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Quantification of Calabrian climate in southern Primory'e, Far East of Russia — An integrative case study using multiple proxies

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ABSTRACT

Early Pleistocene climate dynamics in the Russian Far East (southern Primory'e) is studied using multiple quantitative techniques on various palaeobotanical organ types. Climate data of the time were obtained from a total of 8 macrofloras (fruits and seeds, woods, and leaves) and 18 microfloras collected from a 10 m thick, terrigenous succession exposed in the Pavlovskoe brown coal field. According to magnetostratigraphy, the studied section covers the last 200 kyr of the Calabrian and comprises the early/late Pleistocene transition, a crucial time-span involving the transition from obliquity-forced cyclicity to the strong, eccentricity triggered glacial events. In this first integrative study on palaeoclimate of the Russian Far East, we employ Growth Ring Analysis, Multivariate Anatomical Analysis, Leaf Margin Analysis, Climate Leaf Analysis Multivariate Program, and Coexistence Approach on the different organs, partly originating from the same layer.

The investigation documents the following important outcomes: 1) Climate data obtained from the various methods are proven to be largely consistent. 2) The late Calabrian of the southern Primory'e was characterized by overall cooling and drying. Our climate record displays 2 small scale cycles. Warm peaks (at 19.4–19.8 and 14.0–14.8 m) are tentatively correlated to the global isotope stages MIS 25 and MIS 21, respectively. 3) In the warm phases, the Calabrian climate of southern Primory'e was significantly warmer and wetter when compared to the present, especially regarding the cold season while in cold phases, climate was similar to modern or event slightly cooler. 4) As of today, Early Pleistocene climate of southern Primory'e was warmer and wetter than neighboring areas of the south RFE. 5) The effect of the East Asian Monsoon Systems on the climate of the southern Primory'e was less pronounced compared to the present.

1. Introduction

The Quaternary Period was characterized by dramatic climatic changes expressed in alternations of cold and warm phases (Williams et al., 1988; Frenzel et al., 1992; Lisiecki and Raymo, 2005; Velichko, 2009) associated with strong fluctuations of the global sea-level (Lambeck et al., 2002). Glacial–interglacial climate changes during the Quaternary were largely controlled by cyclic variations in the amount of solar radiation, or insolation received in middle to high latitudes of the Northern Hemisphere. Earth's orbital variations also played an important role in Quaternary climate dynamics and mechanisms driving glacial cycles (Rial and Anaclerio, 2002; Ganopolskii and Calov, 2012). The climate was much more unstable during periods of glaciation as compared to climates of the previous, warmer epochs (Rial and Anaclerio, 2002; Ganopolskii and Calov, 2012). The Early Pleistocene climate dynamics, characterized by the typical "saw-tooth" asymmetry of glacial cycles, was primarily forced by obliquity and precession (Lisiecki and Raymo, 2007). At the Early–Middle Pleistocene transition (from ca. 1.2 Ma on) cyclicity progressively graded into high-amplitude 100 ka eccentricity cycles associated with a substantial increase in global ice-volume at ca. 940 ka. The marine isotope stage (MIS) 22 occurring in the latest Calabrian represents the first strongly cold event of the Pleistocene (Head and Gibbard, 2005).

The modern status of the natural environments characteristic of the Russian Far East (RFE) is a consequence of climate changes in the Quaternary. The East Asian Monsoon (EAM) also was a climatic system that had a strong effect on the southern part of the RFE. In the Quaternary, vegetation of the RFE, especially of the area between 38 and 54°N, was mostly under continental influence in cold phases and under oceanic influence in warm phases. Vegetation zones showed marked southerly shifts in cold phases, and moved to the north in warm ones. Throughout the Quaternary the area of south RFE was not covered with extensive ice sheets but characterized by the presence of small mountain glaciers mostly in the Sikhote-Alin Mountains (Golubeva and Karaulova, 1983; Korotkii et al., 1996).

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The Pleistocene epoch of the Quaternary is an important stage in the development of the modern vegetation of the RFE because the origin of many extant species and the formation of plant communities similar to those existing today took place under the influence of cyclic climate changes during this epoch (Korotkii and Karaulova, 1970; Golubeva, 1972a,b, 1973, 1976; Karaulova, 1973; Karaulova et al., 1978; Golubeva and Karaulova, 1983; Korotkii et al., 1996). First preliminary quantitative data on the Pleistocene climate of this area were presented by Golubeva and Karaulova (1983) and Korotkii et al. (1996). However, they estimated past climate conditions of the south RFE only using climatic preferences of modern phytocoenoses to which the reconstructed Pleistocene vegetation was similar.

Here we present a concise study on quantitative climate fluctuations in southern Primory'e, RFE during the Calabrian (1.806 to 0.781 Ma) using various quantitative techniques. Fossil plant remains are one of the most important proxies for estimating past climate conditions, due to the intimate association that plants have with the atmosphere. The Pavlovskoe brown coal field is the only locality in southern Primory'e with numerous well preserved and taxonomically diverse fossil plant remains of Calabrian age represented by different organ types, namely wood remains, leaf impressions, fruits and seeds, and spores and pollen. To reconstruct the palaeoclimate the following methods were employed: Growth Ring Analysis (Fritts, 1976; Creber and Chaloner, 1984), Multivariate Anatomical Analysis (Wiemann et al., 1998, 1999), Leaf Margin Analysis (Wolfe, 1979), Climate Leaf Analysis Multivariate Program (Wolfe, 1993), and Coexistence Approach (Mosbrugger and Utescher, 1997). This is the first integrative case study on the Early Pleistocene climate in the RFE providing a detailed, consistent palaeoclimate reconstruction and using multiple proxies.

2. Study area

2.1. Geological settings

The Pavlovskoe brown coal field is located 35 km north-east of Ussuriisk city in the Primorskii Region (or Primory'e) of the RFE (Fig. 1). The Pavlovskoe brown coal field, which covers a total area of ~150 km^2, belongs to the “structural–formational zone” of the Neoproterozoic Khankaiskii massif (Bersenev, 1969; Pavlutkin and Petrenko, 2010). The Pavlovskoe brown coal field comprises the Pavlovskii Basin and several isolated small basins (“subbasins”) located at close range (Cherepovskii, 1997). The brown coal of the Pavlovskii Basin is excavated in the Pavlovskii-II open-cast coal mine. The Southern, Eastern and Northern subbasins are exploited in the Pavlovskii-I open-cast coal mine, the Luzanovskii open-cast coal mine is located in the Luzanovskii subbasin (Cherepovskii, 1997).

The Pavlovskii Basin as well as all subbasins mentioned above are filled with Late Oligocene to Quaternary strata, unconformably resting on the Palaeozoic basement. The Cenozoic deposits exposed in the open-cast mines are subdivided into three formations: Pavlovskaya, Ust'-Suifunskaya and Suifunskaya (Krasnyi, 1994; Cherepovskii, 1997; Klimova and Feoktistov, 1997).

The Pavlovskaya Formation is composed of fine to medium-grained siliciclastic sediments, brown coals, and tuffites mainly occurring in the upper part. The age of the Pavlovskaya Formation is latest Oligocene to latest middle Miocene (Krasnyi, 1994). The Ust'-Suifunskaya Formation follows on top with erosional contact, consists of cross-bedded sandstones and gravels, and dates to the Late Miocene (Krasnyi, 1994). The deposits of the overlying Suifunskaya Formation are distributed within the middle reaches of the Razdol'naya River

