Clim. Past Discuss., 11, 3341–3373, 2015
www.clim-past-discuss.net/11/3341/2015/
doi:10.5194/cpd-11-3341-2015

Climate of the Past
Discussions
Open Access

Abrupt climate variability of eastern Anatolia vegetation during the last glacial

N. Pickarski[1], O. Kwiecien[2], D. Langgut[3], and T. Litt[1]

[1]University of Bonn, Steinmann Institute for Geology, Mineralogy, and Paleontology, Bonn, Germany
[2]Ruhr-University Bochum, Sediment and Isotope Geology, Bochum, Germany
[3]Tel Aviv University, Institute of Archaeology, Tel Aviv, Israel

Received: 24 June 2015 – Accepted: 6 July 2015 – Published: 22 July 2015

Correspondence to: N. Pickarski (pickarski@uni-bonn.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Detailed analyses of the Lake Van pollen and stable oxygen isotope record allow the identification of millennial-scale vegetation and environmental changes in eastern Anatolia throughout the last glacial. The climate within the last glacial period (~ 75–15 ka BP) was cold and dry, with low arboreal pollen (AP) levels. The driest and coldest period corresponds to Marine Isotope Stage (MIS) 2 (~ 28–14.5 ka BP) dominated by the highest values of xerophytic steppe vegetation.

Our high-resolution multi proxy record shows rapid expansions and contractions that mimic the stadial-interstadial pattern of the Dansgaard–Oeschger (DO) events as recorded in the Greenland ice cores, and thus, provide a linkage to North Atlantic climate oscillations. Periods of reduced moisture availability characterized at Lake Van by enhanced xerophytic species correlates well with increase in ice-rafted debris (IRD) and a decrease of sea surface temperature (SST) in the North Atlantic. Furthermore, comparison with the marine realm reveals that the complex atmosphere–ocean interaction can be recognized by the strength and position of the westerlies in eastern Anatolia. Influenced by rough topography at Lake Van, the expansion of temperate species (e.g. deciduous *Quercus*) was stronger during interstadials DO 19, 17–16, 14, 12 and 8. However, Heinrich events (HE), characterized by highest concentrations of ice-rafted debris in marine sediments, are identified in eastern Anatolia by AP values not lower and high steppe components not more abundant than during DO stadials. In addition, this work is a first attempt to establish a continuous microscopic charcoal record over the last glacial in the Near East, which documents an initial immediate response to millennial-scale climate and environmental variability and enables the shed light on the history of fire activity during the last glacial.

CPD

11, 3341–3373, 2015

1 Introduction

The last glacial inception was marked by the expansion of continental ice sheets and substantial changes in oceanographic conditions in the North Atlantic as well as in atmospheric temperature and moisture balance in the Northern Hemisphere (e.g. Chapman and Shackleton, 1999; Chapman et al., 2000; Rasmussen et al., 2014; Sánchez Goñi et al., 2005, 2002). Between Marine Isotope Stages (MIS) 5d and 2, the climatic conditions are characterized by numerous abrupt millennial-scale oscillations, known as Dansgaard–Oeschger events (DO; Blunier and Brook, 2001; Bond et al., 1993; Cacho et al., 1999; Dansgaard et al., 1993; Genty et al., 2003; Grootes et al., 1993; Shackleton et al., 2000; Svensson et al., 2006). These are most prominently documented in Greenland ice cores (NGRIP, 2004; Svensson et al., 2008) and exhibit abrupt warming (Greenland interstadials; GI), followed by a steadily cooling and a final rapid temperature drop into a cold Greenland stadial (GS; Sánchez Goñi and Harrison, 2010; Wolff et al., 2010). About 25 such stadial to interstadial transitions, varying in amplitude from 5 to 16 °C, are defined in the NGRIP record during the last glacial period (Rasmussen et al., 2014; Wolff et al., 2010). Although the climatic and environmental impacts of the DO cycles have been intensively studied over the last decades, the mechanism behind is still under debate (e.g. Cacho et al., 2000, 1999; Genty et al., 2003; Rasmussen et al., 2014; Wolff et al., 2010). Main process proposed as a cause for the recurring pattern is freshwater forcing from ice-sheets that affected sea ice extend, ocean heat transport, and Atlantic Meridional Overturning Circulation (AMOC; Bond and Lotti, 1995; Hemming, 2004; Hodell et al., 2008; McManus et al., 1999; Wolff et al., 2010). The most extreme cold intervals during GS are Heinrich Events (HE; Heinrich, 1988; Bond et al., 1992, 1993), characterized by reduced sea surface temperatures (SST; Cacho et al., 1999) with highest concentration of ice-rafted debris (IRD) in marine sediments due to massive iceberg discharges mainly from the Laurentide ice sheet (Alvarez-Solas and Ramstein, 2011).

Long-term pollen records from the central and eastern Mediterranean (e.g. Lago Grande di Monticchio, Italy; Tenaghi Philippon, Greece) demonstrate a clear vegetation response to millennial-scale climate variability. This region is highly sensitive to short-term vegetation changes as recognized by cold/dry steppe landscape prevailing during stadials and increased range of temperate tree taxa during interstadials (e.g. Allen et al., 2000, 1999; Langgut et al., 2011; Müller et al., 2011; Roucoux et al., 2005; Sánchez Goñi et al., 2002, 2000; Shumilovskikh et al., 2014). In contrast to southern Europe, however, highly-resolved and continuous terrestrial sedimentary records displaying abrupt climate oscillations are rare in the Near East.

Since the first long lacustrine sediment sequences were recovered at Lake Van in 2010 (Litt and Anselmetti, 2014; Litt et al., 2012), numerous high-resolution data has been gathered, providing insight into short-term changes in climate and environmental conditions in eastern Anatolia (e.g. XRF measurements by Kwiecien et al., 2014 and sediment color reflectance *b** by Stockhecke et al., 2014a). Sensitivity of this region was already well-documented by previous palynological data sets related to the Late Glacial and the Holocene (Litt et al., 2009; Wick et al., 2003). First palynological results of the new 119 m long composite profile encompassing the last ∼ 600 ka, has been described based at lower temporal resolution (between ∼ 900 and 3800 years; Litt et al., 2014). Detailed high-resolution pollen analysis for the last interglacial (between ∼ 100 and 800 year) is documented in (Pickarski et al., 2015).

In this study we present new biotic data (pollen, microscopic charcoal remains) and combine them with already available abiotic proxies (stable oxygen isotope and element measurements) of the last glacial interval between ∼ 110 and 10 ka BP. Special focus is given to the centennial-to-millennial climate variability, as known from Greenland, and its regional response on vegetation to abrupt paleoenvironmental changes in eastern Anatolia. Furthermore, we provide the first continuous sedimentary microscopic charcoal record to give insights into the coupling and feedbacks between fire activity and major changes in climate, vegetation type, and fuel amount during the last glacial.

CPD
11, 3341–3373, 2015

2 Regional setting

Lake Van (38.6° N, 42.8° E) is a deep terminal alkaline lake (max. depth > 450 m, surface area ∼ 3600 m^2), situated on the eastern Anatolian high plateau at 1647 m above sea level (a.s.l., Fig. 1). It is the largest soda lake in the world (Degens and Kurtman, 1978), which is partly fed by numerous small rivers around the basin. In the south, the lake is surrounded by Bitlis Massif reaching altitudes of more than 3500 m a.s.l. Two large active stratovolcanoes, Nemrut (2948 m a.s.l.) and Süphan (4058 m a.s.l.) border the lake to the west and north (Fig. 1b).

The present-day climate condition in eastern Anatolia is controlled by seasonal changes in the position and strength of the following atmospheric components: (a) the mid-latitude westerlies, (b) the sub-tropical high-pressure system and (c) the Siberian high-pressure system (Akçar and Schlüchter, 2005; Türkes, 1996). The regional climate at Lake Van is continental with warm and dry summers (mean temperature > 20 °C; Turkish State Meteorological Service) and cold winters, marked by regular frosts. The minimum average temperatures of the coldest month are far below 0 °C (−7.9 °C in Van; see Fig. 1b for the location). Total rainfall varies from 385 mm a^{-1} (Van) to 816 mm a^{-1} (Tatvan) and concentrates in the winter months (October to February), with a second rainfall maximum during spring (March to May). The higher elevations of the west–east oriented mountain ranges, along the Bitlis Massif (Fig. 1b), are affected by the strength and position of the "Cyprus cyclones" from the Mediterranean Sea with precipitation values up to 1200 mm a^{-1} in Bitlis (Turkish State Meteorological Service; Litt et al., 2014).

The modern distribution of vegetation at Lake Van is closely related to rough orographic and spatial rainfall variability. The southward slopes of the Bitlis Massif are covered by the Kurdo–Zagrosian oak steppe-forest (*Quercetea brantii*), which extends from Taurus Mountains (east-central Turkey) via the Bitlis complex (SW shore of Lake Van) to the Zagros Mountains (SW Iran; Zohary, 1973). It consists of several oak species along with *Pistacia atlantica, P. khinjuk, Acer monspessulanum, Juniperus*

CPD
11, 3341–3373, 2015

oxycedrus, Pyrus syriaca, Crataegus spp., *Prunus* and *Amygdalus* spp. (Frey and Kürschner, 1989). In the rain-shadow, where rainfall decreases drastically, the north-eastern part of the lake drainage is covered by Irano–Turanian steppe vegetation, dominated by *Artemisia fragrans*, steppe forbs and grasses (Zohary, 1973).

