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The reconstruction of paleo wind directions for the Eifel region (Central Europe) during the period 40.3–12.9 ka BP

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Abstract

A continuous reconstruction of last glacial wind directions is based on provenance analysis of eolian sediments in a sediment core from the Dehner dry Maar in the Eifel region (Germany). This Maar is suitable to archive paleo wind directions due to its location west of the Devonian carbonate basins of the Eifel-North-South-Zone. Thus, eolian sediments with high clastic carbonate content can be interpreted as an east wind signal. The detection of such east wind sediments is applied by a new module of the RADIUS grain size analyze technique. Increased frequencies of east wind occur during the time intervals corresponding with the Heinrich events H1 and H2. The unusual H3 show no higher east wind frequency but so do its former and subsequent Greenland stadials. The LGM (21–18 ka BP) is characterized by a slightly elevated east wind activity. The investigated time period from 40.3–12.9 ka BP can be subclassified in three units: The first time period during Marine Isotope Stage 3 (40.3–36 ka BP) is controlled by relative warm climate leading to an enriched content of organic matter in the sediment. Thus, there is only little accumulation of dust in the Eifel region and Heinrich 4 is not recorded in the archive by our dust proxy. The second time slice (36–24 ka BP) has an increased content of dust accumulation and a high amount of east winds layers (up to 19% of the dust storms per century came from the east). In comparison, the subsequent period (24–12.9 ka BP) is characterized by lower east winds sediments again.

1 Introduction

The climate situation in Central Europe during the Last Glacial Maximum (LGM) and the Late Pleniglacial is characterized by high wind activity and relatively low precipitation (Huijzer and Vandenberghe, 1998). This conclusion is based on a comparison of proxy data and climate simulations. The methods of generating proxy data contain relict dune forms in Central Belgium (Vandenberghe, 1991) and Poland (Godzik, 1991), grain

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size trends of cover sand and loess in the Netherlands (van Huissteden et al., 2001), provenance analyses by heavy mineral composition (Krook, 1993) and wind polished rock surfaces (Christiansen, 2004; Christiansen and Svensson, 1998; Vandenberghe et al., 1999). The balancing of these data with climate model results allows wind direction reconstruction for Central Europe for the LGM and the Late Pleniglacial (Renssen et al., 2007). This combination of meteorological simulations and proxy data shows that the Late Pleniglacial and the LGM were dominated by westerly to north westerly wind directions due to the location of the study area in the mid latitudes. The same situation is postulated for the Younger Dryas (YD), the so called Heinrich-0 event (Isarin et al., 1997). Brauer et al. (2008) have shown an abrupt increase in the strength of the westerlies during the YD at the Meerfelder Maar in the Eifel region. Both models confirm the possibility of a higher number of east winds during the modeled periods. Another simulation reconstructs the atmospheric circulation over the North Atlantic and Eurasia during Heinrich-2 (Hostetler et al., 1999). This model separates the H2 in three different phases of climate conditions. Variables are the thickness of the Laurentide ice sheet (LIS) and the Sea Surface Temperature (SST) in the North Atlantic. According to Hostetler et al. (1999) The second phase, a combination of a lowered ice sheet thickness and an increased post-surge SST during the winter simulation, shows a high pressure cell over Europe, which implies a higher concentration of north-east winds. During the third phase, with an increasing LIS thickness and decreasing SST, the high pressure cell over Europe becomes stronger again.

All presented proxy data mirror the paleo wind directions during Marine Isotope Stage (MIS) 2 very well. The question is if they are qualified to be the basis for simulations on a very high temporal resolution. Regarding the data, the main disadvantage of using sand dune orientations for wind direction reconstructions is the fact that only the last phases of deposition are represented on top of the dune. Otherwise, wind polished rocks represent the main wind direction over a long period, but hide the variations of wind direction in time. The analyses of grain size trends over a transect of dunes carry information about the paleo wind direction and sometimes also about the wind strength.

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But these techniques assume free transport paths over the surface without disturbing topographic barriers (Schwan, 1988). Provenance analyses by heavy minerals or other index materials are very useful, if the potential sources of sediment are well known and the distance to the deposition areas is not too far. Mostly the river sediments that cross the northern part of Central Europe show typical fingerprints and can be used for wind direction reconstructions.