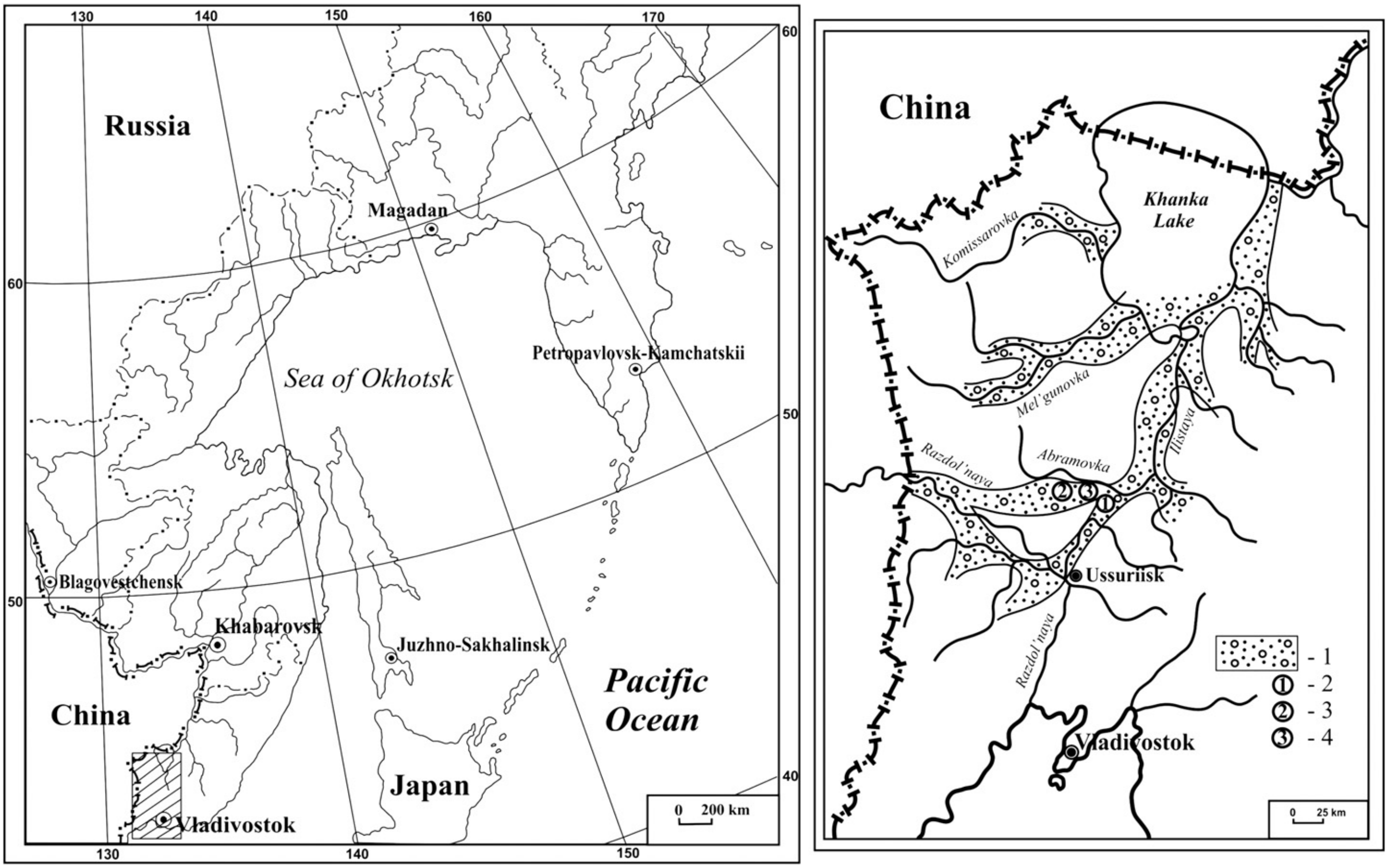

Fig. 1. Map showing location of the study area: 1 — distribution of the sediments of the Suifunskaya Formation (Pavlutkin et al., 1988); 2 — Pavlovskii-I open-cast coal mine; 3 — Pavlovskii-II open-cast coal mine; 4 — Luzanovskii open-cast coal mine.

Basin extending northward to Khanka Lake within Khanka Plain (Fig. 1). Depending on the part of the basin, the Suifunskaya Formation unconformably rests on sediments of various composition and age, from Palaeozoic granites to weakly calcareous, Late Miocene volcanic tuffites and Late Pliocene red clays. The Suifunskaya Formation is placed in the Early Pleistocene (Calabrian), its thickness ranges from 10 to 20 m (Pavlutkin and Petrenko, 2010).

2.2. Studied section and age control

The studied section no. 9035 of the Suifunskaya Formation (cf. Figs. 1 and 2; coordinates: 44°05′N 132°05′E) was measured in the Pavlovskii-II open-cast coal mine (Pavlutkin et al., 1988; Pavlutkin, 1997, 1998; Pavlutkin and Petrenko, 2010). In this section, the deposits of the Suifunskaya Formation, attaining a thickness of ca. 10 m, unconformably rest on coarse grained, unconsolidated sandstones of the Late Miocene Ust'-Suifunskaya Formation. The sandy clays on top of the profile are wide-spread in southern Primory'e and dated as Middle to Late Pleistocene (Korotkii, 1970; Pavlutkin, 1984).

According to Pavlutkin (Pavlutkin et al., 1988, 1991; Pavlutkin, 1998; Pavlutkin and Petrenko, 2010), the section exposes a series of fluvial sedimentary cycles, consisting of cross bedded gravels and small-pebble conglomerates. Silts deposited on top of each cycle contain spores and pollen and plant detritus. Layers with fine gravels in the middle part of the formation contain fossil woods (Fig. 2).

Traditionally, the Suifunskaya Formation was considered to be of Pliocene age (Krasnyi, 1958, 1994; Cherepovskii, 1997; Klimova and Feoktistov, 1997), though some researchers (Ganeshin and Smirnov, 1960; Ganeshin, 1961; Chemekov, 1962) defined its age as Pliocene–Early Pleistocene. This is primarily due to the fact that the Geological Survey of the USSR and then of the Russian Federation up to 2011, allocated the Neogene–Quaternary boundary at 0.7 Ma.

According to Pavlutkin (Pavlutkin, 1997, 1998; Pavlutkin and Petrenko, 2010), the Suifunskaya Formation belongs to the Calabrian, based on evidence from regional geology and pollen zonation. The pollen zonation established for the studied profile can be correlated with palynozones of the later Calabrian in Northern Japan (Kitagawa et al., 1988) and Northeast China (Li and Wang, 1982; Zhou et al., 1983). For more details the reader is referred to Pavlutkin (1997, 1998). Moreover, recent palaeomagnetic studies suggest that the basal part of the Suifunskaya Formation, having normal polarity, corresponds to the Jaramillo magnetic subchronozone. The profile part between depth levels 19 and 8 m in the studied section, showing reverse polarity, is placed in the Matuyama magnetic chronozone (Pavlutkin and Petrenko, 2010). The transition to sandy clays on top of the Suifunskaya Formation marks the early/middle Pleistocene transition in southern Primory'e, at 0.781 Ma. According to Pavlutkin (1984), palaeomagnetic studies on these sandy clays show that all samples analyzed have normal polarity and correspond to the Brunhes magnetic chronozone. Based on these data, the studied section represents a time-span of about 250 ka. However, the sedimentary facies suggests the presence of gaps in the record.

3. Materials

Fossil plant records from the Suifunskaya Formation of the Pavlovskoe brown coal field are represented by different organ

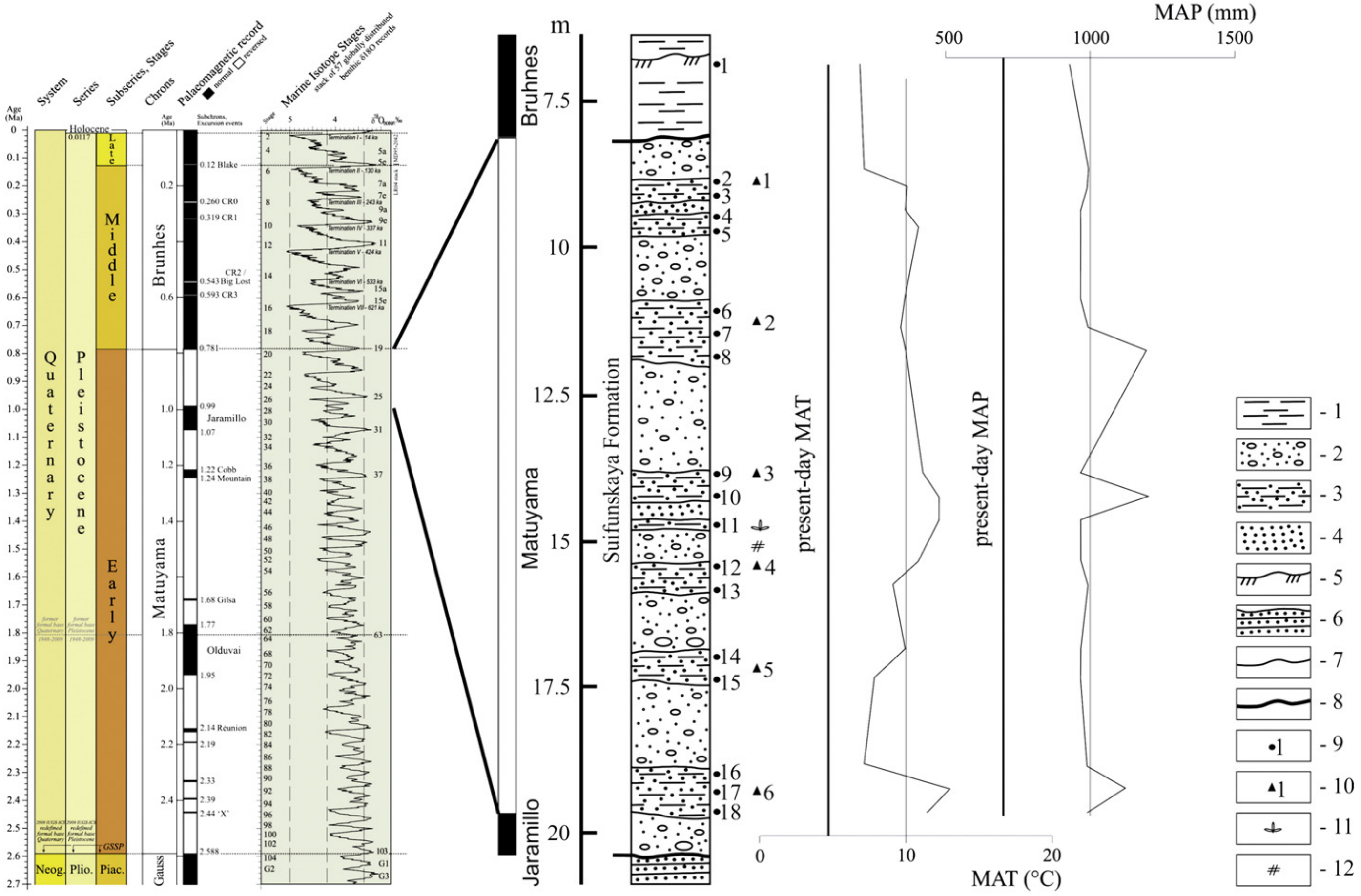

Fig. 2. Lithological profile of the Suifunskaya Formation and correlation with the International Chronological Chart, palaeomagnetic chronozones, marine isotope stages and curves for MAT and MAP as reconstructed from palynofloras: 1 — sandy clays; 2 — gravels; 3 — silts; 4 — sands; 5 — paleosoil; 6 — sandstones; 7 — lithological boundaries; 8 — stratigraphic boundaries; 9 — palynoflora; 10 — carpoflora; 11 — leaf flora; 12 — xyloflora.

types, namely wood remains, leaf impressions, fruits and seeds, and spores and pollen.

