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RESPONSE

Tree-rings and people – different views on the 1540 Megadrought. Reply to Büntgen et al. 2015

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Büntgen et al. (2015; hereinafter B15) present the result of new research which question the results of Wetter et al. 2014, (hereinafter W14) and Wetter et al. (2013, hereinafter W13) regarding European climate in 1540. B15 conclude from tree-ring evidence that the results based on documentary data of W14 "probably overstated the intensity and duration of the 1540

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drought event." W14 termed it "Megadrought" because of its extreme duration and spatial extent compared to other drought events in central Europe, although they note that the term is generally used for decadal rather than for single-year droughts (Seneviratne et al. 2012).

We take the opportunity to recall the following issues. Firstly, when dealing with drought the complexity of this phenomenon should be kept in mind. Meteorological drought defined as a large negative precipitation anomaly during a certain period can trigger agricultural, hydrological, groundwater and socioeconomic droughts. Lloyd-Hughes (2013 and references cited herein) concluded that any workable objective definition of drought does not exist. To quantify

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droughts, various indices based on precipitation, temperature and evapotranspiration are used such as the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Z- index and PDSI. Their calculation depends on different periods (seasons, combination of months) and so different indices may classify the same drought episode differently (e.g. Brázdil et al. 2014).

Secondly, there is no mention in W14 of an "inability of natural proxy archives to record climate extremes," as claimed in B15. Rather, W14 state "Palaeo-climatic evidence of the natural archives, such as tree-rings or grape harvest dates, may fail to detect record-breaking climatic outliers, whereas archives of society usually describe them in most accurate detail." In general human observations deal with weather, not climate, and distinguish between effects of temperature and precipitation on time-scales of days, weeks and months. Such detailed

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information is needed for decision-making on preventive measures to be taken about low probability outcomes with large consequences, as adaptation is place- and context specific (IPCC SPM-1 2014).

Our reconstruction of the 1540 Megadrought is supported by four different kinds of evidence. The first type consists of the direct mention of drought by more than 300 contemporary chroniclers originating from Austria, Belgium, the Czech Republic, England, France, Germany, Hungary, Italy, the Netherlands, Poland, Romania, Slovakia, Spain, Sweden and Switzerland, who report the number and the temporal distribution of days with precipitation or short rain-spells in that year. These memories retained risk information of extreme events for future generations in documents created for humans by humans, comprehensible to everyone, without recourse to sophisticated statistics. In 1540, chroniclers were concerned about the lack of precipitation and the consequent impacts, such as the extremely low levels of large rivers and lakes, the drying out of fountains, brooks and smaller rivers, the extreme soil desiccation, the depletion of groundwater resources, cattle dying from thirst, hunger and heat-stroke, and the withering of legumes, vines and trees, which are all described in detail. Reports about widespread forest fires raging from the Vosges Mountains (France) to the Carpathians (Hungary) are of particular significance for assessing the unique severity of heat and drought (W14).

The second type of documentary weather source is the records of local authorities concerning measures taken in the face of heat and drought. A third source is the weather diary kept by Cracow University rector Marcin Biem. His daily records were used to statistically reconstruct precipitation for Cracow for 1540 (W14). For the core region of the drought, i.e. Eastern France, Switzerland, Southern Germany, the Czech Republic and Northern Italy, consistent documentary evidence is available on meteorological, hydrological, hydrogeological, agricultural and socio-economic drought. Finally, spring-summer (AMJJ) temperatures in 1540 were assessed from a new series of grape harvest dates (1444–2011) for Switzerland including phenological observations on the early maturity of grapes (W13).

We consider that the manifold pieces of the climatic puzzle for 1540 provided by documentary evidence, scattered over a space of 2 to 3 million km^2, fit perfectly together, providing a coherent picture of the large-scale weather situation. Likewise, the rain-day evidence from Switzerland and Poland used to assess seasonal precipitation in 1540 yields results in the same order of magnitude (W14). Results of the documentary index-based reconstruction of temper-

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ature for Central Europe (Dobrovolný et al. 2010) and reconstruction of precipitation for the Czech Lands since 1500 (Dobrovolný et al. 2015) confirm the picture. 1540 stands out as being the driest of the 510 summers from 1501 to 2010 as well as the driest year in the territory of the Czech Lands. The year 1540 was also the warmest in the Central Europe temperature series (Table 1).

