which is also manifested in the very low number of common extreme years. The majority of positive extreme years, common to both Med. W and Med. E, can be related to volcanic eruptions (i.e., 1450±10 Kuwae, 1580+30 Billy Mitchel, 1845 Hekla, 1883 Krakatau, 1914 Sakurajima; Zielinski, 1995, Oppenheimer, 2003) which cause cooler climate over Europe (Esper *et al.*, 2013) and favorable growing conditions in the Mediterranean Basin.

Significant intra- and inter-species associations between TRW-chronologies are largely restricted to a 500 km range (Figure S2, Supporting Information). Nevertheless, we found potential connections over longer distances between a variety of pine species, e.g. *P. heldreichii* and *P. nigra*. In general, the intra-species associations were stronger with some stretching as far as 1500 km. Frank and Esper (2005) found a similar result for a multi-species TRW network in the Alps, as have Kuniholm and Striker (1987) for the Aegean. In the

western Mediterranean, Rolland (2002) found strong correlations between remote (> 500 km) *P. uncinata* stands and Richter *et al.* (1991) between four pine species up to 450 km distance. Mediterranean pine growth associations thus appear to mimic decreasing climatic association trends with increasing distance (Figure S3, Supporting Information). Inter-annual temperature variability shows strong homogeneity within a 2500 km radius (e.g., Jones *et al.*, 1997; Büntgen *et al.*, 2010b), but precipitation and summer drought patterns are more regionalized due to topography and continentality and show weaker connections beyond 500 km. It is worth noting that our analyses were based on grid point data (CRU TS3.1) intended to overcome the absence of long instrumental station data for some regions. These data do not necessarily fully represent local site conditions, particularly for mountain environments, because often is the case that the meteorological stations used to produce any given grid-point interpolation are not always local to that grid-point.

4.2 Climate sensitivity

Our comparison of the east and the west pine sites shows a minor elevational bias (Figure 8d), but elevation does not play a crucial role in the climate signal of the pine composite chronologies (Table S1 and Figure S4, Supporting Information). We found that pine growth at mid and high altitudes (1500 – 2250 m a.s.l.) has a drought or a mixed climate signal, whereas pines at the maximum elevation tree-line sites in the Pyrenees (2250- 2500 m a.s.l.) primarily respond to late spring - summer temperature (Table S1 and Figure S4, Supporting Information). It is important to note that we focused our analysis on strong climate signals in mid-to high elevation pines and thus have not considered the climate response of pine sites below 1500 m a.s.l. in our analyses.

Our Mediterranean TRW network is divided into biogeographically coherent sub-regions despite the potential lack of an evenly distributed network of sampling sites. This implies that environmental factors rather than species-specific influences dominate tree growth (Figure 8).

For instance, *Pinus nigra*, present in the east and west Mediterranean, shows a contrasting response to summer drought, which depresses tree growth in the western Mediterranean but promotes it in the East (Figure 8f). In general, trees in the western Mediterranean share a stronger common signal (explained common variance of 29.5%), but the growth-climate response is more moderate than for the eastern Mediterranean. The stronger common signal in the western pine chronologies can be explained by the smaller geographical range covered by those sites. The low climate sensitivity may be explained by ecological controls on growth: cooler temperatures at high elevations enhance temperature limitations on tree growth (e.g., in the Pyrenees) in addition to drought influences, leading to a mixed climatic response. At lower elevations evaporative demand and precipitation is generally lower whereas in dry regions drought predominantly constrains radial growth (e.g., in central Spain) (Figure S4, Supporting Information).

The western pines thus react negatively to drought and their growth-climate response pattern resembles that identified by Richter *et al.* (1991). These results are in accordance with earlier studies for the Pyrenees, where positive but weak and unstable correlations to summer temperatures were found (Tardif *et al.*, 2003; Büntgen *et al.*, 2010a). A higher diversity of growth-climate relations was found for central Spain. Gutiérrez *et al.* (1989) stated that drought at the beginning of the growing season (March) and in summer (June) affect *P. sylvestris* growth in southern Catalonia. *P. uncinata* from the central plains of Spain (Genova, 1986) and *P. nigra* from the eastern part of the Iberian Peninsula (Martín-Benito *et al.*, 2010) show a summer drought signal, that is further enhanced towards southern Spain (Richter *et al.*, 1991).