3 Material and methods

Sediment core "AR" (Ahlat Ridge; 38°667′ N, 42°669′ E; 357 m water depth) was collected on a bathymetric ridge in the northern part of the Tatvan Basin (Fig. 1b) during the ICDP (International Continental Scientific Drilling Program) project PALEOVAN in 2010 (Litt and Anselmetti, 2014; Litt et al., 2012). Here we present data of the uppermost 3.87–41.72 mcblf-nE (meters composite depth below lake floor-no event; depth scale excluding volcanic ash layers and mass flow deposits), representing the time span from 9.48 to 111.39 ka BP.

3.1 Chronology

The chronology of the Lake Van sedimentary sequence, encompassing the last glacial interval, is based on relative dating methods (synchronization of proxy data by using age control points) and radiometric dating techniques (e.g. radiocarbon ages). The age-depth modal as published in Stockhecke et al. (2014a) for this relevant interval is based on tuning with the GICC05-based NGRIP isotope data (0–116 ka; NGRIP, 2004; Rasmussen et al., 2006; Svensson et al., 2008; Wolff et al., 2010). Additionally, correlation with three $^{40}Ar/^{39}Ar$ dated onshore tephra layers was implemented in the age model of the composite profile, e.g. the Nemrut Formation (NF) at 32.70 ± 2.55 ka BP, the Halepkalesi Pumice (HP-10) fallout at 61.60 ± 2.55 ka BP as well as the Incekaya–Dibekli Tephra at ~ 80 ka BP (Stockhecke et al., 2014b; Sumita and Schmincke, 2013). Finally, the palaeomagnetic Laschamp excursion at ~ 41 ka BP (Vigliotti et al., 2014) could be identified in the core sequence.

CPD
11, 3341–3373, 2015

3.2 Palynology

In total, 216 sub-samples of 4 cm^3 wet sediments were taken at a sampling interval of 20 to 10 cm. In temporal terms, it represents a resolution from ~ 250 years (18.37–21.24 mcblf-nE) to about ~ 500 years (3.87–18.37 and 21.24–41.72 mcblf-nE; Fig. 2).

Pollen samples were processed using standard palynological techniques (Faegri and Iversen, 1993) including chemical treatment with cold 10 % HCL, hot 10 % KOH, cold 40 % HF, acetolysis and final sieving through 10 µm mesh size. In order to calculate the pollen and micro-charcoal (> 20µm) concentrations (grains; particles cm^{-3}), tablets of *Lycopodium clavatum* (Batch No. 483216, Batch No. 177745) were added to each sample (Stockmarr, 1971).

Pollen identifications were carried out to the lowest taxonomic level possible with reference of Beug (2004), Moore et al. (1991), Punt (1976), Reille (1999) pollen atlas as well as by using the pollen reference collections of the Steinmann-Institute, Department of Palaeobotany. Furthermore, we followed the taxonomic nomenclature after Berglund and Ralska-Jasiewiczowa (1986) and the detailed palynological investigation from the western Iran (Van Zeist and Bottema, 1977).

For making these pollen counts statistically representative, a minimum of ~ 500 identified pollen grains per sub-sample were counted for calculation of terrestrial pollen percentages (100 %), composed of arboreal pollen (AP) and non-arboreal pollen (NAP). Spores of algae, dinoflagellates and grains of aquatic taxa were excluded from the pollen sum. Percent calculation, cluster analysis to define pollen assemblage zones (PAZ), and construction of the pollen and charcoal diagram (Fig. 2) was carried out by using TILIA program (version 1.7.14; Grimm, 2011).

3.3 Stable isotope analysis

Lake Van carbonates consist of a mixture of calcite and aragonite precipitated in surface water. The oxygen isotopic record ($\delta^{18}O_{bulk}$) reflects regional climate changes as well as mainly local temperature variability. We selected 200 sub-samples at the same

CPD
11, 3341–3373, 2015

stratigraphic level, which were used for the pollen analysis (20 cm sampling resolution). The freeze-dried and ground sediment samples were analyzed at the University of Kiel using a Finnigan GasBenchII with carbonate option coupled to a DELTAplusXL IRMS. The isotope compositions are given relative to the VPDB standard in the conventional δ-notation and were calibrated against two international reference standards (NBS19 and NBS18). The standard deviation for reference analyses was 0.06 ‰ for $\delta^{18}O$.

Interpretation of the oxygen isotope record of lacustrine carbonates is complex as $\delta^{18}O_{bulk}$ can be influenced by a number of climate variables, such as air and water temperature, seasonality of precipitation, moisture source and precipitation-to-evaporation ratio. According to Litt et al. (2012, 2009) and Lemcke and Sturm (1997), at Lake Van, the $\delta^{18}O$ of carbonates is primarily controlled by evaporation processes. Furthermore, Kwiecien et al. (2014) and Pickarski et al. (2015) mention that changes in seasonal rainfall has a significant effect on lake water isotope values. During the last glacial, the oxygen isotope signature of carbonates is apparently heavier during interstadials and lighter during stadials (Fig. 3b)

3.4 Profiling measurements

Profiling measurements of the complete Lake Van profile (Ahlat Ridge) are published and described in detail by Kwiecien et al. (2014) as well as in the high-resolution study of the last interglacial period by Pickarski et al. (2015).

Here we present a Ca/K XRF record representing a ratio between authigenic carbonate precipitation and siliciclastic detrital input from the drainage (ratio presented in Figs. 3 and 4 are unitless; Kwiecien et al., 2014). In general, the Ca/K measurements show higher values ascribed to higher amount of authigenic carbonate during warmer periods (interstadials), and lower values related to increases detrital input during stadials (Kwiecien et al., 2014; Fig. 3c).

4 Results

4.1 Palynological results

The palynological data are presented in Fig. 2. This sequence can be divided into four pollen assemblage superzones (PAS IIa, IIb, IIIa, IIIb) following the criteria described in Tzedakis (1994), which were applied in Litt et al. (2014) for the low-resolution 600 ka long Lake Van pollen record. The PAS IIa and IIb can be further subdivided into six pollen assemblage zones (PAZ; Fig. 2) based on changes in the AP/NAP values and changes in the relative frequency of individual taxa. Main characteristics of each pollen zone and sub-zone as well as criteria for defining the lower boundaries are given in Table 1.

The pollen spectra vary between ~ 2000 and 40 000 grains cm^{-3}, dominating by herbs in particular by *Artemisia* (5–55 %), Chenopodiaceae (3–64 %) and Poaceae (6–35 %). Arboreal pollen percentages alternate between 0.5 and 67 %, in response to highly variable climatic conditions during the last glacial. The main tree taxa are document by *Pinus* (0–61 %) and deciduous *Quercus* (0–15 %), whereby the most indicative temperate taxon is deciduous *Quercus* characterized by relatively high percentages during interstadials.

4.2 Charcoal results

Microscopic charcoal concentrations vary between < 200 and ~ 15 000 particles cm^{-3} throughout the last glacial (Figs. 2 and 3d). In general, charcoal particles of a size commonly recorded from pollen slides reflect fire on a more regional scale (e.g. Clark et al., 1998; Tinner et al., 1998). Here, the Lake Van charcoal record can be divided into two distinct intervals: (i) the glacial/stadial interval, when global temperatures and terrestrial biomass were relative low, the charcoal particles concentration stay low (< 1000 particles cm^{-3}) and (ii) the early interglacial/interstadial interval, when global

CPD
11, 3341–3373, 2015

temperatures increased and vegetation changed, the charcoal record shows high concentrations (> 1000 particles cm^{-3}).

5 Discussion

5.1 Long-term vegetation dynamics at Lake Van

The long-term vegetation dynamics at Lake Van are characterized by several interstadial and stadial stages. According to Jessen and Milthers (1928) and Litt et al. (2014), interstadial stage indicates an interval of temporary improvement of climate conditions within a glacial phase, which have been either too short to permit full expansion of thermophilous trees or too cold to reach the climate optimum of an interglacial period in the same region. In comparison, stadial stages correspond to cold intervals marked not only by global but also by local ice re-advances (Lowe and Walker, 1984).

The relevance of insolation for the modern climate system has been widely studied by Berger (1978) and Berger et al. (2007). In particular, large-scale changes in the climate system would have affected regional and local atmospheric circulation patterns, for example, the strength and position of the westerlies in the Northern Hemisphere (Akçar and Schlüchter, 2005). Figure 3a shows that peaks in summer insolation lead to the onset of interglacial or pronounced interstadials, and therefore, to a spread of steppe-forest at Lake Van (Litt et al., 2014).

Below, we discuss only major interstadials during the early Weichselian (MIS 5c and 5a) and larger Dansgaard–Oeschger events such as DO 19, 17–16, 14, 12, 8 and 1. All "warm" phases, with favorable conditions for expansion of temperate trees, not explicitly mentioned in the following also corresponds to climate variability, but are small compared to the major changes.