The heat of summer 1540 ranks only behind that of 2003 in central Europe, but it should be kept in mind that the maxima/minima of documentary temperature indices are limited to departures of +/−1.8 standard deviations from normal (Dobrovolný et al. 2010). Therefore, they are not well suited to indicate outstanding temperatures. Finally, the combination of extreme heat and drought is physically consistent considering the role of soil moisture deficits for the generation of heat waves (e.g. Seneviratne et al. 2010; Müller and Seneviratne 2012).

It should be noted that observers from Germany report several days of rainfall after 10 August (Gregorian style), which caused floods in the Main, middle Rhine, Elbe and Danube River systems (Glaser et al. 2010, data from tambora.org). No flood is reported from the Austrian Danube catchment (Rohr 2007). This spell of rain may have provided enough water to support continued growth in the trees in the regions concerned. Observers in Alsace and in Switzerland, however, report only a slight spell of rain for two or 3 days (W14). In general, this spell of rain may have broken the peak of the heat-wave, but drought set in again persisting until the end of the year.

Only a few papers (e.g. Büntgen et al., 2010, Büntgen et al. 2011a) compare extreme values, indicating both wet and dry conditions, between TRW (Tree Ring Width) and documentary or instrumental data. Results from these papers, complemented by data from Dobrovolný et al. (2014) were used in constructing Fig. 1, which shows the top twenty negative TRW deviations (indicating drought) from sampled sites in the region between France and Slovakia for each of the studies cited above. B11a, B11b and D14 only have 4 years in common: 1525, 1616, 1636 and 1653. The order of individual years in each chronology also varies. While there are some years with agreement between negative TRW and documentary or instrumental data, other years disagree or are inconsistent. Thus a general agreement in dry years is lacking. The question thus arises of to what extent extreme years derived from various TRW chronologies are representative and stable.

Büntgen et al. (2011b hereinafter B11b) used a large sample of "11,873 annually resolved and absolutely dated ring width (TRW) measurement series from fir (*Abies alba Mill.*) trees spanning the 962 to 2007 period across France, Switzerland, Germany and the Czech Republic." The authors compared 97 extreme departures in fir growth to temperature and precipitation indices and instrumental measurements for spring (MAM) and summer (JJA) from Germany, Switzerland and the Czech Republic. Negative TRW extremes mainly coincided with dry and temperate springs as well as dry and warm summers, while positive TRW

Table 1 Comparison of rank of 2003 temperature (warm) and precipitation (dry) springs, summers, autumns and years patterns in the Czech Lands with 1540 (Dobrovolný et al. 2010, 2015)

Year	Temp./ Prec.	MAM rank	JJA rank	SON rank	YEAR rank
1540	Temp	3rd	2nd	3rd	1st
1540	Prec	9th	1st	12th	1st
2003	Temp	18th	1st	169th	7th
2003	Prec	159th	28th	187th	40th