Summer drought is also the strongest climate signal in TRW records of the eastern Mediterranean region. The strength of the drought signal generally increases with decreasing latitude and increasing eastern longitude from the Balkans (Med. E2) to Turkey and Cyprus (Med. E1). A rather weak and unstable climate signal was observed in some regional studies,

especially for *P. heldreichii* at high elevation sites in the Balkan region (Panayotov *et al.*, 2010; Seim *et al.*, 2012). Further south, where the Mediterranean climate is more pronounced (Figure 1b), a strong positive influence of summer precipitation has resulted in numerous drought reconstructions derived from a variety of pine species (e.g., D'Arrigo and Cullen, 2001; Touchan *et al.*, 2003; Akkemik and Aras, 2005), and confirms the higher potential for TRW-based drought reconstructions using pines in the eastern rather than the western Mediterranean region. In more detail, Touchan *et al.* (2014) identified even sub-regional patterns and the high potential for seasonal climate reconstructions in a multi-species network study for the eastern Mediterranean.

A potential reason for the seasonal shift in climate response is the development of different strategies to compensate dehydration. Pines in Med. West need to adapt to drought conditions at the beginning of the growing season (spring/ early summer) while pines in Med. East are generally more stressed during summer (Figure 5). Evidence for structural adaption to drought is provided in a study of *P. sylvestris* along a north-south transect across Europe by Palmroth *et al.* (1999). Especially at mountain sites where shallow soils have a limited water storage capacity, water deficit during hot summers causes i) changes in the cell structure by increasing the cell lumen diameter to improve water conduction (Eilmann *et al.*, 2011), and ii) a general reduction in cell number leading to narrower tree rings especially at high altitudes (e.g., Gruber *et al.*, 2010).

4.3 Climate dynamic effects on mountain pine tree growth

The identified groupings of our pine TRW network can only be explained by differences in synoptic climate pattern across the Mediterranean. Mediterranean pine growth is mainly influenced by synoptic-scale patterns of summer drought, which is consistent with the first canonical mode of summer temperature data (1950-1999) across the Mediterranean region found by Xoplaki *et al.* (2003). During summer, insolation is increased, due to predominantly

383 clear skies, and a stable warm high pressure in the Mediterranean Basin (Xoplaki *et al.*,
384 2003).

385 Additionally, the second canonical mode found by Xoplaki *et al.* (2003) highlights differences
386 in climate between the western and the eastern Mediterranean, which supports the poor
387 agreement between our composite chronologies Med. East and Med. West (Figure 4 and 7) .

388 One reason for the east-west difference in summer climate lies in the influence of the East
389 Atlantic jet stream expressed by westerly winds, which have a stronger cooling effect in the
390 West compared to the East (Dükeloh and Jacobeit, 2003; Xoplaki *et al.*, 2003). Moreover,
391 both empirical and ensemble modeling evidence, based on an array of climate variables,
392 identified variability in the western Mediterranean that co-varies with the West African
393 Monsoon (Fontaine *et al.*, 2010). Finally, the summer North Atlantic Oscillation (sNAO) is a
394 strong driver of temperature variability in the eastern Mediterranean, but not in the West
395 (Folland *et al.*, 2009; Trouet *et al.*, 2012).

396 In addition to this, the oceanic-continental gradient ranging from Spain to Turkey is
397 interrupted by the Mediterranean Sea, a pool of permanent heat and vapor exchange, and by
398 regional winds such as the Westerly, Mistral or Sirocco. This leads to a complex
399 Mediterranean climate with multiple drivers, especially in summer (Pauling *et al.*, 2006).