The xyloflora (XF) was collected and studied by several authors (Blokhina et al., 2003, 2005; Blokhina and Bondarenko, 2004, 2005, 2008; Bondarenko, 2006, 2007). According to geologists (Krasnyi, 1958, 1994; Pavlutkin et al., 1988; Cherepovskii, 1997; Pavlutkin, 1997, 1998), fossil woods originate from a single level (Fig. 2) which can be identified in all open-cast mines of the Pavlovskoe brown coal field located at close range (Fig. 1). Fossil woods can be referred to 35 taxa (Appendix Tables 1 and 2). Wood fragments are lignitic, light- to dark-brown in color, abundant, and usually range in diameter from 3–5 cm to 15–18 cm, and from 6–9 cm to 23 cm in length. Few logs of 40–50 cm in diameter and 3–6 m in length were also found. Wood fragments, stumps and logs were found horizontally aligned with respect to the bedding plane, with direction of bed inclination 270° from east to west. Wood was found at the same level within the Pavlovskii-I, the Pavlovskii-II and the Luzanovskii open-cast coal mines. Out of a total of 373 wood specimens studied, 335 had a well preserved wood anatomical structure and were identified.

According to Pavlutkin (Pavlutkin et al., 1988; Pavlutkin, 1997, 1998), leaf flora (LF), carpofloras (CF) and palynofloras (PF) originate from the same section no. 9035 located within the Pavlovskii-II open-cast coal mine.

Information about LF was taken from Pavlutkin (1997, 1998), Klimova (1997), and Klimova and Feoktistov (1997). The impressions come from a single level (Fig. 2) and can be referred to 48 taxa (Appendix Tables 1 and 2) that were identified by Klimova (Klimova and Feoktistov, 1997).

The information regarding CF was taken from Pavlutkin et al. (1988) and Krasnyi (1994). The fruits and seeds were found at six levels (Fig. 2) and belong to 120 taxa (Appendix Tables 1 and 2) identified by Dorofeev (cit. by Pavlutkin et al., 1988).

PF data are taken from Pavlutkin et al. (1988, 1991) and Krasnyi (1994). The microflora originates from a total of 18 levels (Fig. 2) and yields evidence for 53 taxa (Appendix Tables 1 and 2) identified by Belyanina (Pavlutkin et al., 1988). According to Pavlutkin et al. (1988), the youngest PF 1 sample at the depth level 7.0 m originates from the basal part of the sandy clays (Fig. 2).

4. Methods

4.1. Preparation of slides

In order to identify the fossil wood material, the wood pieces were sectioned in three classical planes (transverse, radial and tangential) following the standard technique of Gammerman et al. (1946) for preparing the sections from slightly lignitic, weakly modified wood. A total of ~9000 sections from 335 samples were studied using light microscope «AxioScop-40» (Carl Zeiss).

4.2. Climate reconstruction

In order to reconstruct the palaeoclimate two groups of methodologies were employed. The first group of methods does not need a precise identification of fossil specimens (Growth Ring Analysis, Multivariate Anatomical Analysis, Leaf Margin Analysis and Climate Leaf Analysis Multivariate Program). These approaches take into account the correlation between climate and selected traits of plant physiognomy. The second group of methods is based on finding the systematic affinities of fossil taxa. Here we used the Coexistence Approach employing climatic requirements of nearest living relatives (NLRs) to reconstruct palaeoclimate.

4.2.1. Growth Ring Analysis

As a response to ecological conditions, a growth ring (or the absence thereof) can be a very sensitive adaptive device (Carlquist, 1980). Therefore fossil woods provide a variety of measurements that can be used as proxies in palaeoclimate reconstruction because the mechanism of wood development records in varying degree of the effects of both external and internal factors that affect growth. Data concerning external factors that can be reclaimed, i.e. have climate significance, refer to presence or absence of growth rings, ring widths, relative proportions of early- and latewood and the nature of the transition between them, "false" and "frost" growth rings and evidence of damage by animals, insects or fire, evidenced by the occurrence of reaction wood (Chavchavadze, 1979; Creber and Chaloner, 1984). In order to interpret growth rings in fossil wood the classification scheme of Creber and Chaloner (1984) for different earlywood/latewood relationships was employed.

The analysis of growth rings was made following Fritts (1976). The rings were measured in cross section along a radial line in order to obtain as long a ring series as preservation permitted. If the center of the stem (or branch) was not present, the radius of curvature of the ring was noted to estimate whether the wood specimen was part of a small branch (the inner part of stem) or from the outer part of a large trunk. Minimum and maximum ring width as well as mean growth ring width (MRW) and standard deviation (SD) were recorded for each fossil wood sample. Besides, mean sensitivity (MS), the mean variability in ring width over a series of rings, was calculated according to Fritts (1976) as $MS = (1 / n - 1)\sum(2x_{t+1} - x_t / x_{t+1} + x_t)$, where x is the ring width, n is the number of rings, and t is the year number of each ring. Values of MS can range from 0 (no variation) to a maximum of 2 (greatest variation). According to Fritts (1976), an empirical value of the threshold of 0.3 is taken to separate "complacent" trees that grow evenly under a favorable and uniform climate ($MS < 0.3$) from those that are "sensitive" to fluctuating climate parameters ($MS > 0.3$). In total, ~3000 sections made in transverse plane were used for Growth Ring Analysis.

4.2.2. Multivariate Anatomical Analysis

Wiemann et al. (1998, 1999) developed the statistical models for inferring climate from selected wood anatomical characters. The relationship between anatomical features and climate parameters is represented as regression equations. Five climate variables, namely mean annual temperature (MAT), mean annual range in temperature (MART), cold month mean temperature (CMMT), mean annual precipitation (MAP), and length of dry season (DRY) were determined, using the regression equations of Wiemann et al. (1998, 1999) based on untransformed data, as well as all the arcsine transformation formulae (Wiemann et al., 1999) for comparison.

The limitation of this method is that statistical evaluation requires a large amount of dicot morphotypes (at least 25) within an assemblage. In spite of the insufficient amount of angiosperm wood types in the studied fossil flora, the results are included here for completeness.

4.2.3. Leaf Margin Analysis

Leaf Margin Analysis (LMA) was first introduced by Bailey and Sinnott (1915, 1916), and more recently revisited by Wolfe (1979), Wing and Greenwood (1993), and Wilf (1997). The LMA relies on the correlation that exists between the proportion of toothed vs. non-toothed (entire) woody dicot leaves in a given patch of stable vegetation and MAT. The percentage of entire margined species is employed to predict MAT from this relationship. In the present analysis we used the regression equation according to Su et al. (2010). Being based on Chinese flora we consider it most suitable for our study area even though poor data cover at the higher latitudes brings about uncertainties. The standard error (SE) is calculated according to Miller et al. (2006): $MAT = 27.6 \times P + 1.038$; $R^2 = 0.79$; number of samples = 50, with b being the slope, φ the "overdispersion factor" (0.052), p the proportion of woody dicots with untoothed leaves, and n the total number of woody dicots in a flora.

4.2.4. Climate Leaf Analysis Multivariate Program

A further development of the LMA introduced by Wolfe (1993) is the so-called Climate Leaf Analysis Multivariate Program (CLAMP). In the CLAMP, 31 physiognomic character states that encompass lobing, margin geometry, apex and base shape, and lamina size and shape are used. CLAMP is the most comprehensive foliar physiognomic technique currently available, and with the existing calibration data sets (see the CLAMP website for details: http://clamp.ibcas.ac.cn), it is capable of yielding values for several palaeoclimate variables. Typically, 11 climate variables are correlated with the foliar physiognomic data, namely MAT, warm month mean temperature (WMMT), CMMT, length of growing season (LGS), growing season precipitation (GSP), mean month growing season precipitation (MMGSP), precipitation during the three wettest months (3-WET), precipitation during the three driest months (3-DRY), relative humidity (RH), specific humidity (SH), and enthalpy (ENTHAL).

The palaeoclimate was estimated, using the Physg3arc and Physg3brc CLAMP calibration data sets, together with gridded climatological data, as well as the PhysgAsia1 calibration data set (Jacques et al., 2011b) for monsoonal climates in Asia.

4.2.5. Coexistence Approach

The Coexistence Approach (CA), introduced by Mosbrugger and Utescher (1997) is a well-established method for palaeoclimate reconstruction from the palaeobotanical records. The CA is based on climatic requirements of NLRs of fossil taxa. Climatic tolerances of NLRs, namely various living plants chosen for relatives of a given fossil assemblages, are identified for a given climate variable and made available in a database as ranges. The climate under which the fossil assemblage existed is subsequently characterized by the interval, in which the number of overlapping ranges is at the maximum. The resulting range thus identified for a given climate variable is denoted as coexistence interval.

Seven climate variables (MAT, WMMT, CMMT, MAP, mean precipitation of the wettest (MPwet), warmest (MPwarm), and driest (MPdry) month) were determined for every fossil assemblage. When applying the CA in the present study we use climate requirements of extant taxa available in the Palaeoflora data base (http://www.palaeoflora.de), together with ca. 100 additional climate records compiled for the present study. These records were obtained using the standard procedure described in Mosbrugger and Utescher (1997). As chorological literature resources we used Tutin et al. (1964, 1972, 1993), Ohwi (1965), Khadija and Jafri (1979), Nazimuddin and Quasier (1982), Kharkevich (1985, 1987, 1988, 1989, 1991, 1992, 1995, 1996), FNA Editorial Committee (1993, 1997, 2000, 2002, 2003, 2006a,b,c, 2007a,b, 2009, 2010), Wu and Raven (1994, 1996, 1998, 1999, 2001), Iwatsuki et al. (1995, 1999), Kukkonen (2001), Wu et al. (2001, 2003a,b, 2005, 2006, 2007a,b, 2008a,b, 2010, 2011a,b, in preparation) and Yatskievich (2006, in preparation). As climatological resources we used Müller (1996), New et al. (2002), and WorldClim data set (http://www.worldclim.org/). Climate requirements of modern plant taxa are made available in the Appendix 1.