5.1.1 MIS 5d-5a

The early phase of the last glacial (∼ 111–75 ka BP) is characterized by two pronounced interstadials (MIS 5a and 5c, Fig. 3). MIS 5c (Brørup interstadial; ∼ 108–87 ka BP) indicates low amplitude of temperate tree taxa (e.g. deciduous oak), reduced desert steppe vegetation, decreased detrital input (Fig. 3c) and commences with a short-lived episode of light $\delta^{18}O_{bulk}$ (−1.84 ‰, Fig. 3b). As a result of insolation, the onset of MIS 5c (between ∼ 108 to 105 ka BP) shows a similar positive deviation of the mid-June insolation as the last interglacial (MIS 5e; Berger, 1978; Berger et al., 2007; Litt et al., 2014; Pickarski et al., 2015). In this regard, Litt et al. (2014) have argued that positive summer temperature anomalies and negative winter temperature anomalies during the last interglacial lead to a strong continentality in the eastern Anatolia region. In accordance with the last interglacial (MIS 5e), the cold- and/or summer-dry adapted *Pinus* (Fig. 3e) predominates the interstadial (MIS 5c) between ∼ 103 and 87 ka BP (Litt et al., 2014; Pickarski et al., 2015). Additionally, changes in seasonal rainfall, inferred from the transition to a general positive oxygen isotope signature ($\delta^{18}O_{bulk}$ > 0 ‰ since ∼ 101 ka BP), have a decisive negative impact on moisture-requiring thermophilous plants such as deciduous oaks. Therefore, summer-green *Quercus* may occur in higher altitudes (for example at slopes of the Bitlis Massif) caused by increasing, orography related precipitation values (Litt et al., 2014). As a result, an open oak steppe-forest, which was predominant during the MIS 5e at Lake Van (Pickarski et al., 2015), did not become dominant at any time during the last glacial.

Interestingly, microscopic charcoal remains show that fire frequency has an initial immediate response to climate variability (Fig. 3d). According to previous studies for the Holocene (Wick et al., 2003) and the last interglacial sequences (Pickarski et al., 2015), enhanced global temperature and increased moisture availability, providing considerably more fuel for burning due to higher vegetation productivity (especially due to confiers within MIS 5c, Fig. 3d). During interstadials, the spread of warm-temperate grassland leads to a greater fire frequency (> 1000 particles cm^{-3}), whereas less mi-

CPD
11, 3341–3373, 2015

croscopic charcoal concentration (between 300 and < 850 particles cm^{-3}) characterizes an open dry desert steppe landscape (low vegetation density) during stadials (e.g. MIS 5b; Daniau et al., 2010; Fig. 3d).

Environment conditions of MIS 5a (Odderade interstadial; ∼ 85–77 ka BP) are difficult to resolved due to the eruption of the Incekaya-Dibekli volcano at ∼ 80 ka BP (Sumita and Schmincke, 2013). The fragmentary documentation of the vegetation signal, primarily due to the respective admixture of pyroclastic material (Stockhecke et al., 2014b), complicates the reconstruction of climate conditions at Lake Van. Nevertheless, the brief rising AP levels point to favorable climate conditions and increased moisture availability at the beginning of MIS 5a (Fig. 3e). In contrast to MIS 5b, the temporary warmer and wetter climate condition in eastern Anatolia promote a the expansion of an open grassland vegetation on low amplitude, consisting of Poaceae, deciduous *Quercus*, *Betula* and the sporadic occurrence of *Pistacia* cf. *atlantica* (Fig. 2, Table 1). *Pinus*, which was dominant during MIS 5c and MIS 5e, was reduced, and thus, is no longer growing in the vicinity of the lake (less than 4 % by general lower AP percentages, Fig. 3e). Warm-temperate species, such as deciduous oaks, show similar values as during MIS 5c. Nevertheless, the assumption of a regeneration of short-term warmer environmental conditions correlates well with the shift from depleted oxygen isotope signature (−1.90 ‰) to more positive values (1.81 ‰, Fig. 3b) associated with reduced precipitation and/or high evaporation. Furthermore, fire intensity relatively higher than during MIS 5b (charcoal concentration up to 2000 particles cm^{-3} ; Fig. 3d) as well as less detrital input (Fig. 3c) support the idea of advancing vegetation cover.

5.2 Abrupt climate changes during MIS 2–4

The general dominance of *Artemisia*, Chenopodiaceae and Poaceae in the glacial pollen spectra indicates a wide spread of arid desert steppe vegetation in eastern Anatolia between ∼ 75–12 ka BP (Figs. 2 and 3). This steppe vegetation evolves under pronounced continental climate with marked seasonal dryness (Allen et al., 2000;

CPD
11, 3341–3373, 2015

Kürschner and Parolly, 2012). In comparison, dry conditions in the northern drainage of Lake Van, with rainfall less than 300 mm a^{-1} (data provided by the Turkish State Meteorological Service), are the limiting factor for tree growth and at the same time promoting the expansion of well-adapted dwarf-shrubs steppe vegetation. The total absence of temperate species (e.g. *Ulmus*, *Carpinus* cf. *betulus*) and frost-sensitive taxa (*Pistacia* cf. *atlantica,* evergreen *Quercus*) suggest that woodlands as well as remnants of an oak steppe-forest are restricted to the refugia. Such refugias might be found at the southern foothills of the Bitlis glaciers, which receives moisture from the Mediterranean Sea. Furthermore, the south and south-east of the Black Sea Mountains (Euxinian vegetation) and the Caucasus mountains (Hyrcanian vegetation) serve as refugia due to increased atmospheric moisture and higher orographic precipitation from the Black Sea (Bottema, 1986; Leroy and Arpe, 2007; Shumilovskikh et al., 2012). Especially, the Black Sea region is characterized by mean winter temperatures close to or above 0 °C (Shumilovskikh et al., 2014).

During MIS 4, (~ 74–60 ka BP; PAZ IIb1-IIa4), the general decrease of arboreal pollen (1–14 %; mainly deciduous *Quercus* and *Pinus*) and high percentages of *Artemisia* and Chenopodiaceae reveal rather open landscape dominated by arid steppe vegetation. The predominance of xerophytic taxa, small variations in the tree pollen spectra (Fig. 3e), high input of detrital material (of fluvial and/or eolian origin; Fig. 3c), consistently positive isotope signature (~ 0.77 ‰ ; Fig. 3b) and decreasing charcoal concentration (from ~ 1700 to < 400 particles cm^{-3} ; Fig. 3d) indicate a gradual aridification and cooling in eastern Anatolia after 70 ka. In this regard, low midsummer insolation (Berger, 1978; Berger et al., 2007), increased global ice volume (Shackleton, 1987) and cooler SST (Cacho et al., 2000) combined with the atmospheric effects of a weakening AMOC (Böhm et al., 2015; Bond et al., 1993), would have contributed to a widespread aridity across the Mediterranean region (e.g. Kwiecien et al., 2009; Sánchez Goñi et al., 2002).

Within MIS 3 (~ 60–28 ka BP; PAZ IIa3–2), the most pronounced oscillations of arboreal pollen taxa, demonstrate repeated expansion and contraction of trees, suggesting

CPD
11, 3341–3373, 2015

an alternation of warmer, wetter interstadials and cooler, drier stadials. In particular, the short-term expansion of deciduous *Quercus* during larger interstadials (DO 19, 17–16, 14, 12 and 8; Fig. 4) points to a brief interruption of the general arid condition and marks intervals of short-term increased precipitation in the eastern Mediterranean region. From the evidence of the pollen record, we can infer direct influence of global ice sheet volume, triggered by the resumption of the AMOC and the associated strong increase in SST (Böhm et al., 2015; Bond et al., 1993; Cacho et al., 2000), which brought mild conditions from the North Atlantic over large parts of southern Europe (Allen et al., 1999; Fletcher et al., 2010; Müller et al., 2011; Sánchez Goñi et al., 2002).

The $\delta^{18}O$ signature supports the suggestion of favorable environment by the receipt of isotopically depleted meltwater supply and/or increased precipitation at the beginning of MIS 3 ($\delta^{18}O_{bulk}$ from −1.21 ‰ up to ~ 1 between ~ 57 and 54 ka BP; Fig. 3b). We propose that the interval of constantly heavier $\delta^{18}O_{bulk}$ values during DO 14 to 12 reflect higher evaporation at Lake Van. Furthermore, variability in Ca/K (Fig. 3c) and microscopic charcoal remains (Fig. 3b), both mechanically related to changes in vegetation cover documents the immediately response to rapid climate change. In summary, almost all interstadials at Lake Van can be linked with Greenland interstadials, and therefore to global climate changes. However, we have to recognize the occasionally large offsets of our proxy record to the NGRIP sequence (Fig. 4).

The onset of MIS 2 (~ 28–14 ka BP; PAZ IIa2) is characterized by very low AP percentages (0.5–12 %; Fig. 3e, Table 1), indicating an extreme arid, herb-dominated steppe vegetation (*Artemisia*, Chenopodiaceae and Poaceae). The fragmentary occurrence of deciduous *Quercus* (Figs. 2 and 3e), the total absence of moisture-requiring thermophilous plants such as *Carpinus* cf. *betulus* and *Ulmus,* and the increasing dominance of *Ephedra distachya*-type underline the extensive regional aridity without major climate fluctuations during the last glacial maximum (LGM at 21 ± 2 ka; Tzedakis, 2007) in eastern Anatolia. Over the MIS 2, especially between ~ 28 and ~ 21 ka BP, decreased fire frequency (Fig. 3d) is consistent with the fact that global climate was generally colder (e.g. maximum ice extent) and drier than present, leading to an overall

CPD
11, 3341–3373, 2015

reduction in terrestrial biomass production and thus a decrease in fuel availability. Low Ca/K (Fig. 3c) as well as a drop in $\delta^{18}O_{bulk}$ values (up to −1.6 ‰ ; Fig. 3b) supports the idea of wide open plains around Lake Van. In this context, insolation changes became the major driver, with regional climates responding to increased seasonal contrast in insolation (Fig. 3a; Grootes and Stuiver, 1997; Sánchez Goñi and Harrison, 2010; Wolff et al., 2010).