400 Further reasons for spatial climate differences can be found in the Hadley circulation that
401 triggers the overturning of air masses in the troposphere and shows a descending motion in
402 the subtropics (Hadley, 1735). This circulation is strongly related to west-east jet streams
403 (tropopause-level westerlies) and varies seasonally (Dima and Wallace, 2003). In summer, the
404 Hadley cell moves northwards, towards eastern North Africa, and the impact of the Asian
405 monsoon in the mid-troposphere becomes stronger, particularly in the eastern Mediterranean
406 (Ziv *et al.*, 2004). According to Ziv *et al.* (2004), the Asian monsoon enhances the subsidence
407 of air masses over the east Mediterranean and enforces the Etesian winds equalizing low-level
408 pressure differences between the two regions. The prevailing low-pressure system across the

eastern Mediterranean is linked with high pressure areas in North-West, East but also in Central Europe (Arseni-Papadimitriou *et al.*, 1988; Luterbacher *et al.*, 2012). These linkages are confirmed by Ziv *et al.* (2004) for the sNAO, the leading eigenvector for July/August mean sea level pressure over the North Atlantic (Hurrell and Folland, 2002). Proxy evidence (1768-2008) for a teleconnection pattern between the Balkans and north-western Europe was found by Trouet *et al.* (2012), who developed a temperature reconstruction for Bulgaria (Balkan, eastern Mediterranean) using tree-ring maximum latewood density.

5. Conclusion

A Mediterranean pine network of 2186 individual TRW measurement series from 54 mid- to high-elevation sites was compiled and analyzed. The first PCA contains almost 20% of the total network variance, whereas higher order components demonstrate that tree-ring variability differs significantly between the West and East Mediterranean regions. The east-west dipole in pine growth is supported by the correlation decay of ~500km representing decreasing drought association trends with increasing distance. The climate-growth response of pines in the western part of the network is more moderate favoring warm temperatures in spring and early summer, especially in the Pyrenees, likely caused by site characteristics. By contrast the growth rates of pines in the East are higher under cold-wet conditions. Specific atmospheric circulation patterns and corresponding differences in climatic drivers likely cause the distinct, zonal, inter-annual to decadal-scale growth response patterns. Our results point to a larger potential for TRW-based drought reconstructions in the eastern Mediterranean region as opposed to the West, but demonstrate in general the challenges for climate reconstructions based on mid- to high elevation Mediterranean pines.

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Tables

Table 1. Characteristics of the newly developed composite TRW chronologies with combinations including the number of series per chronology, the start year, the robust period (EPS > 0.85) until the end year, the total length in years, the inter-series correlation (Rbar), the mean sensitivity and mean segment length (MSL).

Comp. TRW-chronology	Number of series	Start year	EPS > 0.85	End year	Length	Rbar (raw)	Mean Sensivity	MSL
Mediterranean	2186	617	1345	2008	1392	0.28	0.22	241
West	1271	924	1330	2008	1085	0.34	0.22	217
West without Italy	1167	924	1305	2008	1085	0.37	0.22	210
East	915	617	1295	2008	1392	0.39	0.22	276
Central Spain	474	1485	1590	2008	524	0.41	0.24	230
Pyrenees	693	924	1330	2007	1084	0.48	0.19	196
Italy	104	1441	1525	2003	563	0.57	0.22	291
Pyrenees plus Italy	797	924	1330	2007	1084	0.42	0.20	208
Balkan	493	617	1295	2008	1392	0.48	0.21	312
Turkey plus Cyprus	422	1379	1555	2004	626	0.45	0.24	234

Figures

Figure 1. (a) Mediterranean TRW network of 54 pine sites and their closest grid-points (CRU TS3.1) (b) Seasonal temperature and precipitation (red and blue lines) variability averaged over the 1961-1990 period and obtained from the CRU TS3.1 data corresponding to the five main TRW network regions.

Figure 2. Replication of the TRW network in alphabetical country order and record lengths.

Each bar represents one individual chronology and colors represent different pine species.

Colors refer to chronologies' length after truncation < 5 series, whereas shadings denote their

full lengths.

Figure 3. (a) Scatter plots of the PCA of all sites (power transformed 150-year spline detrended TRW-chronologies) indicating the main principal components (PCs) Med. West and Med. East and their subgroups (Med. W 1, Med. W2 and Med. E1, Med. E2) for the common period 1862-1976. (b) Spatial distribution of the various PCs (main PCs as ellipse, subgroups in graduated colors) considering the tree species (symbols).

Figure 4. (a) Expressed population signal (EPS) and (b) replication for the (c) PT 150yr SPL detrended and the 20-year (d) low-pass and (e) high-pass filtered composite chronologies West (blue line) and East (red line) with individual (West: blue points; East: red points) and common (asterisks) extreme years. Correlations between West and East were obtained for 338/339-year time windows in grey, and in black for the robust 1330-2008 period.