In addition to the availability of adequate proxy data, the question about the quality of climate models concerning their resolution in space and time must be discussed. Small scale variances of topography and vegetations are not reproduced by low resolution atmospheric simulations. For example the ECHAM wind direction simulation for the Late Pleniglacial and the LGM (Renssen et al., 2007) has a horizontal resolution of 2.8°. This means, that the complete area of Denmark is represented by only one seawater grid cell, but for the Netherlands and Poland the model allocates land cells. Because of the different physical parameters of land and sea cells, the model results for Denmark, the Netherlands and Poland are not comparable to each other. A slightly higher horizontal resolution of 2° is given by the GENESIS AGCM simulations of the atmospheric circulation during Heinrich 2 (Hostetler et al., 1999). The most current modeling approach is done by Sima et al. (2009) with the LMDZ atmospheric circulation model (spatial resolution 60 km). Model results from this dust emission model show a proportional increase of east wind during Heinrich events in comparison to Greenland Stadial (GS) or Greenland Interstadial (GIS) periods.

In this study we will show a continuous record of changing wind directions during the Late Weicheslian. Time transient climate reconstruction with complex coupled climate models is limited by computing power. Because of the complexity of atmospheric simulations, it would be helpful for climate modelers to get high resolution and continuous data of paleo wind direction proxies to find interesting time slices for simulations. Such data could be uses in future specific simulation runs.

2 Methods

Our wind direction dataset depends on provenance analyses of wind transported carbonates. This continuous record over the timespan 40.3–12.9 ka BP has a sample interval of 500 µm, which is equivalent with a mean time resolution of four months. Beneath the high resolution and the totality of the record, the particle detection algorithm of RADIUS (Seelos and Sirocko, 2005) allows the measurement of single particle diameters. So we are able to make statements about the wind strength, too. To calculate the east wind activity for a fixed 100 years interval all single 500 µm segments that show east wind activity are summed after the time correlation procedure.

2.1 Lithology and stratigraphy of the core De3

The sediment core De3 for this study comes from the Dehner Maar, which lies in the northwest of the western Eifel volcanic field (WEVF), north of the town of Reuth (Germany). De3 is part of the ELSA (Eifel Laminated Sediment Archive) dust stack (Seelos et al., 2009). The dry maar is located on the west side of a large carbonate basin that crosses the region in north-south direction. There are no carbonate sources in the nearer western region of the Dehner Maar. All other maar lakes, which are part of the ELSA sediment archive are located at the east side of the basin (Fig. 1). Although it silted up approximately 12 000 years ago, the maar is still recognizable in the landscape. It has a diameter of 950 m and lies at an elevation of 565 m a.s.l. at the crest of a hill. The maar basin is round and does not display any recognizable inflow in the past, but there is an outflow to the south. Thus, the Dehner Maar fulfill the morphological requirement for being suitable to conserve storm sediment layers (Pfahl et al., 2009).

The De3 core consists in all fine-grained sections a reddish tone that can apparently be traced back to fine particles of the Triassic sandstone (Buntsandstein). There are also sections with a yellow tone, which are always composed of silt-sized dust particles that was blown in from the greater surroundings. The core photograph (Fig. 3) shows these two dominant colors, thus the yellow, loess-rich defining cold periods, the red

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tone-rich warm periods. The black colored sections are composed of singular, dm-thick volcanic ash layers.The upper most three meters are composed of solifluction debris.

The age model for the core De3 is based on tuning to Pollen zones and to the ss09sea stratigraphy of the NGRIP ice core (NorthGRIP Members, 2004). The stratigraphy is supported by six uncalibrated 14C samples as well as geochemical evidence for the Laacher See Tephra (LST) at 3.49 m depth, which gives an age of 12 900 years BP (van den Bogaard, 1995) and is also published by Sirocko et al. (2009).

The 40 m long core sequence (3–42 m depth) represents a periode from 40.3 to 12.9 ka BP, and thus covers the late MIS 3, the transition into the MIS 2, the Late Pleniglacial, and Bølling/Allerød. The core sequence is event laminated and there is no evidence for a hiatus. 36 000 years BP (38 m depth) the content of homogeneous dust sediments increases rapidly and reaches the absolute maximum during the LGM (22–18 ka BP). The organic content is very low during this period and increases once again with the Bølling transition 14 ka BP (Seelos et al., 2009). The GIS-2 (19–21 m depth) with a certain amount of organic matter is here an exception.