After the LGM, high mid-June insolation (Fig. 3a), decreasing global ice volume (Wolff et al., 2010), the resumption of the westerly activity, enhanced precipitation and locally rising temperatures promote an expansion of an oak steppe-forest at Lake Van (DO 1 at ∼ 14 ka BP; synonymous with the Bølling–Allerød warm period; Fig. 5b). However, the transition from the late-glacial interstadial to the current interglacial (Holocene) was interrupted by the short-term dry and cold Younger Dryas (YD) climate reversal between ∼ 12.8 to 11.6 ka BP (Litt et al., 2009; Wick et al., 2003). This event is well recognizable by the $\delta^{18}O_{bulk}$ peak (4.46 ‰ ; Fig. 3b), by the drop of the charcoal concentration (< 1000 particles cm^{-3} ; Fig. 3d), as well as by the rapid increase of arid desert steppe plants (up to 70 %; Fig. 2b). Further details of the late-glacial and early Holocene pollen record of Lake Van is not considered here, as vegetation and inferred environmental conditions have been presented in Litt et al. (2009) and Wick et al. (2003).

5.3 Heinrich Events

The high-frequency vegetation and environmental oscillations in the Lake Van pollen record show a reproducible pattern of centennial to millennial-scale alternation between DO interstadials and DO stadials (Fig. 5a; Dansgaard et al., 1993; Grootes et al., 1993; NGRIP, 2004; Sánchez Goñi and Harrison, 2010; Svensson et al., 2006; Wolff et al., 2010). This pattern origins from rapid oceanic changes, e.g. changes in the sea surface temperature, and changes in atmospheric circulations of the Northern Hemisphere (Cacho et al., 2000, 1999; Chapman and Shackleton, 1999; Sánchez Goñi et al., 2002). In the Lake Van record, stadials are characterized by a sharp decline of

CPD
11, 3341–3373, 2015

arboreal vegetation, indicating a reduction in the available moisture (Fig. 5b). The most pronounced DO stadials, more precisely, the stadials preceding DO 1, 4, 8, 12 and 17 refer to Heinrich events (HE) 1, HE 3, HE 4, HE 5 and HE 6 (Bond and Lotti, 1995; Bond et al., 1993; Heinrich, 1988). The reduction of oceanic heat transport (weakening or shut down of the AMOC; Bond and Lotti, 1995; Broecker, 1994; Cacho et al., 1999) led to significant cooler Mediterranean SST's and climate condition in this region (Allen et al., 1999; Müller et al., 2011; Sánchez Goñi et al., 2002; Tzedakis, 2005; Tzedakis et al., 2004). According to Kwiecien et al. (2009) decreasing atmosphere–sea surface thermal gradient of the Mediterranean Sea would have caused a reduction in the frequency and strength of storms tracks, which are responsible for an intensifying aridity in the Eastern Mediterranean region.

However, since tree population was already limited at Lake Van within the last glacial (low amplitude of AP values), the pollen signal is relatively insensitive to severe climatic deterioration such as Heinrich events. Minor drops in tree pollen do not necessarily reflect a minor climatic decline. Hence, both types of events, Heinrich events and Greenland stadials, lead to a similar massive reduction of tree taxa (especially by deciduous *Quercus*), and therefore cannot be clearly distinguish from an average cooling event (Fig. 5b). An exception may be provided by the HE 5 (~ 49 ka BP; Fig. 5a). This event, expressed by a collapse of AP taxa from 10 % to less than 2 % (Fig. 5b) as well as by a short-term detrital supply (Fig. 3c), shows that the impact of HE 5 was as cold/dry as the glacial maximum of MIS 4 between 60 and 70 ka BP.

6 Comparison with palynological records from the Mediterranean and Black Sea region

A regional comparison between Lake Van with pollen records from central (Lago Grande di Monticchio, Italy; Allen et al., 1999) and eastern Mediterranean region (Tenaghi Philippon, Greece; Müller et al., 2011), the south eastern Levantine Basin (Core 9509; Langgut et al., 2011), and from the Black Sea (Shumilovskikh et al., 2014,

2012) is presented in Fig. 5. Palaeoenvironmental investigation indicates a good match based on the similar main trends of the major vegetation elements. Climatic connections between the North Atlantic, Black Sea and different parts of the Mediterranean region are expressed by minima AP during stadials and by an increase of tree vegetation during interstadials (Fig. 5a). During the last glacial, slightly wetter climate conditions occurred between 53.6 and 45.2 ka (DO 14–12; Fig. 5b, grey bars) in the eastern Anatolia. According to Müller et al. (2011), this period was described as the North African Humid Period (NAHP; ca. 55–49 ka BP), where the anatomically modern humans (AMH) migrate from Africa over the Levant to Europe. During that time, climate conditions in eastern Mediterranean were more humid and mild as indicated by a quick shift from desert-steppe vegetation into semi-arid grassland at Lake Van (AP 10 %; Fig. 5b) and to open forest vegetation (AP up to 70 %, Fig. 5e) in the Tenaghi Philippon record (Müller et al., 2011). The marine pollen record from the south eastern Levantine basin (Fig. 5c) also points on increasing AP percentages during ~ 56.0 and 44.5 ka BP (Langgut et al., 2011).

However, there are some differences between the pollen records. More developed forest exists around the central and eastern Mediterranean Sea and the Black Sea compared to the Near East. Especially in southern European pollen records (e.g. Lago Grande di Monticchio and Tenaghi Philippon), thermophilous trees such as summergreen *Quercus* were frequently present even during stadials and increased rapidly during each interstadial without migrational lags (Fig. 5e and f; Fletcher et al., 2010; Müller et al., 2011; Tzedakis et al., 2002). At Lake Van, both the nature of migrational lags and low amplitude of variations in local temperate tree taxa (e.g. deciduous *Quercus*) suggest a greater distances from refugia, the decreasing effects of the cyclone activity from the Mediterranean Sea as well as due to their geographical location in higher elevation. These effects were also perceptible in the Levantine Basin due to minor fluctuations in the pollen spectra (Fig. 5c; Langgut et al., 2011). Moreover, it demonstrates a W–E vegetation gradient from an open temperate forest (including evergreen species) in the central Mediterranean (Müller et al., 2011) to less arid grassland to the Near East, where the availability of precipitation is the limiting factor for the establishment of an open oak steppe-forest. In summary, this moisture gradient reflects an increasing continental affect and decreasing influence of the Atlantic Ocean.

7 Conclusions

1. Our new palynological results show the climatic connection between Lake Van and the Atlantic Ocean. It reflects the complex underlying drivers of high frequency regional climate and environmental variability cause by seasonal insolation changes, ice sheet dynamics, and ocean circulation in the North Atlantic.

2. Comparison with Mediterranean and Black Sea pollen sequences demonstrate the decreasing moisture gradient along W–E Mediterranean due to increasing continental effect and reduction of the Atlantic Ocean impact.

3. Dansgaard–Oeschger cycles are clearly recognized in the Lake Van pollen record as well as in other abiotic proxies. Interstadials are characterized by the spread of temperate vegetation (e.g. deciduous *Quercus*), suggesting regional moisture availability. Stadials can be recognized by the dominance of steppe elements (e.g. *Artemisia*, Chenopodiaceae), pointing to cold and increasing aridity.

4. HEs cannot clearly distinguish from an average cooling event (stadials). They show a similar impact on vegetation and environment.

5. The supply of detrital material seems to have a direct response to changes in the vegetation composition, e.g. the terrestrial supply is low (high authigenic carbonate precipitation) when the vegetation cover in the catchment area is dense. In contrast, open landscape favors physical erosion including local detrital and dust input.

CPD
11, 3341–3373, 2015

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

6. Moreover, the fire frequency at Lake Van indicates an immediate link to climate changes, which is high when global temperature and regional moisture level increases, providing a higher terrestrial biomass production.

Acknowledgements. This study is a contribution to the Lake Van Drilling Project PALEOVAN funded by the International Continental Scientific Drilling Program (ICDP), the Swiss National Science Foundation (SNF) and the Scientific and Technological Research Council of Turkey (Tübitak). Financial support was provided by the German Research Foundation (DFG; LI 582/15-1-2). We thank the scientific PALEOVAN team for their support during the sample collection, and sharing of data. We kindly thank Ulla Röhl, Alex Wülbers and Hans-Joachim Wallrabe-Adams from the IODP Core Repository in Bremen (MARUM) for their help during the sampling campaign. We thank Nils Andersen and his working team at the Leibnitz-Laboratory for Radiometric Dating and Isotope Research for the measurements of the oxygen isotope samples. Special thanks go to Karen Schmeling and Beate Söntgerath for the pollen preparation, Manuela Rüßmann and Hannah Vossel for their support in the lab, and for his comments, and useful recommendations to improve the quality of this manuscript.

References

Akçar, N. and Schlüchter, C.: Paleoglaciations in Anatolia: a schematic review and first results, Eiszeitalter und Gegenwart, 55, 102–121, 2005.

Allen, J. R., Brandt, U., Brauer, A., Hubberten, H.-W., Huntley, B., Keller, J., Kraml, M., Mackensen, A., Mingram, J., and Negendank, J. F.: Rapid environmental changes in southern Europe during the last glacial period, Nature, 400, 740–743, doi:10.1038/23432, 1999.

