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# Strong evidence for the influence of solar cycles on a Late Miocene lake system revealed by biotic and abiotic proxies

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ABSTRACT

The Late Miocene paleogeography of central Europe and its climatic history are well studied with a resolution of c. $10^6$ years. Small-scale climatic variations are yet unresolved. Observing past climatic change of short periods, however, would encourage the understanding of the modern climatic system. Therefore, past climate archives require a resolution on a decadal to millennial scale.

To detect such a short-term evolution, a continuous 6-m-core of the Paleo-Lake Pannon was analyzed in 1-cm-sample distance to provide information as precise and regular as possible. Measurements of the natural gamma radiation and magnetic susceptibility combined with the total abundance of ostracod shells were used as proxies to estimate millennial- to centennial scale environmental changes during the mid-Tortonian warm period.

Patterns emerged, but no indisputable age model can be provided for the core, due to the lack of paleomagnetic reversals and the lack of minerals suitable for absolute dating. Therefore, herein we propose another method to determine a hypothetic time frame for these deposits.

Based on statistical processes, including Lomb–Scargle and REDFIT periodograms along with Wavelet spectra, several distinct cyclicities could be detected. Calculations considering established off-shore sedimentation rates of the Tortonian Vienna Basin revealed patterns resembling Holocene solar-cycle-records well. The comparison of filtered data of Miocene and Holocene records displays highly similar patterns and comparable modulations. A best-fit adjustment of sedimentation rate results in signals which fit to the lower and upper Gleissberg cycle, the de Vries cycle, the unnamed 500-year- and 1000-year-cycles, as well as the Hallstatt cycle. Each of these cycles has a distinct and unique expression in the investigated environmental proxies, reflecting a complex forcing-system. Hence, a single-proxy-analysis, as often performed on Holocene records, should be considered cautiously as it might fail to capture the full range of solar cycles.

## 1. Introduction

Understanding climate-driving mechanisms is a crucial topic in many current research projects from various scientific fields due to the high impact on all life on Earth. Studying recent climate systems is essential to recognize modern climatic patterns; though, future predictions require insights into past climatic evolution.

Unfortunately, historic reports of climatic parameters are scarce. Western scientists started recording temperature and precipitation since 1850 (Versteegh, 2005). This time span, however, covers mainly that part of history where climate was already highly influenced by humans (Tiwari and Ramesh, 2007). Furthermore, direct measurements of sun's emitted energy dates back only to the first satellite documentation from the year 1978 (e.g. Versteegh, 2005; Tiwari and Ramesh, 2007; Lockwood, 2009; Gray et al., 2010). Thus, both observations are too short to allow unequivocal conclusions on natural climate behavior. Despite this problematic issue, the combination of direct measurements of solar energy by satellites as well as weather stations around the globe, verified the positive correlation of sun and climate (Beer et al., 2000; Versteegh, 2005). Temperature and precipitation patterns are influenced by energy sent off by the sun, reaching the Earth's atmosphere as so-called cosmic rays. Though the first impression, this pattern is inconstant. Regular changes could be linked to the sun's movement (Charcátová, 2000; Versteegh, 2005) and phenomena such as solar eruptions or the quasi-periodic in- and decrease of sunspots.

Sunspots, appearing as dark spots on the sun's surface, were recorded already by ancient Chinese astronomers (Hoyt and Schatten, 1998). More intensive studies were possible due to the invention of first telescopes culminating finally in the direct

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observation and measurements by satellites (Eddy, 1976; Hoyt and Schatten, 1998). An iterative process in respect to the amount of visible sunspots was observed for the first time by Schwabe (1844), who reported a steady in- and decrease within a 11-year cyclicity (= Schwabe cylce or sunspot-cycle). Although sunspots cause a local decrease in emitted energy, the surrounding surface of the sun releases energy in a higher degree. Accordingly, a higher number of sunspots leads to more solar power hitting the Earth's atmosphere. Satellite measurements revealed these variations to account for 0.1% of the oscillation of solar irradiance within 11 years (Lean et al., 1995). Longer cycles may modulate the intensity of the shorter ones, causing extreme climatic events. Phases of almost completely lacking sunspots are discussed to correlate with the cool historical periods, such as the Spörer Minimum (1460–1550), the Dalton Minimum (1790–1830) and the Maunder Minimum (1645–1715) (Eddy, 1976; Lean et al., 1995; Versteegh, 2005 and therein). Thus, the longest phase of dearth on sunspots during the late 17th century, also called the Maunder Minimum or the Little Ice Age, is discussed to be severely influenced by solar forcing (Eddy, 1976; Robock, 1979; Mörner, 2010).

The Gleissberg cycle is one of the slightly longer solar cycles, probably modulating the Schwabe cycle (Wolf, 1862; Gleissberg, 1939). Firstly assumed to have a duration of 88-years, Ogurtsov et al. (2002) detected a characteristic split into a low-frequency band signal of 50–80 years and a high-frequency signal between 90 and 140 years.

Except for the Gleissberg cycle, direct satellite measurements display neither enough data nor time to proof the existence of other cycles. Therefore, proxy data are necessary to postulate and test such longer periodicities. The best established method is the analysis of time series of atmospheric radioactive isotopes such as $^{14}$C (e.g. Stuiver and Braziunas, 1989; Damon and Sonett, 1991; Perisykh and Damon, 2003; Solanki et al., 2004) and $^{10}$Be (Beer et al., 1990; Wagner et al., 2001; Usoskin et al., 2003; Solanki et al., 2004) in combination with the total solar irradiance (TSI; e.g. Bard et al., 2000). Their production-rate in the atmosphere is directly linked to the amount of incoming cosmic rays, and thus allows a direct reconstruction of solar intensity (Tiwari and Ramesh, 2007).