2.2 The RADIUS wind direction module

The particle analysis method RADIUS (Rapid Particle Analysis of digital Images by ultra-high-resolution scanning of thin sections, (Seelos and Sirocko, 2005)) was developed to analyze and identify the different sediment structures in sediment cores, especially for cores of the ELSA archive (Sirocko et al., 2005). The application allows the detection of climate controlled sedimentation processes like storm events under cool and dry conditions or fine laminated sequences during warm periods and spontaneous events like volcanic eruptions, slumps and turbidities (Seelos et al., 2009).

To analyze the paleo east wind directions, we developed a new software module, which uses the ELSA dust stack results and combines them with a carbonate detection algorithm. The carbonate tool is a self-contained software module of RADIUS, based on an adapted color detection algorithm to measure the content of carbonates.

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By means of digital image analysis it is not possible to measure a percentage by weight but an area ratio. A calibration study is applied on five artificial samples with certain contents of carbonate particles. Smear slides with a carbonate content of 10, 30, 50, 70, and 90 wt.-% are analyzed by using the RADIUS method. Pure foraminifer mud from the Black Sea is used for the carbonate where as the bright particle fraction consists of pure loess from the sediment core HL2 (Eifel region, Germany). Carbonate content of the loess is removed by cooking the material with hydrochloride acid. The smear slides are scanned under a light microscope with crossed nicols at 40x magnification. An analysis of the projected areas is separately applied for the carbonate particles as well as for the bright particles. Subsequently, the ratio between both results is computed (Fig. 2b). The coefficient of determination R^2 of 0.88 indicates the reliable classification of bright and carbonate particles.

In the ELSA core sequences the content of dust and carbonates (20–63 µm) carries information about the provenance of the windblown particles. Wind transported carbonates are detected in layers as single grains inside the dust sections with the same grain size as the other non-carbonate dust components. Sometimes aggregation layers in the core sequences can be found, which depend on secondary mobilized, soluted carbonates in the sediments. These layers are not detected as eolian carbonates (Fig. 2, because the sizes of these interconnected packages are much higher than the upper detection size of 63 µm. The authigenic carbonate production in the maar lakes during this dry and cold period is very low. The measured ground noise signal for the content of authigenic carbonates over all core sequences is about 0.2%. To reconstruct information about the dominant wind directions for the Eifel region, we analyzed the ELSA core sequence De3 (Dehner Maar, Fig. 1) about the content of carbonates and loess.

The algorithm of the RADIUS wind direction module works in the following way: if the content of carbonates (20–63 µm) in a detected dust sequence (which is defined as such if the probability of a dust event is higher than 70%) of the De3 core is higher than 1%, we assume east winds, because the wind crosses the carbonate basin and lime particles are looped up. Higher mean size values of carbonate particles in a loess

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sequence are regarded as an indicator for wind strength, concerning the theoretical model of dust transport which has been proposed by Pye (1987). If the climate situation changes to warm and wet conditions, the content of dust decreases at the same time and the wind detection algorithm is set to zero.

3 Results and discussion

For the ELSA dust stack the Dehner Maar core sequence provides a high resolution reconstruction of wind directions for Central Europe by provenance analyses. Two main modes according to wind speed and strength can influence deflating areas: (i) transport of fine grained silty material (<20 µm) at high altitude over very long distances, (ii) transport of coarser material over short distances. Our results correspond to the second model of dust transport (Pye, 1987) as coarse silt material has been blown from the nearby river valleys as well as from the Devonian carbonate basins. The core sequence 2–42 m depth represents the transition form MIS-3 to MIS-2 and the whole MIS-2 including the LGM and the Heinrich events 1–3. The fixed combination of dust detection results exclude misinterpretations in the case of high authigenic carbonate productivity in the lake. The RADIUS detection results are presented as 20 point arithmetic mean records (Fig. 3).

Regarding the whole record, west winds are dominating the period 40.3–12.9 ka BP. The lowest content is about 0.2%, representing the highest west wind activity during the period 24–22.5 ka BP. The maximum content of east wind formed sediments in a hundred years interval is 19.4% (32 ka BP).