Allen, J. R. M., Watts, W. A., and Huntley, B.: Weichselian palynostratigraphy, palaeovegetation and palaeoenvironment; the record from Lago Grande di Monticchio, southern Italy, EDLP – Med Special, 73–74, 91–110, doi:10.1016/S1040-6182(00)00067-7, 2000.

Alley, R. B., Meese, D. A., Shuman, C. A., Gow, A. J., Taylor, K. C., Grootes, P. M., White, J. W. C., Ram, M., Waddington, E. D., Mayewski, P. A., and Zielinski, G. A.: Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event, Nature, 362, 527–529, 1993.

Alvarez-Solas, J. and Ramstein, G.: On the triggering mechanism of Heinrich events, P. Natl. Acad. Sci. USA, 108, E1359–E1360, doi:10.1073/pnas.1116575108, 2011.

Berger, A.: Long-term variations of daily insolation and Quaternary climate changes, J. Atmos. Sci., 35, 2362–2367, doi:10.1175/1520-0469(1978)035<2362:LTVODI>2.0.CO;2, 1978.

Berger, A., Loute, M. F., Kaspar, F., and Lorenz, S. J.: Insolation during interglacial, in: The Climate of Past Interglacial, edited by: Sirocko, F., Claussen, M., Sánchez Goñi, M. F., and Litt, T., Elsevier, Amsterdam, 13–27, 2007.

Berglund, B. E. and Ralska-Jasiewiczowa, M.: Pollen anaylsis and pollen diagrams, in: Handbook of Holocene Palaeoecology and Palaeohydrology, edited by: Berglund, B. E., and Ralska-Jasiewiczowa, M., John Wiley and Sons, 455–484, 1986.

Beug, H.-J.: Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete, Pfeil, München, 2004.

Blunier, T. and Brook, E. J.: Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, Science, 291, 109–112, doi:10.1126/science.291.5501.109, 2001.

Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M. B., and Deininger, M.: Strong and deep Atlantic meridional overturning circulation during the last glacial cycle, Nature, 517, 73–76, doi:10.1038/nature14059, 2015.

Bond, G. C. and Lotti, R.: Iceberg discharges into the North Atlantic on millennial time scales during the Last Glaciation, Science, 267, 1005–1010, doi:10.1126/science.267.5200.1005, 1995.

Bond, G., Heinrich, H., Broecker, W. S., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S.: Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period, Nature, 360, 245–249, 1992.

Bond, G. C., Broecker, W. S., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G.: Correlations between climate records from North Atlantic sediments and Greenland ice, Nature, 365, 143–147, doi:10.1038/365143a0, 1993.

Bottema, S.: A late quaternary pollen diagram from Lake Urmia (Northwestern Iran), Rev. Palaeobot. Palyn., 47, 241–261, doi:10.1016/0034-6667(86)90039-4, 1986.

Broecker, W. S.: Massive iceberg discharges as triggers for global climate change, Nature, 372, 421–424, doi:10.1038/372421a0, 1994.

Cacho, I., Grimalt, J. O., Pelejero, C., Canals, M., Sierro, F. J., Flores, J. A., and Shackleton, N.: Dansgaard–Oeschger and Heinrich event imprints in Alboran Sea paleotemperatures, Paleoceanography, 14, 698–705, doi:10.1029/1999PA900044, 1999.

Cacho, I., Grimalt, J. O., Sierro, F. J., Shackleton, N. J. S., and Canals, M.: Evidence for enhanced Mediterranean thermohaline circulation during rapid climatic coolings, Earth Planet. Sc. Lett., 183, 417–429, doi:10.1016/S0012-821X(00)00296-X, 2000.

Chapman, M. R. and Shackleton, N. J.: Global ice-volume fluctuations, North Atlantic ice-rafting events, and deep-ocean circulation changes between 130 and 70 ka, Geology, 27, 795–798, doi:10.1130/0091-7613(1999)027<0795:GIVFNA>2.3.CO;2, 1999.

Chapman, M. R., Shackleton, N. J., and Duplessy, J.-C.: Sea surface temperature variability during the last glacial–interglacial cycle: assessing the magnitude and pattern of climate change in the North Atlantic, Palaeogeogr. Palaeocl., 157, 1–25, doi:10.1016/S0031-0182(99)00168-6, 2000.

Clark, J. S., Lynch, J., Stocks, B. J., and Goldammer, J. G.: Relationships between charcoal particles in air and sediments in west-central Siberia, Holocene, 8, 19–29, doi:10.1191/095968398672501165, 1998.

Daniau, A.-L., Harrison, S. P., and Bartlein, P. J.: Fire regimes during the Last Glacial, Quaternary Sci. Rev., 29, 2918–2930, doi:10.1016/j.quascirev.2009.11.008, 2010.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdottir, A. E., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250 kyr ice-core record, Nature, 364, 218–220, 1993.

Degens, E. T. and Kurtman, F.: The Geology of Lake Van, The Mineral Research and Exploration Institute of Turkey, Ankara, 1978.

Faegri, K. and Iversen, J.: Bestimmungsschlüssel für die nordwesteuropäische Pollenflora, Gustav Fischer, Jena, 1993.

Fletcher, W. J., Sánchez Goñi, M. F., Allen, J. R. M., Cheddadi, R., Combourieu-Nebout, N., Huntley, B., Lawson, I., Londeix, L., Magri, D., Margari, V., Müller, U. C., Naughton, F., Novenko, E., Roucoux, K., and Tzedakis, P. C.: Millennial-scale variability during the last glacial in vegetation records from Europe. Vegetation response to millennial-scale variability during the Last Glacial, Quaternary Sci. Rev., 29, 2839–2864, doi:10.1016/j.quascirev.2009.11.015, 2010.

Frey, W. and Kürschner, H.: Die Vegetation im Vorderen Orient. Erläuterungen zur Karte A VI 1 Vorderer Orient. Vegetation des "Tübinger Atlas des Vorderen Orients", Reihe A, Tübinger Atlas des Vorderen Orients, Wiesbaden, 1989.

CPD
11, 3341–3373, 2015

Genty, D., Blamart, D., Ouahdi, R., Gilmour, M., Baker, A., Jouzel, J., and Van-Exter, S.: Precise dating of Dansgaard–Oeschger climate oscillations in western Europe from stalagmite data, Nature, 421, 833–837, doi:10.1038/nature01391, 2003.
Grootes, P. M. and Stuiver, M.: Oxygen 18/16 variability in Greenland snow and ice with 103 to 105 year time resolution, J. Geophys. Res., 102, 26455–26470, doi:10.1029/97JC00880, 1997.
Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S., and Jouzel, J.: Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, Nature, 366, 552–554, doi:10.1038/366552a0, 1993.
Heinrich, H.: Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130 000 years, Quaternary Res., 29, 142–152, doi:10.1016/0033-5894(88)90057-9, 1988.
Hemming, S. R.: Heinrich events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint, Rev. Geophys., 42, RG1005, doi:10.1029/2003RG000128, 2004.
Hodell, D. A., Channell, J. E. T., Curtis, J. H., Romero, O. E., and Röhl, U.: Onset of "Hudson Strait" Heinrich events in the eastern North Atlantic at the end of the middle Pleistocene transition (~ 640 ka)?, Paleoceanography, 23, PA4218, doi:10.1029/2008PA001591, 2008.
Jessen, A. and Milthers, V.: Stratigraphical and paleontological studies of interglacial freshwater deposits in Jutland and Northwest Germany, Danmarks Geologiske Undersøgelse, 48, 1–379, 1928.
Kürschner, H. and Parolly, G.: The central Anatolian steppe, in: Eurasian Steppes. Ecological Problems and Livelihoods in a Changing World, Plant and Vegetation, edited by: Werger, M. J. A., and van Staalduinen, M. A., Springer, Heidelberg New York London, 149–171, 2012.
Kwiecien, O., Arz, H. W., Lamy, F., Plessen, B., Bahr, A., and Haug, G. H.: North Atlantic control on precipitation pattern in the eastern Mediterranean/Black Sea region during the last glacial, Quaternary Res., 71, 375–384, doi:10.1016/j.yqres.2008.12.004, 2009.
Kwiecien, O., Stockhecke, M., Pickarski, N., Heumann, G., Litt, T., Sturm, M., Anselmetti, F., Kipfer, R., and Haug, G. H.: Dynamics of the last four glacial terminations recorded in Lake Van, Turkey, Quaternary Sci. Rev., 104, 42–52, doi:10.1016/j.quascirev.2014.07.001, 2014.
Langgut, D., Almogi-Labin, A., Bar-Matthews, M., and Weinstein-Evron, M.: Vegetation and climate changes in the South Eastern Mediterranean during the Last Glacial–