In order to narrow down the variable ranges all CA-based climate data obtained in this study are calibrated using modern climatic space. The procedure follows the original description of the calibrated Coexistence Approach (CA_{cal}) given in Utescher et al. (2009), and uses data processing introduced in Utescher et al. (2012). The climatic space is defined here by six dimensions, namely MAT, CMMT, WMMT, MAP, MPwet, and MPdry. Minima and maxima of these variables, obtained from the application of the CA on the fossil floras, are then compared with a world climate data set (New et al., 2002), in order to extract for each sample a climatic sub-space, interpreted as present-day analog for the fossil climate. The climatic sub-space is used to calibrate the data obtained from the CA by defining the calibrated coexistence intervals (CA_{cal}) for MAT, CMM, WMM, MAP, MPdry, and MPwet as 1-dimensional projections of the climatic sub-space (Utescher et al., 2012). The application of the CA_{cal} is considered as appropriate, particularly when studying younger palaeobotanical records because boundary conditions and climates were comparatively close to present. Climate intervals obtained from the CA_{cal} may be considerably narrower compared to primary CA ranges (cf. Utescher et al., 2009) and thus can improve the resolution of palaeoclimate reconstruction.

4.2.6. Monsoon indices

In order to measure the EAM intensity during the Early Pleistocene, various indices were calculated. Using the results of CLAMP, the monsoon intensity index (MSI) according to Xing et al. (2012) was calculated as: MSI = (3-WET − 3-DRY) × 100 / GSP. Since the above variables are not returned by CA we calculated additional indices to estimate monsoon intensity using mean monthly precipitation. A monsoon index, roughly comparable to the monsoon index intensity (MSH) according to Liu and Yin (2002) based on seasonal temperature and precipitation differences, namely $(T_S - T_W) \times (R_S - R_W)$, was calculated using monthly values following the assumptions by Liu et al. (2011) as MSH = (WMMT − CMMT) × (MPwarm − MPdry).

According to Jacques et al. (2011a), the ratios of MPwet and MPdry of MAP are good indicators of the strength of the East Asian Summer Monsoon (EASM) and the Winter Monsoon (EAWM), respectively. These indices were calculated for the early Pleistocene Suifunskaya Formation and for modern conditions (Vladivostok meteorological station; Müller, 1996).

5. Results

5.1. Growth Ring Analysis

Distinct growth rings are characteristic of the both gymnospermous and angiospermous fossil woods from the Suifunskaya Formation evidencing a well pronounced seasonality.

The ratio of early- to latewood is directly reflecting the changing environmental conditions at successive stages through the growing season. The percentage of latewood and the nature of the earlywood/latewood transition seem to be at least partly controlled by the water supply (Creber and Chaloner, 1984). In order to assist in the interpretation of growth rings in fossil wood, Creber and Chaloner (1984) devised a classification scheme to categorize different earlywood/latewood relationships. According to this classification, the fossil woods from the Suifunskaya Formation are characterized by four growth ring types in total: "B", "C", "D", and "E" (Appendix Table 3).

The type "B" was found in 87 fossil wood samples. In this type of growth rings the transition from early- to latewood is gradual and a wide band of latewood indicates a long growing season with an adequate water supply. The type "C" was observed for 98 fossil wood samples. This type of transition between early- and latewood indicates growth in the environments with very gradual changes during the growing season. The types "D" and "E" are characteristic of 210 and 148 fossil wood samples respectively. Types "D" and "E" are essentially similar to each other: both indicate growing seasons that are relatively uniform but each has a terminal event representing a cessation or retardation of cambial activity. However, the growth ring boundary is more marked in the type "D", while in the type "E" it is so faint that it almost escapes notice.

Drought period hinders the increase in radial diameter of cells in the cell expansion zone therefore if the drought is followed by a period of rainfall, larger cells will again develop, and a so-called "false" growth ring is forming (Chavchavadze, 1979; Creber and Chaloner, 1984). According to Creber and Chaloner (1984), in general, earlywood is less likely to be affected by drought than latewood because it forms when the tree is drawing upon stored moisture in the soil in the early part of the growing season. In the fossil woods studied, "false" growth rings occurred in the wood of *Picea jezoensis* (Siebold et Zucc.) Carr., *P. koraiensis* Nakai, *Piceoxylon pavlovskiense* Blokh. et Bondar., *P. ussuriense* Blokh. et O.V. Bondarenko, *Piceoxylon* sp. 1, *Piceoxylon* sp. 2, *Larix gmelinii* (Rupr.) Rupr., *L. olgensis* A. Henry and *Micromeles alnifolia* (Siebold et Zucc.) Koehne, and were observed often in earlywood.

One of the most obvious and direct influences of temperature on wood growth is a formation of so-called "frost" growth rings (Bailey, 1925). Such a ring consists of two parts: an inner part composed of cells killed by the frost and an outer part formed by the cells that develop abnormally after the frost, often with abundant traumatic vertical resin canals, ducts or cysts. In the fossil woods studied, "frost" growth rings were not observed but abundant traumatic vertical resin ducts or cysts were found in the wood of *Abies* aff. *sachalinensis* Fr. Schmidt, *Picea jezoensis*, *P. koraiensis*, *Piceoxylon pavlovskiense*, *P. ussuriense*, *Piceoxylon* sp. 1, *Piceoxylon* sp. 2, *Larix gmelinii*, and *L. olgensis*.

A total of 264 growth ring series were measured, ranging in length from 3 to 71 (mean 17.1) growth rings (Appendix Table 3). MRW per tree ranged from 0.14 to 4.26 mm, and MS ranged from 0.262 to 0.618. MS < 0.3 is characteristic of only 2 fossil wood samples out of 264 ones studied. This indicates that trees grew evenly under a favorable and uniform climate. The other 262 wood samples had MS > 0.3, i.e. trees were "sensitive" to fluctuating climate parameters.

On the basis of Growth Ring Analysis, the climate is estimated as well pronounced seasonal, temperate, probably sometimes with relatively severe weather conditions.

5.2. Multivariate Anatomical Analysis

Among 335 fossil wood samples identified, 51 belong to angiosperm wood. Dicotyledonous fossil woods attribute to 14 fossil species representing 13 wood types. The wood type is a wood with distinctive combination of characters. For example, fossil woods of *Ulmus japonica* (Rehd.) Sarg. and *U. laciniata* (Trautv.) Mayr studied herein represent the same wood type. The dataset presented in Table 1 consists of 13 wood types and 13 wood anatomical characters.

The climate was estimated using Wiemann et al.'s (1998) method as cool temperate and very humid, with MAT of 0.3 °C, MART of 28.9 °C, CMMT of −13.7 °C, MAP of 2372.9 mm, and with long dry season of 5.4 months (Table 2). By Wiemann et al.'s (1999) method MATs range from −4.2 to 39.1 °C (Table 2).

5.3. Leaf Margin Analysis

A total of 26 dicotyledonous taxa were used for the LMA. MAT was estimated with MAT of 10.06 °C, with the SE of 1.04 °C (Table 3).

5.4. Climate Leaf Analysis Multivariate Program

To apply CLAMP, a total of 26 taxa were scored. Generally climate parameters calculated by three CLAMP calibration datasets are similar (Table 3). The climate was estimated using CLAMP as temperate and rather humid with MAT of 10.4–11.5 °C and GSP of 837.5–1074.7 mm.

5.5. Coexistence Approach

Climate data of the time of Suifunskaya Formation were obtained for 6 CFs, one LF and one XF — macrofloras and 18 PFs — microfloras (Appendix Table 1; Fig. 2; Appendix 1).

The number of taxa contributed with climate data in each macroflora ranged from 10 to 48 (mean 24). The analysis of 18 microfloras was based on 18 to 35 (mean 24.7) climate datasets of extant reference taxa. Mean number of taxa was 24.3 and, according to Mosbrugger and Utescher (1997), it was sufficient for all the floras to obtain reliable results, except the CF 1 at the depth level of 8.8 m (10 taxa only). In the case of the LF climate data were calculated based on identification at the species and genus levels, respectively, because species identification based on leaf imprints is considered less reliable in general. The NLR concept of all taxa presently considered is given in Appendix 1. Generally, among 233 different NLRs used in the analysis only 3 taxa were identified as outliers (Table 4). In 20 out of 26 cases, all NLRs can coexist, in all other cases over 95% of taxa attributing high significance.

When reconstructing MAT CA intervals obtained from macrofloras are relatively narrow (mean width of CA intervals near 3.4 °C), in MAP reconstruction results are less precise (CA interval width around 420 mm at a mean). For microfloras all NLRs coexist in each case, however, owing to the commonly high taxonomic level of NLR assignment resulting CA ranges are comparatively wide. For MAT the width of CA intervals is ca. 8 °C at the mean (varies from 5 °C to 14.5 °C). The resolution is reduced by ca. 50% when compared to the macroflora.

Being applicable on all kinds of organs the CA allows for the reconstruction of a detailed climate record of the Suifunskaya Formation profile (Figs. 3 and 4). When integrating over macro- and microfloras an overall cooling trend is identified comprising two climate cycles. The lower cycle starts with a warm phase at 19.4–19.8 m, with CMMT of 0.6–1.45 °C, MAT of 11.25–13.35 °C, and WMMT of 21.8–22.25 °C. On the basis of the macroflora this phase was also the wettest in the section, with MAP being at least 974 mm, and according to microflora possibly over 1152 mm. In the part of the profile between 19.0 and 17.3 m the CMMT and the WMMT dropped by at least 3 °C, and the MAT by at

Table 1
Wood types of dicots from the Suifunskaya Formation of Pavlovskoe brown coal field.