The whole studied time period can be subdivided into three units: (i) The first time period during MIS 3 (40.3–36 ka BP) is controlled by relative warm MIS 3 climate. Thus, there is only little accumulation of dust in the Eifel region. H4 (39.4–37.2 ka BP) obviously has no significant effect of dust accumulation in the Eifel region, too. So the analysis of carbonate bearing east wind layers is not possible for this time slice. The strong increase in dust accumulation starts quiet after the GIS-8. (ii) When the LIS began to crow (36 ka BP) the climate transisted into a colder and dryer state in middel Europe. Thereupon, our data show that the content of east wind sediments increases. During this declining phase of MIS 3 (36–32 ka BP) thick east wind layers are accumulated (Fig. 3 D), but the frequency of east wind activity is moderate. During the following period (32–24 ka) the content of dust sediments is always high (around 75%), whereas the content of organics decreases to a very low level. The east wind frequency is relatively stable on a high level about 9% of east wind events per 100 years until the end of H2, with maximum values during 32.5–30.5 ka BP (shortly before the H3 event), during 28.5–27 ka BP (corresponding with the time slice of GIS-3 and 4), and during 25–24.5 (H2 event). (iii) The period between H2 and the LGM is characterized by a principle change in the climate system over Europe. The content of east wind transported sediments drop to a level about 2%. The number of east wind events per century decrease rapidly but the appearance of strong storm events is still high (detected by coarse carbonate particles). The content of organics reaches a maximum during GIS-2 (22.5–21 ka BP). During the LGM (21–18 ka BP) and the subsequent Heinrich-1 event (16.6 ka BP) the content of east wind sediments is once again noticeable high (mean value is around 6% per century).

Dominations of west winds are also approved by our data. The continuous high resolution dust records of the ELSA dust detection allow very detailed analyses of wind direction changes for the complete time period 40.3–12.9 ka BP. One result of this study is a correlation of increased east wind frequency with extreme cold phases like Heinrich events or the maximum advance of the LIS during the LGM.

3.1 Increased east wind frequency during extreme cold phases?

Both, the Greenland Stadials (GS) before and after the Heinrich-3 (30.2–28.7 ka BP) are characterized by the highest number of east winds during MIS 2, the former one up to 160 identified storms per century. However, the time slice representing the H3 has only a little amount of east wind sediments. It seems that the climate situation during H3 is in contrast with other Heinrich events (Gwiazda et al., 1996) and is coupled to relatively stable high-pressure systems over the east part of Europe.

In contrast to H3, H2 (24.8–23.2 ka BP) is dominated by strong east winds, but the number of detected events per century drops to a value around 20. A comparison of two core sequences shows significant differences between the interstadial GIS-2 and the previous Heinrich-2 (Fig. 4). During GIS-2, the wind system is stable and west winds dominate during the whole period (indicated by low content of wind transported carbonate particles). However, about 24 ka BP after the H2 event we recognize a principle change in the climate system over Europe.

H1 (16.6–15.2 ka BP), which is not recorded in the NGRIP micro particles, shows according to H2 a high amplitude in the record of east wind activity. A higher east wind activity is also modeled by Renssen et al. (2007) for the time slice of the late pleniglacial (18–15 ka BP).

The period of 21–18 ka (LGM) is characterized by a lower east wind activity than the Heinrich events H1 and H2 and the wind transported particles are smaller, indicating decreasing wind velocities. However, the time slice 20.5–19.5 ka BP shows numerous of east wind events (about 12% per century). In addition our results show a slightly increased east wind frequency during the LGM within the period between 24 and 17 ky BP. This contradicts earlier climate simulations for the LGM (Renssen et al., 2007), which shows a low east wind activity and increasing west winds.

3.2 Outlook

Our continuous data show a high variability in changing wind directions. With this paper we want to address the climate modeling community. Climate simulation might help to answer the question what can possibly cause east winds during extreme cold climate conditions. Earlier results give some hints of atmospheric states.

Simulations of the LGM suggest that the LIS had major effects on atmospheric circulation patterns. A glacial anticyclone, produced during summer months by high atmospheric pressure over the ice sheet, generated an easterly surface wind anomaly directly to the south of the ice sheet (Bartlein et al., 1998; COHMAP Members, 1988;

Kutzbach and Wright, 1985). Some models show a permanent easterly flow south of the ice sheet (COHMAP Members, 1988; Kutzbach and Wright, 1985), but recent simulations show that easterly flow are less pronounced and more seasonally with a westerly flow returning in winter months (Whitlock et al., 2001; Bartlein et al., 1998). Evidence from eolian deposits in North America verify that the glacial anticyclone altered surface wind patterns and affected eolian systems during the LGM (Sweeney et al., 2004). Similar atmospheric processes are suggested for the European region, too. Katabatic and zonal winds controlled by the Weichselian Ice Sheet might be irrelevant: Dominating easterly wind directions only existed in areas being deglaciated or located immediately in front of the ice sheet during its maximum extension (Christiansen and Svensson, 1998; Renssen et al., 2007).