CPD
11, 3341–3373, 2015

Abrupt climate variability of eastern Anatolia vegetation

N. Pickarski et al.

Interglacial cycle (86 ka): new marine pollen record, Quaternary Sci. Rev., 30, 3960–3972, doi:10.1016/j.quascirev.2011.10.016, 2011.
Lemcke, G. and Sturm, M.: δ^{18}O and trace element measurements as proxy for the reconstruction of climate changes at Lake Van (Turkey): preliminary results, in: Third Millennium BC Climate Change and Old World Collapse, NATO ASI Series, edited by: Dalfes, H. N., Kukla, G., and Weiss, H., Springer, Berlin Heidelberg, 653–678, 1997.
Leroy, S. A. G. and Arpe, K.: Glacial refugia for summer-green trees in Europe and south-west Asia as proposed by ECHAM3 time-slice atmospheric model simulations, J. Biogeogr., 34, 2115–2128, doi:10.1111/j.1365-2699.2007.01754.x, 2007.
Litt, T. and Anselmetti, F. S.: Lake Van deep drilling project PALEOVAN, Quaternary Sci. Rev., 104, 1–7, doi:10.1016/j.quascirev.2014.09.026, 2014.
Litt, T., Krastel, S., Sturm, M., Kipfer, R., Örcen, S., Heumann, G., Franz, S. O., Ülgen, U. B., and Niessen, F.: "PALEOVAN", International Continental Scientific Drilling Program (ICDP): site survey results and perspectives, Quaternary Sci. Rev., 28, 1555–1567, doi:10.1016/j.quascirev.2009.03.002, 2009.
Litt, T., Anselmetti, F. S., Baumgarten, H., Beer, J., Çagatay, N., Cukur, D., Damci, E., Glombitza, C., Haug, G., Heumann, G., Kallmeyer, J., Kipfer, R., Krastel, S., Kwiecien, O., Meydan, A. F., Orcen, S., Pickarski, N., Randlett, M.-E., Schmincke, H.-U., Schubert, C. J., Sturm, M., Sumita, M., Stockhecke, M., Tomonaga, Y., Vigliotti, L., Wonik, T., and the P. scientific team: 500 000 years of environmental history in eastern Anatolia: the PALEOVAN drilling project, Scientific Drilling Journal, 14, 18–29, doi:10.5194/sd-14-18-2012, 2012.
Litt, T., Pickarski, N., Heumann, G., Stockhecke, M., and Tzedakis, P. C.: A 600,000 year long continental pollen record from Lake Van, eastern Anatolia (Turkey), Quaternary Sci. Rev., 104, 30–41, doi:10.1016/j.quascirev.2014.03.017, 2014.
Lowe, J. J. and Walker, M. J. C.: Reconstructing Quaternary Environments, 2nd edn., Longman, Edinburgh, 1984.
McManus, J. F., Oppo, D. W., and Cullen, J. L.: A 0.5 million-year record of millennial-scale climate variability in the North Atlantic, Science, 283, 971–975, doi:10.1126/science.283.5404.971, 1999.
Moore, P. D., Webb, J. A., and Collinson, M. E.: Pollen Analysis, Blackwell Science, 1991.
Müller, U. C., Pross, J., Tzedakis, P. C., Gamble, C., Kotthoff, U., Schmiedl, G., Wulf, S., and Christanis, K.: The role of climate in the spread of modern humans into Europe, Quaternary Sci. Rev., 30, 273–279, doi:10.1016/j.quascirev.2010.11.016, 2011.

NGRIP: High-resolution record of Northern Hemisphere climate extending into the last interglacial period, Nature, 431, 147–151, doi:10.1038/nature02805, 2004.
Pickarski, N., Kwiecien, O., Djamali, M., and Litt, T.: Vegetation and environmental changes during the last interglacial in eastern Anatolia (Turkey): a new high-resolution pollen record from Lake Van, Palaeoecology, 435, 145–158, , 2015.
Punt, W.: The Northwest European Pollen Flora, Elsevier, Amsterdam, 1976.
Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E., and Ruth, U.: A new Greenland ice core chronology for the last glacial termination, J. Geophys. Res.-Atmos., 111, D06102, doi:10.1029/2005JD006079, 2006.
Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S. J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W. Z., Lowe, J. J., Pedro, J. B., Popp, T., Seierstad, I. K., Steffensen, J. P., Svensson, A. M., Vallelonga, P., Vinther, B. M., Walker, M. J. C., Wheatley, J. J., and Winstrup, M.: A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy, Quaternary Sci. Rev., 106, 14–28, doi:10.1016/j.quascirev.2014.09.007, 2014.
Reille, M.: Pollen et spores d'Europe et d'Afrique du nord, Laboratoire de Botanique Historique et Palynologie, Marseille, 1999.
Roucoux, K. H., de Abreu, L., Shackleton, N. J., and Tzedakis, P. C.: The response of {NW} Iberian vegetation to North Atlantic climate oscillations during the last 65 kyr, Quaternary Sci. Rev., 24, 1637–1653, doi:10.1016/j.quascirev.2004.08.022, 2005.
Sánchez Goñi, M. F., Cacho, I., Turon, J.-L., Guiot, J., Sierro, F. J., Peypouquet, J.-P., Grimalt, J. O., and Shackleton, N. J.: Synchroneity between marine and terrestrial responses to millennial scale climatic variability during the last glacial period in the Mediterranean region, Clim. Dynam., 19, 95–105, doi:10.1007/s00382-001-0212-x, 2002.
Sánchez Goñi, M. F. and Harrison, S. P.: Introduction: millennial-scale climate variability and vegetation changes during the Last Glacial: concepts and terminology, Quaternary Sci. Rev., 29, 2823–2827, doi:10.1016/j.quascirev.2009.11.014, 2010.
Sánchez Goñi, M. F., Turon, J.-L., Eynaud, F., and Shackleton, N. J.: Direct land/sea correlation of the Eemian, and its comparison with the Holocene: a high-resolution palynological record off the Iberian margin, Neth. J. Geosci., 79, 345–354, 2000.

Sánchez Goñi, M. F., Loutre, M. F., Crucifix, M., Peyron, O., Santos, L., Duprat, J., Malaizé, B., Turon, J.-L., and Peypouquet, J.-P.: Increasing vegetation and climate gradient in Western Europe over the Last Glacial Inception (122–110 ka): data-model comparison, Earth Planet. Sc. Lett., 231, 111–130, doi:10.1016/j.epsl.2004.12.010, 2005.

Shackleton, N. J.: Oxygen isotopes, ice volume and sea level, Quaternary Sci. Rev., 6, 183–190, doi:10.1016/0277-3791(87)90003-5, 1987.

Shackleton, N. J., Hall, M. A., and Vincent, E.: Phase relationships between millennial-scale events 64,000–24,000 years ago, Paleoceanography, 15, 565–569, doi:10.1029/2000PA000513, 2000.

Shumilovskikh, L. S., Tarasov, P., Arz, H. W., Fleitmann, D., Marret, F., Nowaczyk, N., Plessen, B., Schlütz, F., and Behling, H.: Vegetation and environmental dynamics in the southern Black Sea region since 18 kyr BP derived from the marine core 22-GC3, Palaeogeogr. Palaeocl., 337–338, 177–193, 2012.

Shumilovskikh, L. S., Fleitmann, D., Nowaczyk, N. R., Behling, H., Marret, F., Wegwerth, A., and Arz, H. W.: Orbital- and millennial-scale environmental changes between 64 and 20 ka BP recorded in Black Sea sediments, Clim. Past, 10, 939–954, doi:10.5194/cp-10-939-2014, 2014.

Stockhecke, M., Kwiecien, O., Vigliotti, L., Litt, T., Pickarski, N., Schmincke, H.-U., and Çağatay, N.: Chronology of the 600 ka old long continental record of Lake Van: climatostratigraphic synchronization and dating, Quarternary Sci. Rev., 104, 8–17, 2014a.

Stockhecke, M., Sturm, M., Brunner, I., Schmincke, H., Sumita, M., Kipfer, R., Cukur, D., Kwiecien, O., and Anselmetti, F. S.: Sedimentary evolution and environmental history of Lake Van (Turkey) over the past 600 000 years, Sedimentology, 61, 1830–1861, 2014b.

Stockmarr, J.: Tablets with spores used in absolute pollen analysis, Pollen et Spores, 13, 615–621, 1971.

Sumita, M. and Schmincke, H.-U.: Impact of volcanism on the evolution of Lake Van II: temporal evolution of explosive volcanism of Nemrut Volcano (eastern Anatolia) during the past ca. 0.4 Ma, J. Volcanol. Geoth. Res., 253, 15–34, doi:10.1016/j.jvolgeores.2012.12.009, 2013.

Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Parrenin, F., Rasmussen, S. O., Röthlisberger, R., Seierstad, I., Steffensen, J. P., and Vinther, B. M.: A 60 000 year Greenland stratigraphic ice core chronology, Clim. Past, 4, 47–57, doi:10.5194/cp-4-47-2008, 2008.

CPD
11, 3341–3373, 2015

Abrupt climate variability of eastern Anatolia vegetation

N. Pickarski et al.

Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Rasmussen, S. O., Röthlisberger, R., Peder Steffensen, J., and Vinther, B. M.: The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: Comparison to other records, Critical Quaternary Stratigraphy, 25, 3258–3267, doi:10.1016/j.quascirev.2006.08.003, 2006.

Tinner, W., Conedera, M., Ammann, B., Gaggeler, H. W., Gedye, S., Jones, R., and Sagesser, B.: Pollen and charcoal in lake sediments compared with historically documented forest fires in southern Switzerland since AD 1920, Holocene, 8, 31–42, doi:10.1191/095968398667205430, 1998.

Türkes, M.: Meteorological drought in Turkey: a historical perspective, 1930–1993, Drought Network News, 84, 1996.

Tzedakis, P. C.: Hierarchical biostratigraphical classification of long pollen sequences, J. Quaternary Sci., 9, 257–259, doi:10.1002/jqs.3390090306, 1994.

Tzedakis, P. C.: Towards an understanding of the response of southern European vegetation to orbital and suborbital climate variability, Quaternary Sci. Rev., 24, 1585–1599, doi:10.1016/j.quascirev.2004.11.012, 2005.