Figure 5. Growth-climate response pattern between PT 150yr SPL detrended Med., Med. West and Med. East composite chronologies and averaged gridded temperature, precipitation and drought data (CRU TS3.1) calculated over the 1901-2002 periods using the 18 month window. Raw Rbar values are shown for each PC subset over their full length and red (dashed) lines indicate the (95%) 99% significance level.

Figure 6. 31-year running correlation of JJA (a) temperature, (b) precipitation and (c) scPDSI gidded data (CRU TS3.1) against composite TRW-chronology Med. (black), Med. West (blue) and Med. East (red) over the 1901-2002 period. Red (dashed) lines indicate the (95%) 99% significance level.

Figure 7. Spatial field correlations for composite TRW chronologies Med. (left), Med. W (center), and Med. E. (right) against JJA (a) temperature (CRU TS3.1) and (b) precipitation (CRU TS3.1) for the 1901-2002 periods.

Figure 8. JJA-scPDSI grid point correlations of each site computed against its respective (a) mean segment length (MSL), (b) average growth rate (AGR), (c) number of series, (d) elevation, (e) inter-series correlation, (f) species, (g) JJA-temperature means and (h) JJA-precipitation sums. R^2 describes the trend of a linear regression model. Please note changes in scales and inverse axes in (f).

681 **Table S1.** Site locations used in this study.