Atmospheric blocking as mentioned by Rimbu et al. (2007, 2008) is a large-scale, mid-latitude atmospheric phenomenon often associated with persistent quasi-stationary, synoptic-scale, high-pressure systems. The formation, maintenance and collapse of atmospheric blocking cause large-scale circulation anomalies and strongly impact weather patterns. Such a situation can block the large-scale westerly flow over the northeast Atlantic and influence the wind direction over Europe.

The shutdown or reduction in strength of the North Atlantic meridional overturning allows the spread of winter sea ice across the North Atlantic, thus causing much colder winter from Greenland to Asia (Denton et al., 2005). A widespread sea ice cover might lead to an eastward relocation of the Icelandic Low.

4 Conclusions

1. The Dehner Dry maar is suitable to archive paleo wind directions due to its location west of Devonian carbonate basins. So, eolian Sediments with high carbonate content from the Dehner Maar (Eifel, Germany) can be interpreted as an east wind signal.

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2. The problem remains to propose a regional atmospheric situation from a single sample location. However, Pfahl et al. (2009) have shown that the allocation of storm layers in maar lake sediments to recent regional meteorological data is statistically highly significant for at least the last decades. Thus, we suggest that our results from the Dehner Maar are correspond to a regional atmospheric state.

3. Increased east wind frequencies occur during the time intervals corresponding to the Heinrich events H1 and H2. Whereas the unusual H3 show no increased east wind frequency. The former and subsequent Greenland stadial intervals do so. However, dust sedimentation in Central Europe reaches maximum values during Heinrich events, which is also suggested by Antoine et al. (2009) and Rousseau et al. (2007) for the Nussloch section (Germany).

4. The LGM (21–18 ka BP) is characterized by a slightly elevated east wind activity contradicting former model results (Renssen et al., 2007). However, the wind transported particles are smaller, which indicates decreasing wind speed velocities.

5. The studied time period from 40.3–12.9 ka BP can be subdivided into three units: The first time period during MIS 3 (40.3–36 ka BP) is controlled by relative warm MIS 3 climate. Thus, there is only little accumulation of dust in the Eifel region and Heinrich 4 is not recorded in the archive by a dust proxy. The second time slice (36–24 ka BP) has an increased content of dust accumulation as well as of carbonate particles in comparison to the third unit (24–12.9 ka BP), which is characterized by lower east winds sediments again.

6. This division into two atmospheric patterns is indicated by the microparticle-curve of the NGRIP ice core (Ruth et al., 2007), in which the pre-Heinrich-2 time slice is dominated by Dansgard/Oeschger like cycles, whereas the subsequent period shows a rather stable amount of dust concentrations. A significant change of

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atmospheric patterns, which resulted in a change in wind directions near to the surface is first shown in this study.

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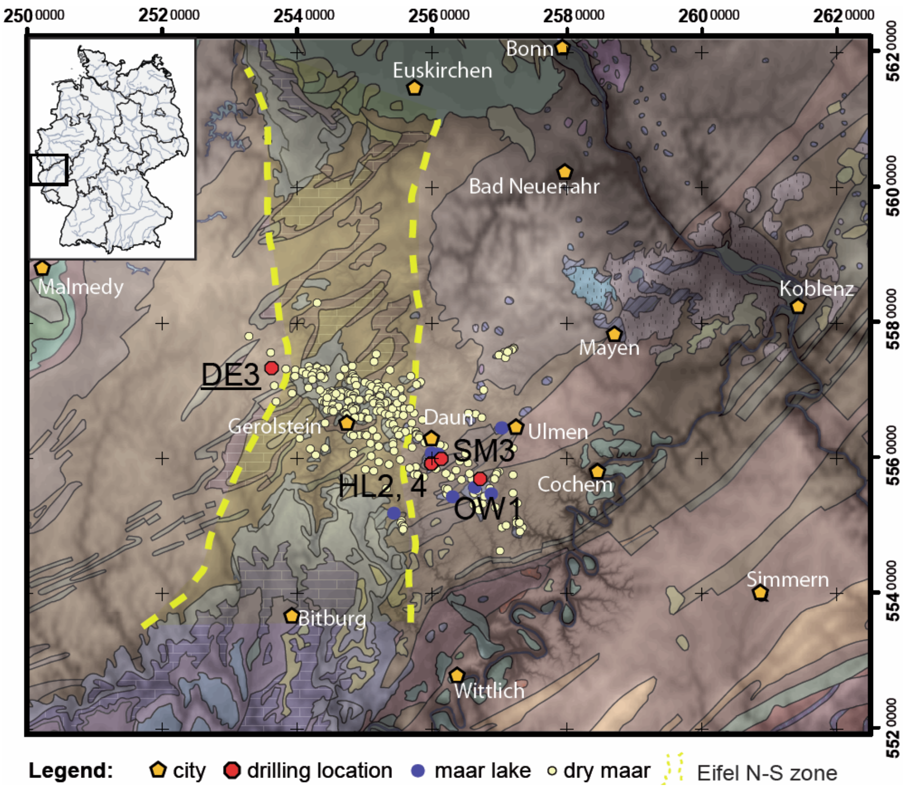