Tzedakis, P. C.: Seven ambiguities in the Mediterranean palaeoenvironmental narrative, Quaternary Sci. Rev., 26, 2042–2066, doi:10.1016/j.quascirev.2007.03.014, 2007.

Tzedakis, P. C., Lawson, I. T., Frogley, M. R., Hewitt, G. M., and Preece, R. C.: Buffered tree population changes in a quaternary refugium: evolutionary implications, Science, 297, 2044–2047, doi:10.1126/science.1073083, 2002.

Tzedakis, P. C., Frogley, M. R., Lawson, I. T., Preece, R. C., Cacho, I., and de Abreu, L.: Ecological thresholds and patterns of millennial-scale climate variability: the response of vegetation in Greece during the last glacial period, Geol. Soc. Am. Bull., 32, 109–112, doi:10.1130/G20118.1, 2004.

Van Zeist, W. and Bottema, S.: Palynological investigations in western Iran, Palaeohistoria Bussum, 19, 19–85, 1977.

Vigliotti, L., Channell, J. E. T., and Stockhecke, M.: Paleomagnetism of Lake Van sediments: chronology and paleoenvironment since 350 ka, Quaternary Sci. Rev., 104, 18–29, doi:10.1016/j.quascirev.2014.09.028, 2014.

Wick, L., Lemcke, G., and Sturm, M.: Evidence of Lateglacial and Holocene climatic change and human impact in eastern Anatolia: high resolution pollen, charcoal, isotopic and geo-

chemical records from the laminated sediments of Lake Van, Holocene, 13, 665–675, doi:10.1191/0959683603hl653rp, 2003.
Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O., and Svensson, A.: Millennial-scale variability during the last glacial: the ice core record. Vegetation response to millennial-scale variability during the Last Glacial, Quaternary Sci. Rev., 29, 2828–2838, doi:10.1016/j.quascirev.2009.10.013, 2010.
Zohary, M.: Geobotanical Foundations of the Middle East, Gustav Fischer Verlag, Swets & Zeitlinger, Stuttgart, Amsterdam, 1973.

CPD
11, 3341–3373, 2015

Abrupt climate variability of eastern Anatolia vegetation

N. Pickarski et al.

Table 1. Synoptic description of pollen assemblage superzones (PAS) and zones (PAZ).

PAS/ PAZ	Age (ka BP)	Criteria for lower boundary	Pollen assemblages (minimum–maximum in %)
IIa1	09.48–14.26	Occurrence of *Pistacia*; *Quercus* > 3 %	Chenopodiaceae (18–49 %) – Poaceae (6–33 %) – *Artemisia* (6–33 %) – *Ephedra distachya*-type (1–11 %) – dec. *Quercus* (0–6 %) – *Betula* (0–3 %) – *Pistacia* cf. *atlantica* (0–2 %) – *Juniperus* (0–1 %) – *Pinus* (0–2 %)
IIa2	14.26–44.80	Quercus < 2 %	Chenopodiaceae (23–60 %) – *Artemisia* (10–55 %) – Poaceae (7–26 %) – *Ephedra distachya*-type (0–7 %) – dec.*Quercus* (0–4 %) – *Pinus* (0–2 %) – *Betula* (0–1 %)
IIa3	44.80–59.50	Quercus > 2 %; Chenopodiaceae < 50 %	Chenopodiaceae (15–57 %) – *Artemisia* (12–37 %) – Poaceae (10–28 %) – dec. *Quercus* (0–5 %) – *Ephedra distachya*-type (0–3 %) – *Betula* (0–2 %) – Cyperaceae (0–2 %) – *Pinus* (0–2 %)
IIa4	59.50–67.72	Chenopodiaceae > 50 %	Chenopodiaceae (29–64 %) – *Artemisia* (12–31 %) – Poaceae (6–22 %) – *Betula* (0–1 %) – *Ephedra distachya*-type (0–1 %) – *Pinus* (0–1 %) – dec. *Quercus* (0–1 %)
IIb1	67.72–84.91	*Quercus* > 5 %; Chenopodiaceae < 50 %	*Artemisia* (16–40 %) – Chenopodiaceae (8–57 %) – Poaceae (7–35 %) – dec. *Quercus* (0–12 %) – *Pinus* (0–9 %) – *Betula* (0–5 %) – *Ephedra distachya*-type (0–2 %) – *Juniperus* (0–1 %)
IIb2	84.91–87.24	*Pinus* < 20 %; Chenopodiaceae > 50 %	Chenopodiaceae (44–62 %) – *Artemisia* (11–23 %) – Poaceae (7–12 %) – *Pinus* (0–16 %) – dec. *Quercus* (0–4 %) – *Betula* (0–1 %) – *Ephedra distachya*-type (0–1 %)
IIIa	87.24–102.67	*Pinus* > 20 %; Chenopodiaceae < 20 %	*Pinus* (7–61 %) – Poaceae (8–29 %) – *Artemisia* (5–25 %) – Chenopodiaceae (3–50 %) – dec. *Quercus* (3–15 %) – *Betula* (0–2 %) – *Alnus* (0–1 %) – *Ephedra distachya*-type (0–1 %) – *Juniperus* (0–1 %) – *Pistacia* cf. *atlantica* (0–1 %)
IIIb	102.67–111.70	Chenopodiaceae > 20 %	Chenopodiaceae (14–57 %) – Poaceae (8–22 %) – *Artemisia* (7–36 %) – dec. *Quercus* (1–9 %) – *Pinus* (0–22 %) – *Juniperus* (0–5 %) – *Betula* (0–4 %) – *Ephedra distachya*-type (0–3 %) – *Fraxinus* (0–1 %) – *Pistacia* cf.*atlantica* (0–1 %)

CPD
11, 3341–3373, 2015

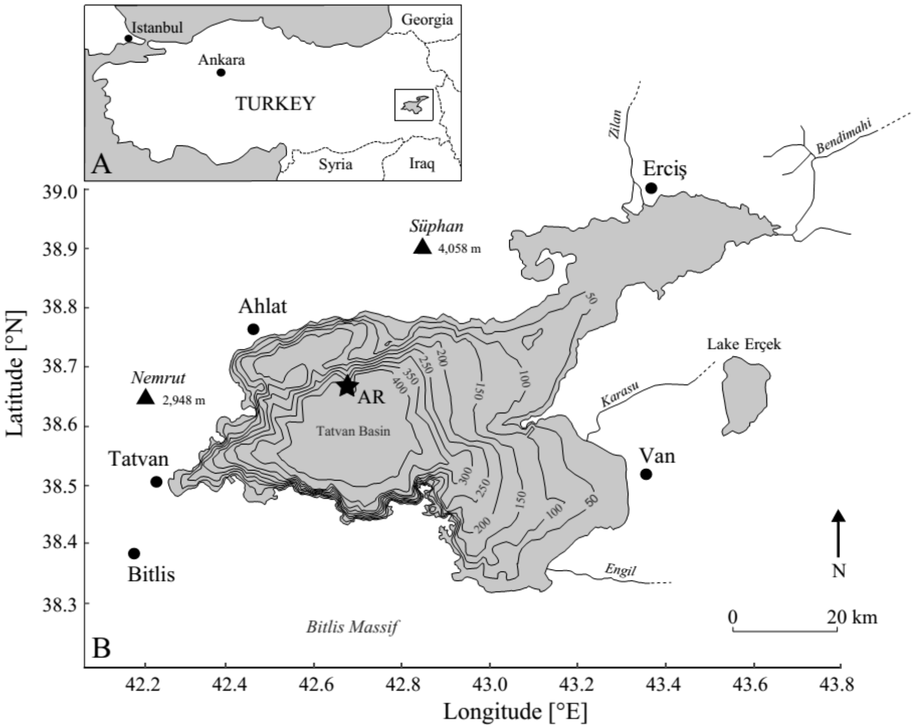

Figure 1. (a) Location of Lake Van in eastern Anatolia (Turkey) and **(b)** the bathymetry of Lake Van including the main ICDP drill site Ahlat Ridge (AR, black star). Major cities (black dots) and rivers are represented. The black triangle indicates the positions of the active volcanoes Nemrut and Süphan. The Bitlis Massif in the south towers up to 3500 m a.s.l.

CPD
11, 3341–3373, 2015

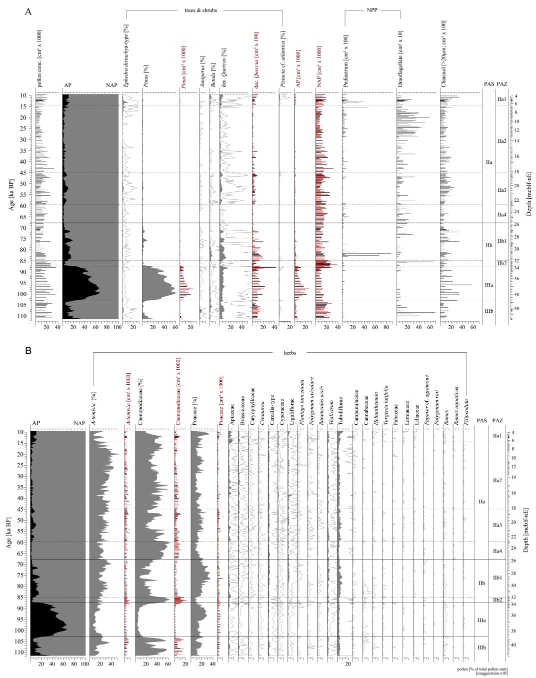

Figure 2. Pollen diagram for the analyzed last glacial period from the Ahlat Ridge composite profile plotted against age (ka BP) and depth (mcblf-nE; meter composite below lake floor-no Event). **(a)** Selected arboreal pollen (AP) taxa in percent (gray) including arboreal/non-arboreal ratio (AP/NAP) as well as selected pollen concentration [grains cm^{-3} in red bars] of the most important taxa discussed in the text; charcoal particles [cm^3 × 100] and non-pollen palynoporphs (NPP) such as Pediastrum [cm^3 × 100] and dinoflagellates [cm^3 × 10] are shown in black bars; **(b)** selected non-arboreal pollen percentages as well as pollen concentration. An ×10 exaggeration line (gray) of the horizontal scale is used to show changes in low percentages. PAS – Pollen assemblage superzone; PAZ – Pollen assemblage zone.