Wood type	Vessels					Rays				Axial parenchyma			Fibers
	tang	mult	spir	<100 μm	RP	homo	het4+	>10ser	stor	para	marg	abs	sept
1. *Acer* aff. *tegmentosum*	0	0	1	1	0	1	0	0	0	1	1	1	0
2. *Betula* aff. *davurica*	0	1	0	1	0	1	0	0	0	0	1	0	0
3. *Cerasus sargentii*	0	0	1	1	0	0	0	0	0	0	0	1	0
4. *Eleutherococcus* aff. *sessiliflorus*	1	0	1	1	0	0	1	0	0	1	0	0	0
5. *Fraxinus* sp.	0	0	0	X	1	1	0	0	0	1	1	0	0
6. *Malus mandshurica*	0	0	0	1	0	1	0	0	0	0	0	0	0
7. *Micromeles alnifolia*	0	0	1	1	0	1	0	0	0	1	0	0	0
8. *Padus* aff. *maackii*	0	0	1	1	0	0	1	0	0	1	1	1	0
9. *Populoxylon* sp.	0	0	0	1	0	1	0	0	0	0	1	1	0
10. *Pyrus ussuriensis*	0	0	1	1	0	1	0	0	0	1	0	0	0
11. *Quercis primorica*	0	0	0	X	1	1	0	1	0	1	0	0	0
12. *Sambucus* sp.	0	0	1	1	0	1	0	0	0	1	0	0	0
13. *Ulmus japonica*, *U. laciniata*	1	0	1	X	1	1	0	0	0	1	1	0	0

Note: wood anatomical characters (definitions according to Wiemann et al., 1998, 1999): tang — tangential arrangement, mult — vessels with multiple perforations, spir — spiral thickenings present in the vessels, <100 μm — vessel mean tangential diameter less than 100 μm, rp — wood ring-porous, homo — rays exclusively homocellular, het4+ — rays heterocellular with 4 or more rows of upright cells, >10ser — rays commonly more than 10 cells wide, stor — rays storied, para — parenchyma predominantly paratracheal, marg — marginal parenchyma present, abs — parenchyma rare or absent, sept — fibers septate; 0 — character absent, 1 — character present, X — character cannot be used (= character "<100 μm" has no sense for ring-porous woods (Sakala, 2007)).

Table 2
Climate variable formulae.

Equation	Value of variable
No transformation (the quantities in parentheses are the percentage occurrences of the characters whose abbreviation are given)[a]	
1) $\mathrm{MAT} = 13.40 - 0.250(\mathrm{spir}) + 0.637(>10\mathrm{ser}) + 0.255(\mathrm{het4+}) + 0.416(\mathrm{stor}) - 0.213(\mathrm{abs})$	0.3 ± 1.7
2) $\mathrm{MART} = 4.16 + 0.319(\mathrm{spir}) + 0.135(<100\ \mu\mathrm{m}) - 0.373(>10\mathrm{ser}) - 0.154(\mathrm{het4+})$	28.9 ± 2.4
3) $\mathrm{CMMT} = 9.91 - 0.355(\mathrm{spir}) - 0.098(<100\ \mu\mathrm{m}) + 0.845(>10\mathrm{ser}) + 0.368(\mathrm{het4+}) + 0.528(\mathrm{stor}) - 0.210(\mathrm{abs})$	−13.7 ± 2.6
4) $\mathrm{MAP} = -6.06 + 6.332(\mathrm{sept}) + 7.901(\mathrm{abs})$	2372.9 ± 940
5) $\mathrm{DRY} = 6.81 - 0.186(\mathrm{mult}) - 0.122(\mathrm{sept})$	5.4 ± 1.4
No transformation[b]	
1) $\mathrm{MAT} = 4.69 + 0.356(\mathrm{para})$	29.3
2) $\mathrm{MAT} = 21.31 + 0.855(\mathrm{stor}) - 0.258(\mathrm{marg})$	9.4
3) $\mathrm{MAT} = 37.76 - 0.404(<100\ \mu\mathrm{m}) + 0.277(\mathrm{RP})$	13.1
4) $\mathrm{MAT} = 25.14 + 0.785(\mathrm{stor}) - 0.188(\mathrm{marg}) - 0.500(\mathrm{abs})$	1.1
5) $\mathrm{MAT} = 3.49 + 0.282(\mathrm{mult}) - 0.125(\mathrm{homo}) + 0.455(\mathrm{para})$	27.5
6) $\mathrm{MAT} = 28.91 - 0.230(\mathrm{homo}) + 0.781(\mathrm{stor}) - 0.501(\mathrm{abs})$	−4.2
7) $\mathrm{MAT} = 38.17 + 0.266(\mathrm{mult}) - 0.212(\mathrm{spir}) - 0.437(<100\ \mu\mathrm{m}) + 0.391(\mathrm{RP})$	2.6
8) $\mathrm{MAT} = 7.46 + 0.428(\mathrm{tang}) + 0.309(\mathrm{mult}) - 0.277(\mathrm{spir}) - 0.169(\mathrm{homo}) + 0.377(\mathrm{para})$	12.5
Arcsine transformation (the quantities in parentheses are the arcsine of the square roots of the proportions of the characters)	
9) $\mathrm{MAT} = -4.30 + 34.14(\mathrm{para})$	29.2
10) $\mathrm{MAT} = 21.70 + 38.23(\mathrm{stor}) - 20.29(\mathrm{marg})$	6.5
11) $\mathrm{MAT} = 27.82 - 15.16(<100\ \mu\mathrm{m}) + 24.17(\mathrm{stor})$	11.6
12) $\mathrm{MAT} = 24.78 + 36.57(\mathrm{stor}) - 15.61(\mathrm{marg}) - 16.41(\mathrm{abs})$	3.5
13) $\mathrm{MAT} = 14.80 - 16.89(\mathrm{homo}) + 24.86(\mathrm{stor}) + 14.92(\mathrm{para})$	11.4
14) $\mathrm{MAT} = 30.47 - 19.39(\mathrm{homo}) + 35.35(\mathrm{stor}) - 19.27(\mathrm{abs})$	−1.6
15) $\mathrm{MAT} = 17.07 + 25.23(\mathrm{stor}) - 23.17(\mathrm{abs}) + 13.79(\mathrm{sept})$	3.4
16) $\mathrm{MAT} = 6.25 + 27.15(\mathrm{mult}) - 15.72(\mathrm{spir}) - 21.83(<100\ \mu\mathrm{m}) + 16.88(\mathrm{RP}) + 33.43(\mathrm{para})$	39.1

[a] From Wiemann et al. (1998).
[b] From Wiemann et al. (1999).

least 2 °C. At the same the data suggest a slight drying, but the resolution of the data does not allow for this to be quantified. According to our data, it is not quite clear which depth levels in each case represent the coolest part of the cycles. These difficulties are also due to the differing time resolution that the micro- and macrofloras provide. From the macrofloras it can be assumed that the temperature culminates (CMMT −12.9–(−12.0) °C, MAT 3.3–5.3 °C, and WMMT around 20 °C) at the depth level of 15.0 m, where the XF was collected, conditions are among the coolest in the studied section, and also comparatively dry (MAP 742–850 mm). However, when comparing the XF data with the LF and PF data of the adjacent stratigraphical levels, a methodological bias referring to the NLR concepts used in each case cannot be excluded. Data based on PF imply that temperatures had already started to rise again from the depth level 17.5 m.

According to the PF, the second climate cycle begins with a warm phase at depth level from 14 to 14.5 m in the Suifunskaya profile. The signal obtained from the CF 3 at 14.0 m is less distinct (CMMT, WMMT), or not resolved (MAT). Subsequent cooling, starting at the depth level of 14.0 m, is consistently reflected, especially in the CMMT record. MAP data first show an increase (up to 11.9 m), before also declining. For the youngest macroflora CF 1, sampled at 8.8 m, the cool limits of CA intervals are among the lowest, but due to the low diversity of CF 1 the validity of the results is questionable. Regarding MAP there is a declining trend observed between depth levels 11.9 m and 11.0 m, the evolution in the youngest part of the section is not resolved with the present data.

5.6. Monsoon indices

The monsoon indices calculated are given in Table 5. MSI was estimated as 42.2–49.6 for LF at the depth level of 14.8 m. MSH varied from 834.4 to 2802.8 (mean 1343.1; standard deviation 570) during the Early Pleistocene. Our results show that the MPwet accounted for 11.0 to 17.5% (mean 13.3%; standard deviation 1.4) of MAP, whereas the MPdry accounted for 1.9 to 4.0% (mean 3%; standard deviation 0.5) of MAP.

6. Discussion

6.1. Comparison of climate data from different organs and methods

The Early Pleistocene climate of southern Primory'e was reconstructed using different types of fossil plant records and methods. Each type of palaeoclimate proxy has its advantages and limitations.

Table 3
Palaeoclimate data reconstructed for the Calabrian leaf flora recorded at the depth level 14.8 m of the section using LMA, CA (mean variables using species/genus level), CLAMP (calibration datasets: Gridded Physg3arc, Gridded Physg3brc, PhysgAsia1), and present-day climate data for the Southern Primory'e.

Climate parameter	LMA	CA	CLAMP			Present-day climate of Primory'e	
			Gridded Physg3arc	Gridded Physg3brc	PhysgAsia1	New et al. (1999)	New et al. (2002)
MAT (°C)	10.06	8.8/10.05	10.4	11.5	11.2	4.8	4.9
WMMT (°C)		20.25/22.15	22.3	23.2	22.9	20.8	20.9
CMMT (°C)		−5.35/0.05	−0.9	0.9	0.9	−14.0	−13.5
LGS (month)			6.3	6.8	6.6	5.1	5.1
GSP (mm)		707/1120[a]	1073.6	1074.7	837.5	467.4	470.1
MMGSP (mm)			157.8	158.4	124.2	92.0	92.0
3-WET (mm)			615.1	662.2	550.7	327.4	329.8
3-DRY (mm)			160.9	170.5	133.7	40.8	38.6
RH (%)			67.3	70.8	70.5	72.3	73.7
SH (g/kg)			5.9	6.5	6.7	4.99	5.3
ENTHAL (kj/kg)			306.8	310.4	311.4	298.0	299.3

[a] MAP (mm).