Fig. 1. Geological sketch map and elevation model of the Eifel region, including the Eifel N-S-zone with limestone bearing "Kalkmulden" and the locations of Maar lakes and dry maars after Büchel (1994). The map is based on the Geological Map of Germany 1:1 000 000 (BGR 2002), GCS Deutsches Hauptdreiecksnetz, Gausszone 2, Bessel 1841. Locations of the sediment cores from the ELSA dust stack(see text) are marked with red dots. The core De3 from the Dehner dry maar, which is focused in this study, is underlined.

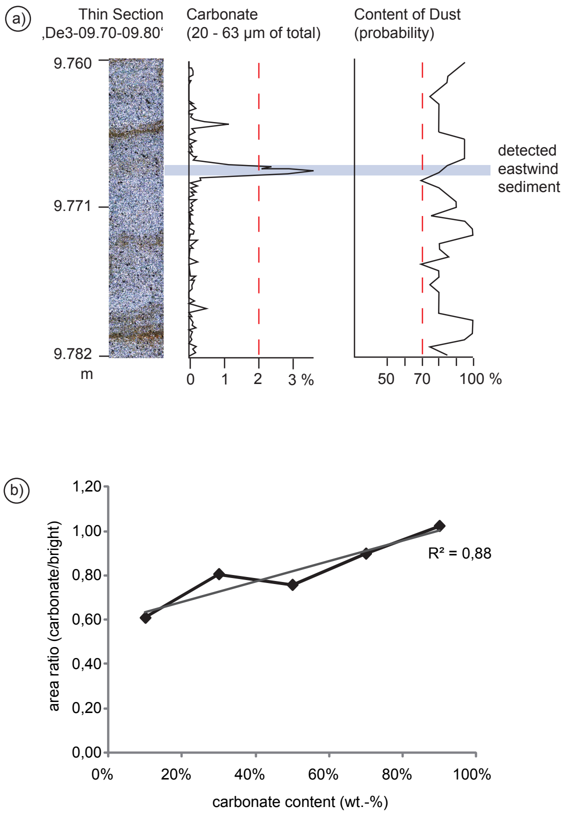

Fig. 2. **(a)** Example of a dust sequence of core De3 showing a detected east wind layer (silt sized carbonate content greater than 2% and probability of dust scores greater than 70%) during the LGM. The eolian transported carbonate particles of such layers are of the same mean size as the corresponding quartz grains. **(b)** Scatter plot of the area percentage of carbonate particles over bright particles versus the the carbonate content by weight shows the reliable classification of carbonate particles.