CPD
11, 3341–3373, 2015

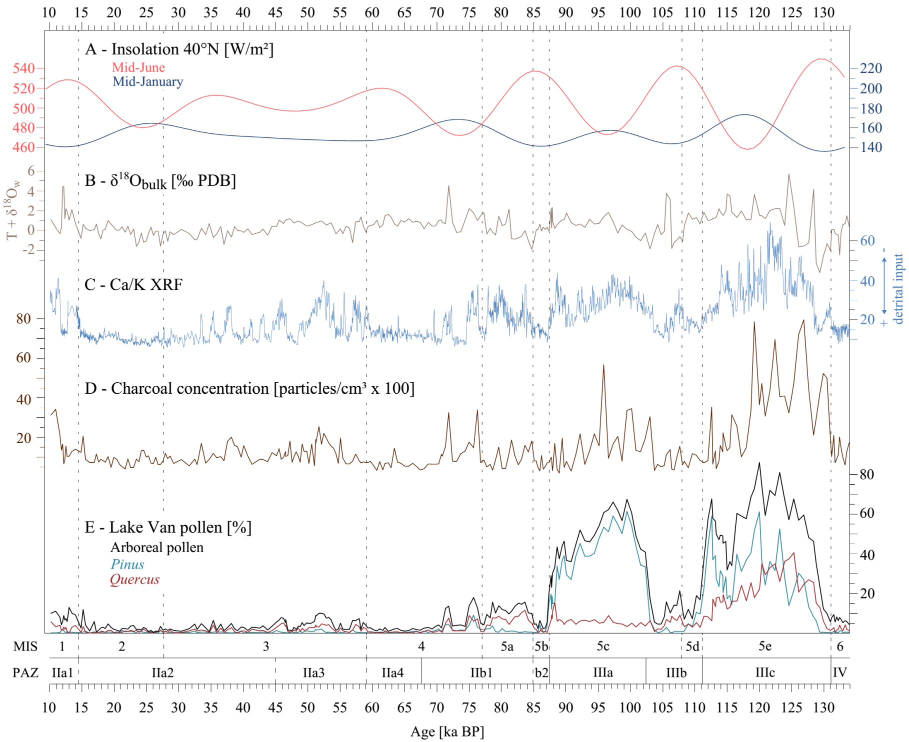

Figure 3. Comparative study of Lake Van palaeoenvironmental sequence spanning the last glacial–interglacial cycle. **(a)** Mid-June and mid-January Insolation at 40° N (Berger, 1978; Berger et al., 2007); **(b)** Lake Van oxygen isotope record [$\delta^{18}O_{bulk}$ in ‰ PDB] of autochthonous precipitated. Shown is the temperature (T) and isotopic composition ($\delta^{18}O_w$) of epilimnion; **(c)** calcium/potassium ratio (Ca/K) after Kwiecien et al. (2014); **(d)** microscopic charcoal concentration [particles cm^{-3} × 100, this study]; **(e)** selected Lake Van arboreal pollen percentages (AP, *Pinus*, *Quercus*; this study, Pickarski et al., 2015). MIS – Marine Isotope Stage; PAZ – Pollen assemblage zone.

CPD
11, 3341–3373, 2015

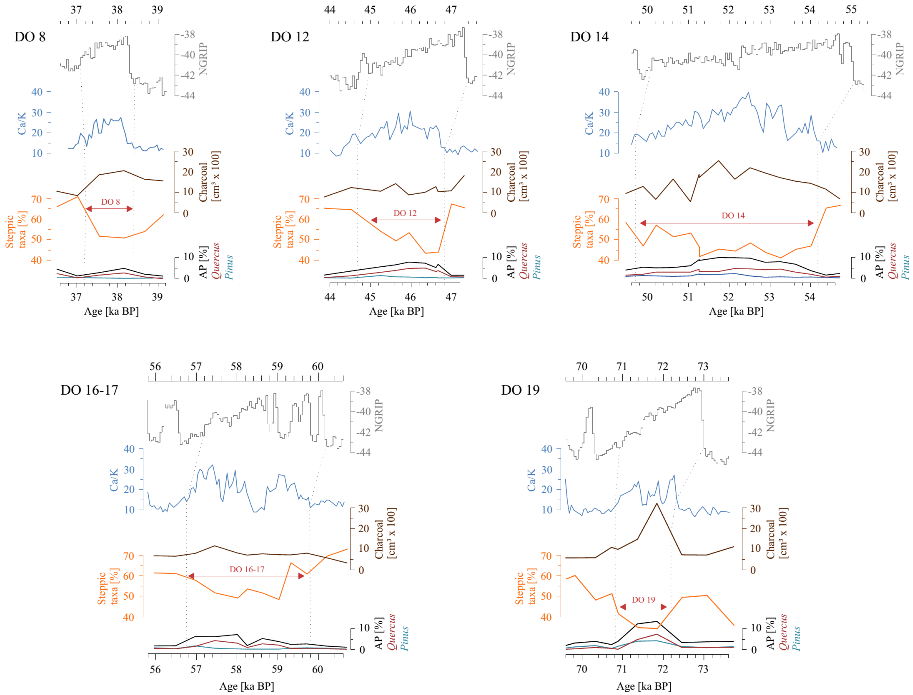

Figure 4. The longest Dansgaard–Oeschger events DO 8, DO 12, DO 14, DO 16–17 and DO 19 are plotted in extra graphs, demonstrating a good connection of eastern Anatolia vegetation dynamics and environmental conditions between the Greenland ice cores (NGRIP, 2004), calcium/potassium ratio (Ca/K) after Kwiecien et al. (2014), microscopic charcoal concentration [particles cm^{-3} × 100, this study], selected Lake Van arboreal pollen (AP, *Pinus*, *Quercus* in %, this study). The term "Steppic taxa" includes only major dry-adapted plants such as Chenopodiaceae and *Artemisia*.

CPD
11, 3341–3373, 2015

Abrupt climate variability of eastern Anatolia vegetation

N. Pickarski et al.

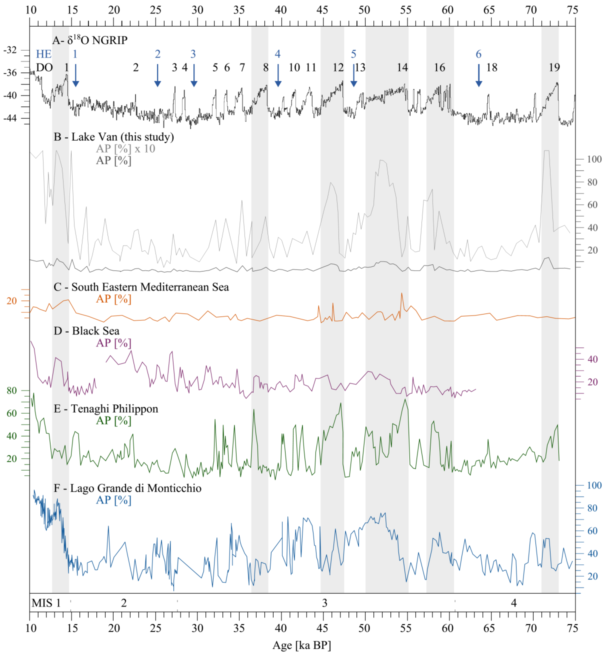

Figure 5. Regional comparison of vegetation dynamics and climate variability in central and eastern Mediterranean area and Black Sea region concerning Dansgaard–Oeschger cycles (DO) and Heinrich events (HE). **(a)** δ^{18}O-profile from NGRIP ice core, Greenland (NGRIP, 2004), labelled with DO 1 to 19 and HE 1 to HE 6 (Bond et al., 1993); **(b)** Lake Van arboreal pollen record [AP in %, black line] with x10 exaggeration (gray line); **(c)** marine arboreal pollen record (Core 9509) obtained from the south eastern Levantine Basin (south eastern Mediterranean Sea; Langgut et al., 2011); **(d)** AP record from the SE Black Sea (Core 22-GC3 for the period from 10–18 ka BP after Shumilovskikh et al. (2012) and sediment core 25-GC1 for the sequence between 19 and 63 ka BP (Shumilovskikh et al., 2014)). **(e)** Arboreal pollen record from Tenaghi Philippon, Greece (Müller et al., 2011); **(f)** AP record from Lago Grande di Monticchio, southern Italy (Allen et al., 1999). MIS – Marine Isotope Stage.

CPD
11, 3341–3373, 2015

Abrupt climate variability of eastern Anatolia vegetation

N. Pickarski et al.