Country	Site name	Spec.	Lat. (N)	Long. (E)	Elev. (m asl)	Period	Length	Series	MSL	AGR	Rbar	Contributor	JJA Temp	JJA Precip
Albania	C. Partisan	PIHE	40.70	20.13	1900-2100	1405-2008	604	124	310	0.92	0.57	A. Seim	-0.21	0.06
Albania	Thethi	PIHE	42.42	19.77	1700-1900	1303-2007	705	54	275	0.94	0.54	A. Seim	-0.25	0.16
Albania	Lura	PIHE	41.80	20.23	1800-2000	617-2008	1392	124	397	1.02	0.53	A. Seim	-0.16	0.09
Bulgaria	Vihren Nat. Park	PIHE	41.77	23.38	1920	1721-1981	261	22	183	1.26	0.55	F. Schweingruber	-0.24	0.33
Bulgaria	Vihren Nat. Park	PIHE	41.75	23.43	2150	1206-2008	759	53	441	0.73	0.58	M. Panayotov	-0.15	0.22
Cyprus	Plano platres (humid)	PINI	34.90	32.90	1600	1742-1981	240	22	153	1.47	0.51	F. Schweingruber	-0.35	0.27
Cyprus	Plano platres (dry)	PIBR	34.90	32.90	1620	1703-1981	279	22	151	0.97	0.69	F. Schweingruber	-0.31	0.20
Cyprus	Troodos Mountains	PINI	34.92	32.88	1600	1594-1978	385	11	236	1.25	0.45	P.I. Kuniholm, C. Griggs	-0.35	0.21
Cyprus	Armiantos	PIBR	34.92	32.90	1550	1584-2002	419	33	419	0.96	0.62	R. Touchan, M. Hughes	-0.17	0.03
Cyprus	Armiantos	PINI	34.92	32.90	1640	1554-2002	449	38	321	0.93	0.54	R. Touchan, M. Hughes	-0.55	0.24
Cyprus	Chionistra	PINI	34.93	32.87	1770	1379-2002	624	44	332	0.74	0.61	R. Touchan, M. Hughes	-0.30	0.37
Greece	Scotida Forest, Kastoria	PINI	40.30	20.90	1500	1751-2003	253	42	100	1.74	0.51	P.I. Kuniholm, N. Riches	-0.41	0.42
Greece	Katara Pass, Metsovon	PILE	39.80	21.22	1750	1673-1981	309	22	215	1.31	0.58	F. Schweingruber	-0.37	0.29
Greece	Olympos Oros	PILE	40.08	22.42	2250	1583-1981	399	30	207	1.47	0.56	F. Schweingruber	-0.16	0.21
Greece	Grevena	PILE	39.92	21.17	1600	1243-2004	762	22	398	0.90	0.58	P.I. Kuniholm	-0.45	0.30
Italy	Aetna, Linguaglossa	PINI	37.78	15.05	1800	1773-1980	208	20	65	1.56	0.51	F. Schweingruber	0.03	-0.14
Italy	Camosciara e Monte Amaro	PINI	41.77	13.82	1550	1750-1987	238	16	184	0.93	0.52	F. Biondi	-0.34	0.04
Italy	Mt. Pollino, Serra di Crispo	PILE	39.43	16.23	2000	1441-1980	540	22	301	1.15	0.61	F. Schweingruber	0.04	0.04
Italy	Mt. Pollino, Serra di Crispo	PILE	39.93	16.20	2054	1464-2003	540	46	378	0.89	0.68	L. Todaro	0.21	-0.01
Pyrenees	France, Pic de sept Hommes	PIUN	42.29	2.25	2300	1798-2005	208	42	113	1.43	0.51	U. Büntgen	0.14	0.00
Pyrenees	France, Roc de Perches Blancas	PIMG	42.60	2.05	2100	1769-1977	209	22	169	1.23	0.57	F. Schweingruber	0.27	-0.18
Pyrenees	France, Eyne	PIUN	42.28	2.07	2400	1736-2004	269	83	126	1.18	0.49	U. Büntgen	0.29	0.05
Pyrenees	France, Pic d'Anie	PIMG	42.97	-0.73	1750	1659-1977	319	20	212	0.91	0.59	F. Schweingruber	0.15	0.01
Pyrenees	Spain, Hecho Puerto de Acher	PISY/ PIUN	42.80	-0.70	1625	1605-1985	381	30	196	1.19	0.53	K. Richter	0.09	0.10
Pyrenees	Spain, Sobrestivo	PIUN	42.42	0.06	2500	1499-2005	507	58	233	0.75	0.48	U. Büntgen	-0.04	0.10
Pyrenees	Spain, Port de Cabus	PIUN	42.32	1.25	2450	1377-2005	629	42	213	0.72	0.55	U. Büntgen	-0.08	0.08
Pyrenees	France, Lac d'Aumer	PIUN	42.51	0.09	2400	1324-2005	682	82	173	0.97	0.57	U. Büntgen	0.14	0.09
Pyrenees	Spain, Cabanas	PIUN	42.36	1.01	2400	1186-2007	822	114	248	0.66	0.54	U. Büntgen	0.14	0.14
Pyrenees	Spain, Gerber	PIUN	42.38	0.59	2400	924-2005	1082	200	209	0.80	0.54	U. Büntgen	0.14	0.19
Spain	Navafria II	PISY	41.02	-0.12	1630	1791-1992	202	28	152	1.48	0.64	I. Yuste Herederu	0.16	0.05
Spain	Navafria III	PISY	41.02	-0.12	1525	1787-1992	206	24	150	1.67	0.69	I. Yuste Herederu	0.05	0.02
Spain	Penota	PISY	40.67	-0.33	1650	1763-1991	229	18	185	1.64	0.55	A. Fernandez-Cancio, M. Genova Fuster	-0.07	-0.04
Spain	Guadarrama, Iniesto	PISY	40.80	-3.98	1800	1749-1983	235	39	174	1.52	0.55	K. Richter	-0.20	-0.01
Spain	Guadarrama, Camorca	PISY	40.82	-4.05	1550	1726-1983	258	27	138	1.30	0.63	K. Richter	-0.16	0.02
Spain	Pedrizza	PISY	40.70	-4.20	1650	1715-1988	274	14	189	1.30	0.56	M. Genova Fuster, A. Fernandez-Cancio	-0.04	0.20
Spain	Andrinal	PINI	40.43	-4.93	1500	1687-1989	303	12	221	1.18	0.58	M. Genova Fuster	-0.05	0.07
Spain	Navafria I	PISY	40.02	-0.12	1900	1685-1992	308	31	188	1.31	0.53	I. Yuste Herederu, A. Fernandez-Cancio	0.26	0.05
Spain	Guadarrama, Loma de Noruego	PISY	40.78	-3.80	1950	1661-1985	325	26	186	1.44	0.54	K. Richter	-0.03	0.05
Spain	Tajo	PINI	40.87	-2.13	1750	1610-1988	379	16	205	1.24	0.62	M. Genova Fuster, A. Fernandez-Cancio, A. Perez Antelo	-0.04	0.39
Spain	Guadarrama, Rascafría	PISY	40.80	-3.95	1850	1599-1984	386	23	234	1.29	0.56	K. Richter	0.00	0.06
Spain	Puerto Llano	PINI	37.82	-2.95	1800	1585-1985	401	26	323	0.95	0.67	K. Richter	-0.22	0.19
Spain	Puerto da Navacerrada	PISY	40.80	-4.03	2050	1534-1976	443	22	183	1.51	0.49	F. Schweingruber	0.16	-0.04
Spain	Valsain (VA)	PISY	40.79	-4.04	1800-1900	1554-2008	455	74	328	0.86	0.52	L. Fernandez Donado	0.06	-0.09
Spain	Peñalara (RU)	PISY	40.79	-4.04	1850	1551-2008	458	31	201	1.10	0.53	L. Fernandez Donado	0.09	0.04
Spain	Siete Picos	PISY	40.87	-4.10	1950	1527-1988	462	22	326	0.83	0.54	M. Genova Fuster, A. Fernandez-Cancio	0.17	-0.06
Spain	Riscopel	PINI	40.78	-4.00	1600	1523-1988	466	24	241	1.08	0.68	M. Genova Fuster, A. Fernandez-Cancio	-0.03	0.28
Spain	Torreton	PINI	40.18	-2.08	1500	1485-1988	504	17	406	0.71	0.60	M. Genova Fuster, A. Fernandez-Cancio, A. Perez Antelo	0.00	0.26
Turkey	Kirazli	PINI	39.33	29.08	1650	1794-2002	209	38	175	0.91	0.65	R. Touchan, M. Hughes	-0.29	0.41
Turkey	Aligalani	PINI	39.27	28.85	1650	1771-2002	232	23	162	1.12	0.58	R. Touchan, M. Hughes	-0.22	0.42
Turkey	Kirazli, Aligalani, Atalani	PINI	39.28	28.93	1600	1771-2004	234	79	173	1.02	0.57	R. Touchan, M. Hughes	-0.29	0.45
Turkey	Kozlu Pinari	PINI	36.65	32.20	1633	1586-2000	415	25	295	1.10	0.52	R. Touchan, M. Hughes	-0.25	0.19
Turkey	Around Alanya-Cevizli	PINI	37.50	32.50	1500	1567-1995	429	36	280	0.80	0.45	Ü. Akkemik	-0.43	0.36
Turkey	Aziyiye	PINI	37.42	30.28	1601	1511-2001	491	35	204	1.38	0.52	R. Touchan, M. Hughes	-0.25	0.40
Turkey	Circitepe	PINI	37.63	35.43	1500	1475-2001	527	17	390	0.58	0.60	R. Touchan, M. Hughes	-0.32	0.23