Table 4
Climatic outliers identified in CA analysis.

Fossil taxon	NLR(s)	Flora	Climatic parameter for out			
			MAT (°C)	CMMT (°C)	WMMT (°C)	MAP (mm)
Keteleeria zhilinii Blokh. et O.V. Bondarenko	*Keteleeria davidiana* (Bertr.) Beissner, *K. fortunei* (Andr. Murray) Carr., *K. evelyniana* Masters.	XF	++	++		+
Eleocharis maximowiczii Zins. foss.	*Eleocharis maximowiczii* Zins	CF 3		−		
Caulinia foveolata A. Br. foss.	*Najas foveolata* A. Br. ex Magn.	CF 5, 6	++	+	++	

Note: (+, ++) — too warm/wet, (−) — too cold.

Data from fossil woods were only obtained for a single depth level within the Suifunskaya section. Growth Ring Analysis is not capable of quantitatively reconstructing climate parameters, but it reveals qualitative characteristics of the climate. Growth ring width is known as one of the anatomical characters that most sensitively respond to changing conditions of tree growth (Yatstenko-Khmelevskii, 1954). MRW per each fossil wood sample studied varies quite markedly, ranging from 0.14 to 4.26 mm (Appendix Table 3). This indicates that some trees grew evenly under favorable conditions, although, some of them grew under more stress. The mean MS of the fossil wood samples studied is 0.489, i.e. >0.3 (Appendix Table 3). This indicates that climate parameters fluctuated but were close to the conditions most favorable for those species. The types of growth rings indicate that growing seasons were long and relatively uniform, mainly with an adequate water supply and environmental changes during the growing season were gradual. On other hand, the presence of “false” growth rings mainly in earlywood probably can be explained by the existence of a monsoon type climate at that time. At present, the EAM climate in southern Primory'e

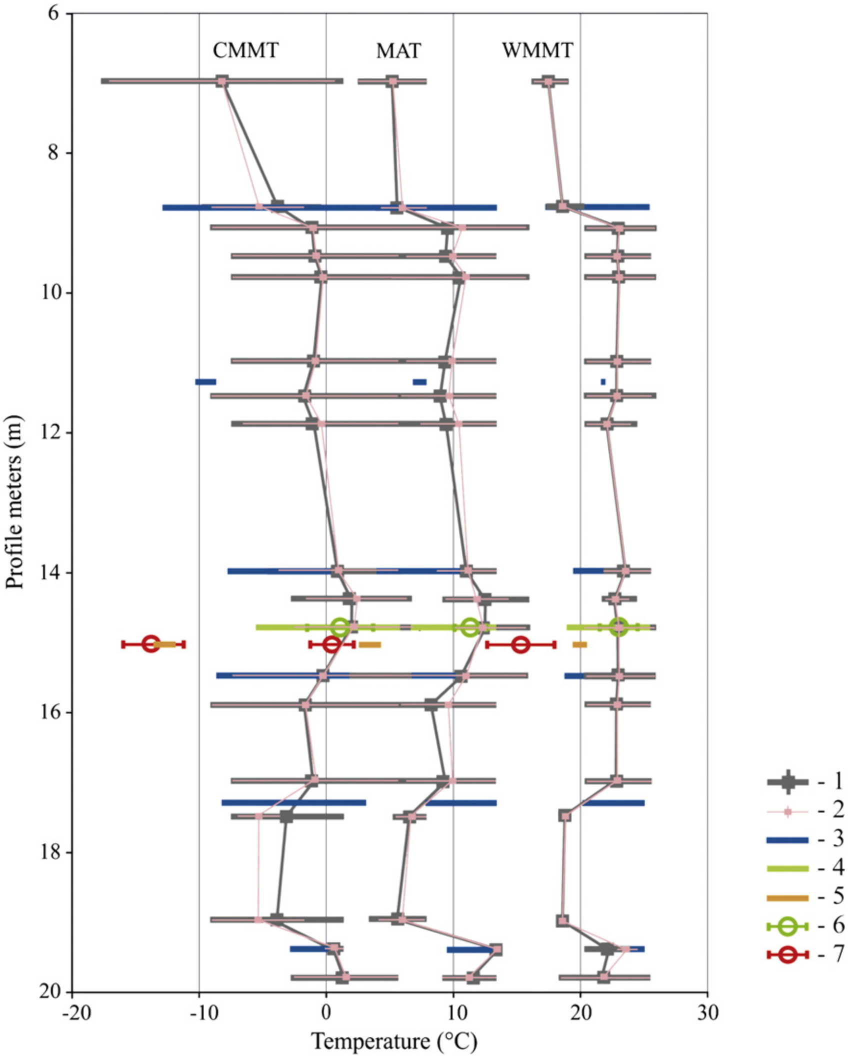

Fig. 3. Temperature records (CMMT, MAT, WMMT) for the Calabrian of the southern Primory'e reconstructed by various methods using multiple proxies: 1 — CA data obtained from palynofloras; 2 — climate data for palynofloras using the calibrated CA; 3 — CA data obtained from carpofloras; 4 — CA data obtained from the leaf flora; 5 — CA data obtained from the xyloflora; 6 — CLAMP data obtained from the leaf flora; 7 — climate data for the xyloflora based on the approach of Wiemann et al. (1998).

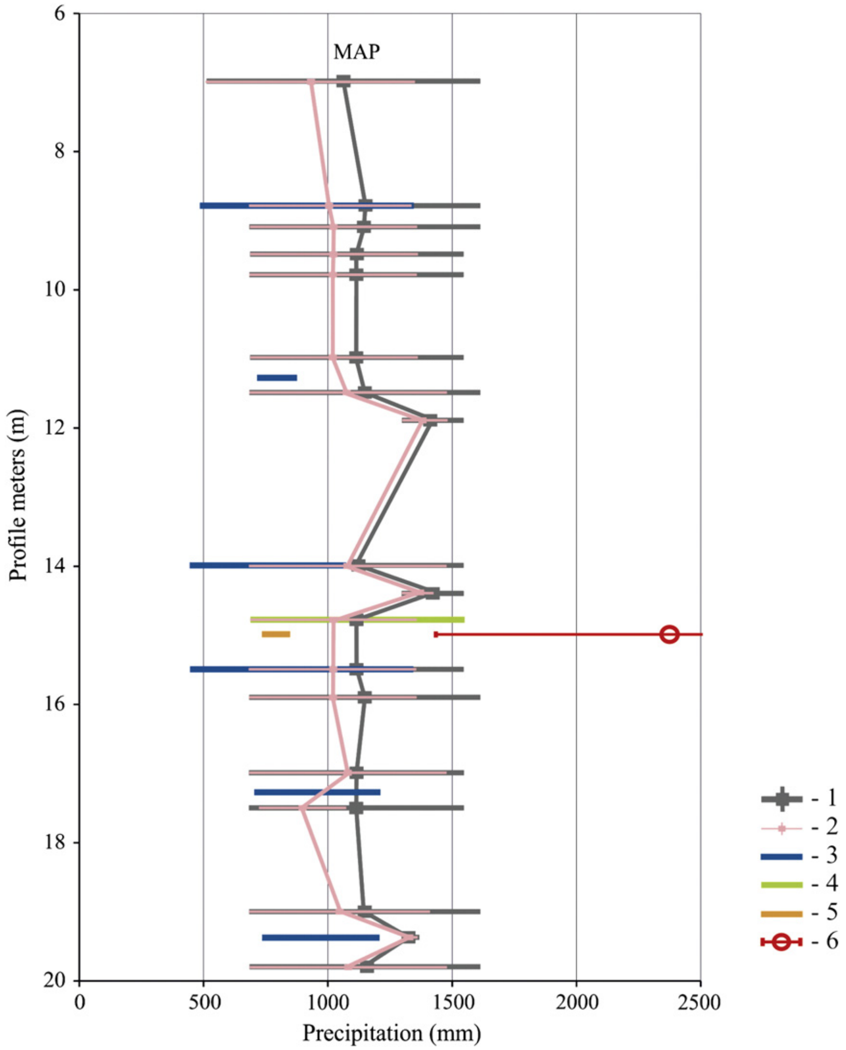

Fig. 4. Precipitation record (MAP) for the Calabrian of the southern Primory'e reconstructed by various methods using multiple proxies: 1 — CA data obtained from palynofloras; 2 — climate data for palynofloras using the calibrated CA; 3 — CA data obtained from carpofloras; 4 — CA data obtained from the leaf flora; 5 — CA data obtained from the xyloflora; 6 — CLAMP data obtained from the leaf flora; 7 — climate data for the xyloflora based on the approach of Wiemann et al. (1998).

is characterized by wet summers and dry winters, and therefore has water shortage in the soil in the early part of the growing season but a rather high GSP (Lau and Chan, 1983).

The CMMT estimate from fossil woods according to Wiemann et al.'s (1998) method that is similar to that reconstructed by the CA, was accounting for −13.7 °C and −12.9 to −12.0 °C, respectively. With MAT < 6 °C and WMMT < 20 °C (Fig. 3) the XF is by far the coolest flora in the present reconstruction. The low temperature could perhaps be explained by transportation of fossil woods to the site of deposition by a watercourse from an upland growth site or from a more continental interior setting. According to Blokhina and Bondarenko (2011), the alignment of fossil woods studied suggests their transportation to the site of deposition by a watercourse running in an east–west direction, somewhere in the foothills of the southern Sikhote-Alin Range (maximum from 200 to 300 km). The taphocoenosis based on XF represents an assemblage of woody plants characteristic of valley and slope habitats and reconstructs a possible altitudinal vegetation zonation (Blokhina and Bondarenko, 2011). Another explanation might be that the XF, as the only flora collected from a coarse grained level in the section, represents the cold part of a climate cycle.