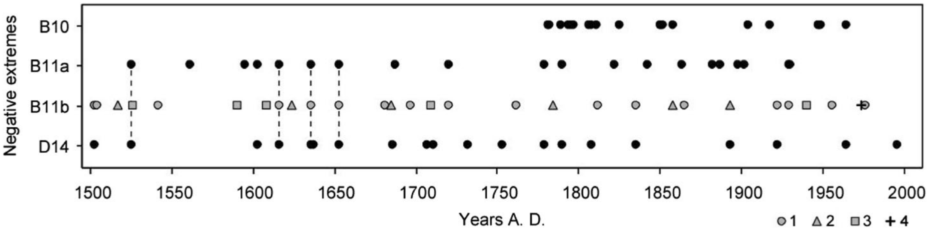

Fig. 1 Comparison of years with 20 most negative deviations in TRW series after AD 1500: B10 – Büntgen et al. (2010a), pine (*Pinus sylvestris*), Slovakia, JJA PDSI, 1744–2006; B11a – Büntgen et al. (2011a), fir (*Abies alba* Mill.), Southern Moravia, MJ Z-index, 1500–2007; B11b – Büntgen et al. (2011b), fir (*Abies alba* Mill.), Central Europe, A.D. 962–2007; D14 – Dobrovolný et al. (2014), oak (*Quercus sp*), Czech Lands, A.D. 1501–2010. Explanation for B11b: 1 (all) – France, Switzerland, Germany, Czech Lands; 2 – (West-Mid) France, Switzerland, Germany, 3 – (Mid-East) Germany, 4 – (West–east) Germany, Czech Lands

extremes matched cooler and wetter spring and summer conditions. Well-known hot and dry extremes such as 1616, 1636 and 1976 (B11b) show negative TRW extremes in all series, while in some years the response of the rings to the drought lags for 1 year (B11b, Table 1). Tree growth may integrate effects from previous year climatic and ecological conditions leading to lagged autocorrelations (Frank et al. 2007). An example of a lagged TRW is 1720, which followed the hot and dry year 1719 (e.g., Pfister 1999; Brázdil et al. 2013). A small TRW is also seen in 1541, which B11a interpreted as a response to the severe drought in 1540. They point out that "the response shift [to 1540] is well in line with the high first order auto-correlative structure of the fir TRW data." This large sample of fir TRW measurements therefore confirms the existence of an extreme heat and drought in 1540 (B11b), in contrast to the result from the recent study from a somewhat larger number of different tree species led by the same author (B15). Likewise, the tree-ring study by Nicault et al. (2006) supports the existence of an extreme drought in 1540 in the large Mediterranean land area (Fig. 2).

The Letter of B15 leads to a discussion of the much wider issue of whether the summer of 2003 was indeed the hottest since 735, as B06 concluded from their analysis of a regional alpine valley series. On this point, Jolly et al. (2005) found a divergent vegetation growth

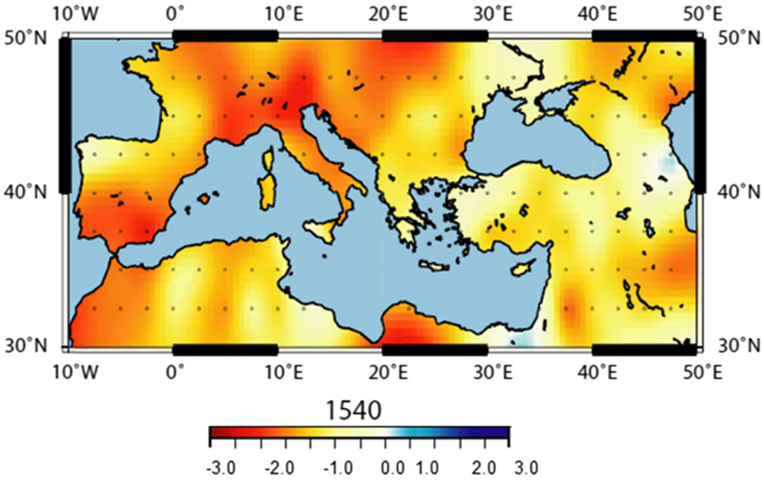

Fig. 2 Spatial pattern of PDSI over the Mediterrean basin for 1540 (Nicault et al. 2008)

response during the 2003 event in the Swiss Alps characterized by high elevation growth enhancement and low elevation growth suppression in response to the extreme summer temperatures and low-altitude drought conditions. Their result suggests that the top MXD value for 2003 in the B06 paper may well be related to both extremely high temperatures and a substantial availability of moisture whereas earlier hot summers in Switzerland were dry (BUWAL 2004). In considering these different interpretations we should not forget that tree-rings are the only evidence available to document low-probability, high-impact events prior to the High Middle Ages in western and central Europe, and much later in other regions of the world. A systematic comparison of tree-ring extremes with documentary and instrumental extremes in the overlapping period is thus needed to get a detailed understanding of the response of tree species to extreme heat and drought.

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