Figure S1. Dendrogram using average linkage between groups (Pearson correlation) for the period 1862 – 1976 AD.

Figure S2. Individual correlations (grey points and triangles) and their averages over 100 km distance classes lagged by 50 km (black points and triangles) and the corresponding replication (black lines) for a) within species (grey triangles) and b) between species (grey circles). Red dashed lines indicate the 99.9% significance level and R^2 describes the explained variance of a second degree polynomial regression model.

Figure S3. Individual correlations (grey points) and their averages over 100 km distance classes lagged by 50 km (black points) and the corresponding replication (black lines) for a) DJF and b) JJA temperature means, c) DJF and d) JJA precipitation amounts and e) DJF and f) JJA scPDSI values (CRU TS3.1). Red dashed lines indicate the 99.9% significance level and R^2 describes the explained variance of a second degree polynomial regression model.

Figure S4. Growth-climate response patterns between PT 150yr spline detrended subgroup chronologies and averaged gridded temperature, precipitation and drought data (CRU TS3.1) calculated over the 1901-2002 periods using the 18-month window. Raw Rbar values are shown for each PC subset and red (dashed) lines indicate the (95%) 99% significance level.

Figure S5: Spatial field correlations of sub-group composite TRW chronologies against JJA temperature (left) and precipitation (right; CRU TS3.1) for the 1901-2002 periods.