MAP estimated from fossil woods by the above mentioned methods was very different: very high (2372.9 mm) by Wiemann et al.'s (1998) method and considerably lower (742–850 mm) by the CA. However, the Multivariate Anatomical Analysis (Wiemann et al., 1998) has its limitation because statistical evaluation requires a large number of dicot morphotypes (at least 25) within an assemblage. Because of the insufficient amount of angiosperm wood types from the Suifunskaya Formation, MAP estimated by Wiemann et al.'s (1998) method could be overstated.

The LF originates from a clay level and probably represents a warm part of the climate cycle. MAT and WMMT reconstructed by LMA, CLAMP and CA (both, species and genus based data) are closed to each other. As regards temperature variables CLAMP data almost equal the means of CA intervals obtained for the microflora from the same level (Fig. 3). Based on the genus level, the CMMT reconstructed by the CA is rather wide (from −5.5 to 5.6 °C), using CLAMP results range from −0.9 to 0.9 °C, depending on the calibration data set used (Table 3). With the species concept, considerably lower values compared to CLAMP are obtained (around −5.5 °C). Precipitation estimated by the CA using climate requirements of genera (MAP 693–1547 mm) is largely in agreement with CLAMP data (GSP 835.5–1074.7 mm). With MAP of 693–721 mm obtained using the species concept, the CA reconstruction is clearly drier compared to CLAMP. In the PhysgAsia1 calibration data set our site plots among Japanese sites and close to Chinese sites (Fig. 5).

In this context it is worth mentioning that CLAMP tends to underestimate CMMTs in cold regimes and may have reduced resolution

Table 5
Monsoon indices calculated for the Early Pleistocene Suifunskaya Formation and related values calculated from modern climate: MSI (Xing et al., 2012), MSH (Liu and Yin, 2002), MPwet/MAP and MPdry/MAP ratios (Jacques et al., 2011a); all calculations based on uncalibrated data.

	Depth (m)	CMMT (°C)	WMMT (°C)	MPwarm (mm)	MPwet (mm)	MPdry (mm)	MAP (mm)	MSI	MSH	MPwet/MAP	MPdry/MAP
XF	15.0	−12.45	20.0	99.5	139.0	14.5	796.0	–	2758.3	0.175	0.024
LF	14.8	0.05	22.15	117.5	159.0	31.0	1120.0	42.2–49.6	1911.7	0.110	0.019
CF	8.8	−12.4	18.8	81.0	125.0	33.0	740.5	–	1497.6	0.133	0.032
	11.3	−9.5	21.8	83.5	105.0	18.0	740.5	–	2050.2	0.137	0.026
	14.0	−3.55	21.35	117.5	142.0	32.5	805.0	–	2116.5	0.164	0.038
	15.5	−3.45	21.1	87.0	122.0	27.5	651.5	–	1460.7	0.120	0.027
	17.3	−2.7	22.55	134.0	138.5	23.0	77.5	–	2802.8	0.145	0.024
	19.4	−1.15	23.3	108.0	138.5	27.0	974.0	–	1980.5	0.142	0.024
PF	7.0	−8.2	17.5	73.0	136.5	25.0	1065.0	–	1233.6	0.145	0.033
	8.8	−3.9	18.55	73.0	139.0	26.0	1152.0	–	1055.2	0.136	0.040
	9.1	−1.15	22.95	73.0	139.0	26.0	1152.0	–	1132.7	0.136	0.040
	9.5	−0.95	22.8	70.5	139.0	26.0	1119.5	–	1056.9	0.136	0.031
	9.8	−0.35	22.95	70.5	139.0	26.0	1119.5	–	1036.9	0.136	0.031
	11.0	−0.95	22.8	63.0	139.0	26.0	1119.5	–	878.8	0.136	0.031
	11.5	−1.75	22.95	73.0	139.0	26.0	1152.0	–	1160.9	0.121	0.035
	11.9	−0.95	22.25	70.5	170.0	29.5	1426.0	–	951.2	0.119	0.025
	14.0	0.85	23.5	76.5	147.0	26.0	1119.5	–	1143.8	0.131	0.029
	14.4	2.05	22.95	76.5	170.0	29.5	1426.0	–	982.3	0.119	0.025
	14.8	2.05	22.95	70.5	139.0	26.0	1119.5	–	930.1	0.136	0.031
	15.5	−0.35	22.95	70.5	139.0	26.0	1119.5	–	1036.9	0.136	0.031
	15.9	−1.75	22.8	73.0	139.0	26.0	1152.0	–	1153.9	0.136	0.039
	17.0	−0.95	22.8	76.5	147.0	32.0	1119.5	–	1056.9	0.131	0.029
	17.5	−3.1	18.8	70.5	139.0	32.0	1119.5	–	843.2	0.124	0.029
	19.0	−3.9	18.55	73.0	139.0	32.0	1152.0	–	920.5	0.121	0.028
	19.4	0.6	22.25	80.0	150.5	39.5	1333.0	–	933.5	0.113	0.030
	19.8	1.45	21.8	73.0	145.0	32.0	1152.0	–	834.4	0.126	0.028
Modern		−14.7	20.0	145.0	145.0	10.0	721.0	61.3–62.0	4684.5	0.200	0.140

when CMMTs well below freezing are regarded. This is explained by the fact that the climate of the cold season is less clearly encoded in leaf morphology compared to growing season climate (Spicer et al., 2004). In our CMMT reconstruction, CLAMP results agree with the warm, regional signal obtained from the PFs, and with the comparatively unspecific result using the CA at the genus level, but is too warm by ca. 5 °C when relying on the species interpretation of the fossil record.

Moreover it is known that leaf floras may have a cooler climatic aspects compared to carpofloras or palynofloras occurring at the same stratigraphic level (Utescher et al., 2000). In the case of our flora, leaves were transported to the site of deposition most probably from nearest plant habitats, i.e. over a distance of 100–200 m at a maximum, therefore in contrast to XF, LF recorded the microclimate at the site. The plant association points to a riparian wetland, an environment characterized by cooler and more humid conditions compared to zonal habitats (Rykken et al., 2007).

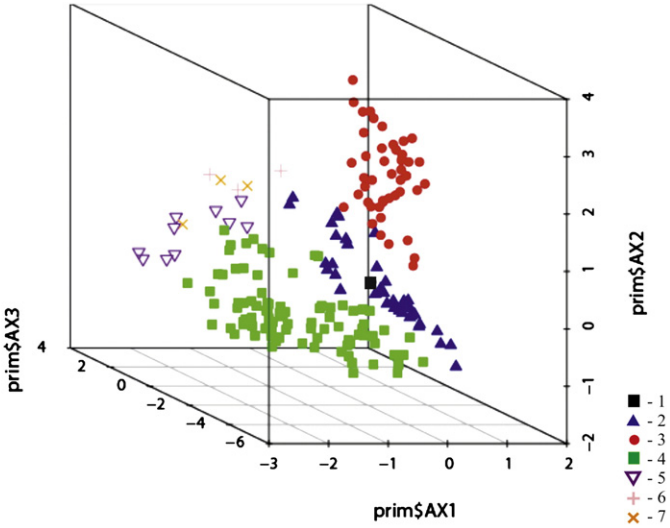

Fig. 5. Southern Primory'e leaf site plotted among CLAMP data using the PhysgAsia1 calibration data set: 1 — the southern Primory'e site; 2 — Japanese sites; 3 — Chinese sites; 4 — North American sites; 5 — New Caledonia sites; 6 — Puerto-Rico sites; 7 — Fiji sites.

As already stated above the CA can be used for various types of fossil plant records, however, every type has its advantages and limitations for methodological reasons. In particular, climatic resolution of macrofloras studied is considerably higher compared to microfloras because NLRs for macrofloras have mainly a lower taxonomic level, therefore CA ranges for macrofloras are narrower than those of microfloras. According to Utescher et al. (2012), CA data obtained from microflora are easily capable of reflecting temporal trends due to more frequent occurrences of microfloras. However, in the majority of cases CA data based on microfloras do not allow for quantifying minor climatic changes (Utescher et al., 2012). In our case, the microfloras originate from a total of 18 levels therefore they provide a good time resolution in the climate record and CA displays more details of the temporal changes in climate.

From 18 PFs studied 5 PFs originate from levels where macrofloras were found, and where this occurs the reconstructed climate data are largely congruent (Figs. 3 and 4). However, the overall narrower climate ranges obtained from the mainly local macroflora tend to cover the cooler and/or dryer ends of the broader ranges derived in the microflora-based reconstruction which has a lower climatic resolution and reflects regional rather than local climate. The fact that microflora-based data tend to indicate warmer conditions is explained by a mainly northward aeolian transport of pollen grains during summer (cf. monsoon).

6.2. Cyclicity in the section

Microflora-based CA data reveal an overall cooling and drying trend within the Calabrian climate in southern Primory'e. Moreover, climate reconstruction reveals small-scale climate variability, with two distinct warm phases at depth levels 19.4–19.8 and 14.0–14.8 m and a third, less clear, at depth level 9.1–9.8 m (Figs. 2 and 3). Based on the available time control outlined in Section 2, the observed cycles, not only expressed in temperature fluctuations but also in the proportion of MPwet to annual rainfall (Fig. 2), can tentatively be correlated to the global oxygen isotope record (Lisiecki and Raymo, 2005), with the two distinct warm peaks in our record corresponding to MIS 25 and MIS 21, respectively. However, it can be assumed that the record we obtained in this fluviolacustrine environment is not complete. Most coarse-grained parts of the strata are not represented by data, and thus our record may mainly document the climate and environments of warm phases while the cold parts of the cycles are missing. In the Quaternary, the area of south RFE was not covered with ice sheets and was characterized only by the presence of small mountain glaciers, mostly in the Sikhote-Alin Mountains (Golubeva and Karaulova, 1983; Korotkii et al., 1996). Therefore, glacial sediments are absent in the profile. However, we assume that the finer-grained, flora-bearing sediments in the section accumulated during warmer phases, whereas the gravels were deposited during cooler phases, under a low eustatic sea-level. This concept is supported by that fact that the only flora found in the gravels (XF at depth level 15.0 m) revealed coolest conditions (Fig. 2).