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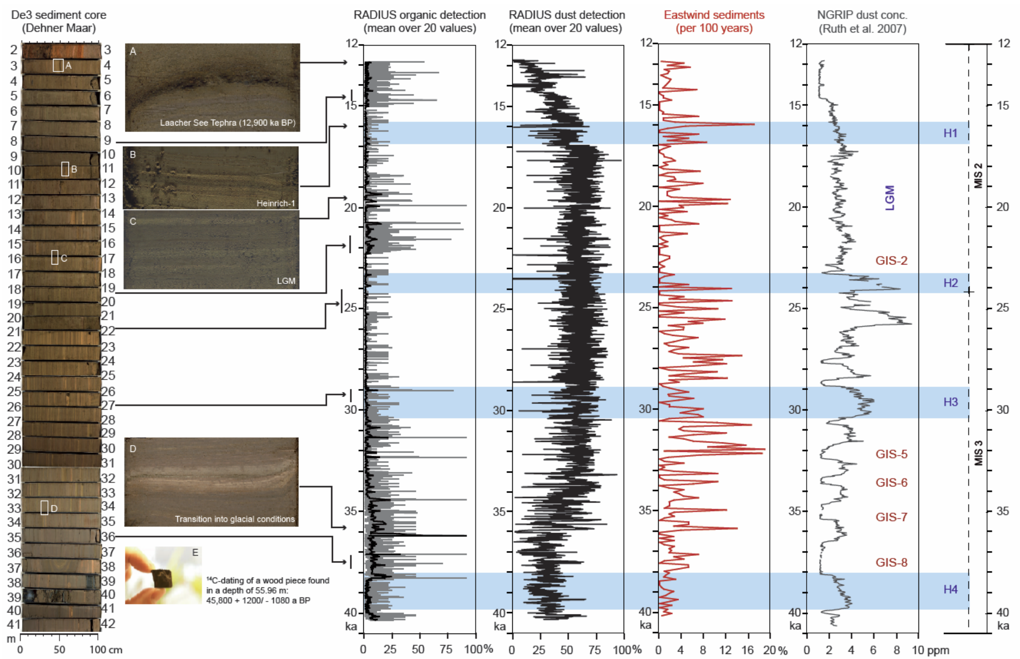

Fig. 3. Core sequence De3 12 800–40 300 a (Dehner Maar): left: core images over the whole sequence (2–46 m); center-left: detailed sediment images: **(A)** Laacher See Tephra (LST, 12 900 years BP), **(B)** Heinrich-1 layer, **(C)** example of a LGM layer, **(D)** transition into MIS-2, **(E)** 14C-dating of a piece of wood (spruce) found in a depth of 55.96 m (45 800+1200/−1080 years BP); center-right: Radius detection records for the content of organics, Radius detection of dust (both with an original sampling resolution of 500 µm, Seelos et al. (2009)). Frequency of carbonate rich east wind sediments per 100 years (red). The comparison with the micro particles record (gray) from Greenland (Ruth et al., 2007) shows a common process of eolian dynamics linking North Atlantic and the European region. Blue bars: marking of Heinrich events.

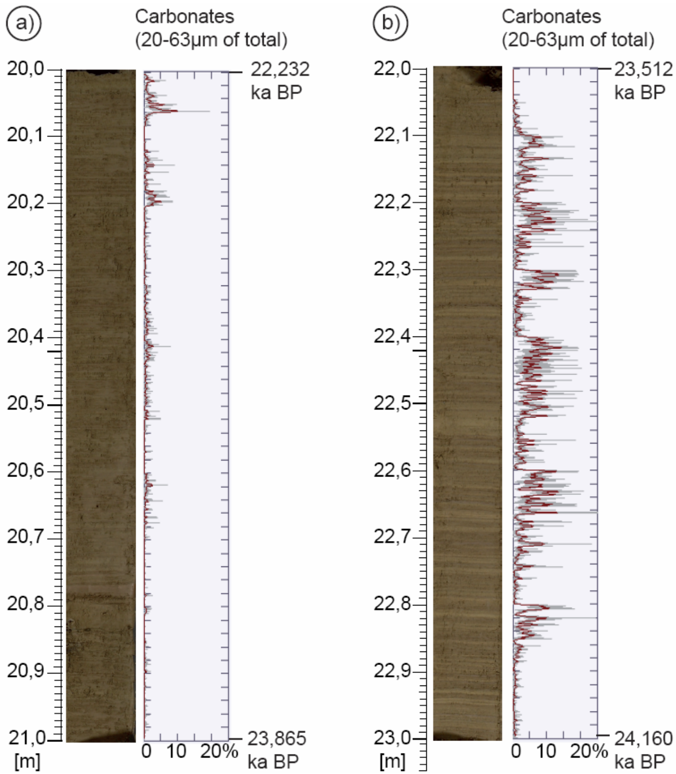

Fig. 4. The comparison of two sediment core sequences. De3 20–21 m (22 232–22 865 years BP) and De3 22–23 m (23 512–24 160 years BP) shows the variation of sediment structures for the periods of **(a)** the interstadial GIS-2 and **(b)** the previous Heinrich-2. It is obvious, that the core sequence 22–23 m is characterized by coarse lamination in consequence of variable sediment compilations. This alternation of carbonate rich and carbonate poor sections is caused by often changing wind directions.