6.3. Comparison with Early Pleistocene climate data from neighboring areas of the south RFE

According to Golubeva and Karaulova (1983) and Korotkii et al. (1996), the overall cooling of the climate in the late Pliocene–early Pleistocene provoked a decrease in the diversity and composition of thermophilic broad-leaved deciduous forests in Primory'e. In the Early Pleistocene, the vegetation of the southern and south-eastern parts of Primory'e was similar to the deciduous forests now growing in the northern part of the Honshu Island, under a climate with MAT of 9–10 °C, CMMT of −2–(−3) °C, and WMMT of 22–24 °C. However, the southern part of the Khanka Plain and surrounding foothills, probably, were already covered by a more continental-type, forest-steppe vegetation. The vegetation existing in the south-western part of Primory'e was similar to the modern vegetation of the temperate to warm-temperate subzone of north China and the northern part of the Korean Peninsula, with MAT of 6–13 °C (Golubeva and Karaulova, 1983; Korotkii et al., 1996).

In the first half of Early Pleistocene, the vegetation of the area of lower Amur River basin was similar to the modern one of southern Primory'e and the northern part of the Korean Peninsula with MAT of 2–6 °C, CMMT of −6–(−12) °C, WMMT of 18–24 °C, and MAP of up to 1000 mm, i.e. climate was warmer than at present (Golubeva and Karaulova, 1983).

Today, the area of upper Amur River basin occupies an intermediate position between the area under the influence of the EASM and that with strongly continental climate. However, in the Late Pliocene–Early Pleistocene, the vegetation of this region continued to have a significant similarity to the vegetation of Primory'e and the lower Amur River basin. Significant differences appeared in the second half of Early Pleistocene because of intensification of continental climate (Golubeva and Karaulova, 1983).

Aleksandrova (1972) compared the vegetation growing in the middle part of Sakhalin Island in the beginning of Early Pleistocene with the modern vegetation of the Khanka Plain and the Hokkaido Island. On the base of this compilation she supposed the following characteristics of the Early Pleistocene climate in the Sakhalin Island: MAT of 6–8 °C, CMMT of −6–(−10) °C, WMMT of up to 20 °C, and MAP of 400–700 mm.

Thus, according to a compilation of Early Pleistocene climate data of some areas of the south RFE (Table 6), the Early Pleistocene climate of southern Primory'e reconstructed using multiple proxies was warmer and wetter in comparison with neighboring areas of the south RFE.

6.4. Comparison with modern climate of southern Primory'e

The south of RFE is located between 42 and 48°N in the temperate zone, under a strong influence of the EAM Systems. The specifics of the natural environment depend on many factors, the major one being its geographical position at the eastern margin of a large continental area which strongly cools in winter and warms up in summer. In winter, this area is under the influence of cold and dry air masses flowing to the south-east (the EAWM). In summer, the area is affected by relatively cool and moist air of the Sea of Japan, and air flow is directed mainly to the north-west (the EASM). The temperature for different areas of southern Primory'e varies and mainly depends on atmospheric circulation and relief. The precipitation is distributed irregularly over the year and depends on specific regions of Primory'e, while most of the precipitation falls during summer (Khramtsova, 1966a,b).

According to our reconstruction the climate of the southern Primory'e was significantly warmer and wetter in Calabrian time when compared to the present (Figs. 3 and 4), at least during the warm phases. For instance, in the warm phase at the depth level of 19.4 m, the mean MAT was 13.35 °C, the CMMT was 0.6 °C and the WMMT was 23.65 °C. According to New et al. (1999, 2002), the MAT of southern Primory'e at present is 4.8–4.9 °C, the CMMT is −13.5–(−14.0) °C and the WMMT is 20.8–20.9 °C (Table 3). Interestingly, highest anomalies with respect to the present of almost 10 °C are evident for the CMMT. In the cooler phases, annual mean and summer temperatures were close to the present, CMMTs however usually stayed above the present level. This might point to the fact that the Siberian High had not reached its present-day intensity at that time. Only on basis of fossil woods which originate from the coarse sediments of the Suifunskaya Formation (Fig. 2), there is evidence that during glacial phases the CMMT had fallen to the present-day level (Fig. 3). Additionally we also observe a reduction of precipitation from the Calabrian to present time (Table 3), especially for the dry season. According to New et al. (1999, 2002), GSP of southern Primory'e at present is 467.4–470.1 mm with 3-DRY

Table 6
Climate reconstruction for the southern Primory'e (this study) compared to other areas of southern RFE in the Early Pleistocene, and present-day climate of southern Primory'e.

Climate parameter	Early Pleistocene southern Primory'e, total range of observed climatic variability (this study)	Southern and south-eastern Primory'e (Golubeva and Karaulova, 1983; Korotkii et al., 1996)	South-western Primory'e (Golubeva and Karaulova, 1983; Korotkii et al., 1996)	Area of the lower Amur River basin (Golubeva and Karaulova, 1983)	Sakhalin Island (Aleksandrova, 1972)	Present-day climate of southern Primory'e (New et al., 1999, 2002)
MAT (°C)	2.5–13.3	9–10	6–13	2–6	6–8	4.8–4.9
WMMT (°C)	18.9–25.7	22–24	–	18–24	Up to 20	20.8–20.9
CMMT (C°)	−10.5–2.05	−2–(−3)	–	−6–(−12)	−6–(−10)	−13.5–(−14.0)
MAP (mm)	707–1330	–	–	Up to 1000	400–700	467.4–470.1

38.6–40.8 mm, whereas in the Calabrian (at the depth level 14.8 m) GSP is 837.5–1074.7 mm with 3-DRY 133.7–170.5 mm (Table 3).

6.5. Monsoon

All our precipitation data point to a reduced intensity of the EAM Systems in the Calabrian compared to present day (Table 5). This is indicated by a lower MSI from 42.2 to 49.6 in the Calabrian, compared to 61.3–62.0 at present. The MSH value for the Suifunskaya Formation Early Pleistocene varies from 834.4 to 2802.8 (mean 1343.1), in comparison to 4684.5 obtained for the present-day situation. The similar or higher past WMMT coupled with similar or lower CMMT indicates a lower (in the basal part of the profile) or similar (for XF at the depth level 15.0 m) seasonality of temperature during the Early Pleistocene compared to today. The proportions of MPwet and MPdry to yearly precipitation according to Jacques et al. (2011a) support these results. Except for XF where a MPwet/MAP value of 0.175 is only slightly below the present day ratio (0.2) the calculated proportions of summer and winter precipitation suggest that both, EASM and EAWM were considerably weaker than today. However, the Early Pleistocene climate of Primory'e was characterized by a pronounced seasonality of precipitation (MPwet 105–170 mm; MPdry as 18–39.5 mm). MPwet/MAP and MPdry/MAP ratios obtained from the PFs tend to be lower compare to macroflora-based data. This may be attributed to the generally wider CA intervals that the calculation is based on. While no clear trend is shown for MPdry/MAP along the section, the proxy for EAWM intensity, the MPwet/MAP index, considered as indicative for the intensity of the EASM, displays a long-term increasing trend along the section, together with small-scale variations, in line with the temperature variability (Fig. 2).

There are vast literature resources discussing the Pleistocene evolution of the EAM Systems that are based on various proxies, partly leading to controversial results and conclusions. Commonly, a strong coupling of monsoon intensity with glacial/interglacial cycles is assumed (e.g., An et al., 1990; Ding et al., 1995; Liu and Ding, 1998; Tian et al., 2004; Hao and Guo, 2005; Ao et al., 2010). On the other hand, there are also other factors controlling monsoon intensity such as the uplift of the Himalayan–Tibetan edifice (e.g., An et al., 2001; Liu and Yin, 2002; Xiong et al., 2006). Our data do not resolve any distinct increasing or decreasing trend of EAWM intensity during the Calabrian in southern Primory'e but expose EASM increase along the regarded time-interval. Moreover, our data indicate that a significant intensification of the EAM Systems occurred in post-Calabrian times. This coincides with observations made from susceptibility measured from loess sections in the central Chinese Loess Plateau where strongest increase of EAM intensity and amplitudes of variation occurred at ca. 0.6 Ma, postdating our sequence (Xiong et al., 2006). As regards short-term variability of the MPwet/MAP index, present results point to a stronger EASM impact on the southern Primory'e in the warmer parts of the climate cycles.

7. Conclusions

Two large climatic cycles with warmer intervals at ca. 19.4–19.8 and 14.0–14.8 m were observed during the overall cooling and drying trend of the Calabrian climate in southern Primory'e. During the warm phases, the climate of southern Primory'e in the Calabrian time was significantly warmer and wetter, especially the cold season. In the cold phases, climate was similar to modern, or even slightly cooler. The fluctuations of temperature variables, indicating warmer intervals at ca. 19.4–19.8 and 14.0–14.8 m, can tentatively be correlated to the global oxygen isotope record with the warm peaks corresponding to MIS 25 and MIS 21, respectively. The Early Pleistocene climate of southern Primory'e, as reconstructed using multiple proxies, was warmer and wetter compared to neighboring areas of the south RFE. The effect of the East Asian Monsoon Systems on the climate of the southern Primory'e was less pronounced than at present.

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