Consequently, a ~208 year-cyclicity, named de Vries or Suess cycle (Damon and Sonett, 1991; Stuiver and Braziunas, 1993; Wagner et al., 2001), is documented in various Holocene records (e.g. Schimmelmann et al., 2003; Raspopov et al., 2008; Taricco et al., 2009; Incarbona et al., 2010; Di Rita, 2011). It might as well be present from historical sunspot observations (Ma and Vaquero, 2009). Its influence on several climatic parameters has been discussed by Raspopov et al. (2007), who document a non-linear response of the climate system in various geographic regions.

Longer time-period sun cycles display frequencies of ~500 to 550 years (Stuiver et al., 1995; Chapman and Shackleton, 2000), ~1000 years (Stuiver et al., 1995; Chapman and Shackleton, 2000; Debret et al., 2007) and ~2400 years (Hallstatt cycle) (Damon and Sonett, 1991; Charcátová, 2000; Nederbragt and Thurow, 2005). Although these cycles appear in many studies their impact on climate is poorly resolved. A climate-link to wind stress and humidity/aridity is suggested only for the Hallstatt cycle (Nederbragt and Thurow, 2005). No direct nexus is published for the other cycles, but highly expected since they all depend on solar activity.

Most studies on solar cycles are confined to Pleistocene and Holocene records due to limits set by the radioactive isotopes (Bard and Frank, 2006). A further problem is the availability of solid age-models with an appropriate high time-resolution. Therefore, studies outside the '$^{14}$C-range' usually concentrate on annually preserved records such as lake varves (Milana and Lopez, 1998; Raspopov et al., 2008; Lenz et al., 2010).

Nearly all the studies, however, center on a single proxy, which may represent only individual feedback patterns to solar activity. Therefore, we try to achieve a more detailed and complex picture by analyzing three independent but coeval 600-data-point-sets comprising natural gamma radiation, magnetic susceptibility and the total amount of ostracods. The target is a 6-m-long core with Upper Miocene lake sediments of ancient Lake Pannon in the Vienna Basin (Austria).

## 2. Geological setting

Lake Pannon (Fig. 1) covered the Pannonian Basin complex in central and south-eastern Europe during the Miocene and Pliocene. It formed at c. 11.6 Ma when the marine Paratethys Sea retreated to the east. The remaining lake was a brackish and slightly alkaline lacustrine system (Magyar et al., 1999; Harzhauser et al., 2004; Piller et al., 2007; Harzhauser and Mandic, 2008). Lake Pannon experienced its maximum extension of c. 290,000 km² during the Tortonian between 10.5 and 10.0 Ma.

In the Vienna Basin, this phase is recorded by the Bzenec Formation, which crops out at the opencast pit Hennersdorf (Fig. 1), situated app. 10 km south of the center of Vienna. It currently exposes roughly 14 m of blue-grey clays and silts with several mollusc coquinas and scattered plant debris. Information about the lithology and biostratigraphy of the Hennersdorf section was already published in more detail by Harzhauser and Mandic (2004) and Harzhauser et al. (2008). The mollusc fauna represents assemblages of the regional middle Pannonian stage, corresponding to the middle Tortonian (Magyar et al., 1999). Magnetostratigraphy allowed a correlation with the long normal chron C5n (Magyar et al., 1999). Correlation with astronomically tuned well-logs in the Vienna Basin suggests an absolute age of 10.5–10.4 Ma for the section (Harzhauser et al., 2004; Lirer et al., 2009).

In 2009, a 15-m-long core was drilled in the clay pit of which the lower 6 m could be drilled without core break. The core comprises grey-green silty clay with occasionally occurring plant debris and mollusc coquinas; bioturbation is rare. The lower 6 m are rather homogenous; a slight fining upward trend occurs in the lower part indicated by a gradual shift from clayey silt (samples 1540 to 1230) to silty clay (sample 1231 to 979). Upsection follows again silty clay (sample 980 to 940). The upper part of the core, which is not analyzed herein, displays a coarsening upward trend with increasing amounts of silt and few fine sand layers in the uppermost part (Fig. 2a).

## 3. Methods

### 3.1. Sampling

The herein analyzed 6-m-core with a diameter of 15 cm was drilled at the clay pit of Hennersdorf (N48°05′52.6″ E016°21′15.8″). We focus on the samples from core-depth 1540 cm (named sample 1540) up to 941. This results in a total of 600 continuous and equal-spaced data points. All parts of the core were marked with a 1-cm-scale on the outside, before they were divided into two halves. One of these is kept for future studies in the Natural History Museum Vienna.

First, lithology and macroscopic fossil content such as mollusc debris and plant fossils were evaluated for each sample-cm. By the same strict sample distance, 600 measurements were taken for natural gamma radiation and magnetic susceptibility. Natural gamma radiation was measured with a hand held "Compact Gamma Surveyor" (Scintillation Gamma Radiameter) and the magnetic susceptibility was measured with an "SM-20" magnetic susceptibility meter with a sensitivity of $10^{-6}$ SI units (GF Instruments, Brno, Czech Republic). Afterwards the core was cut into 1-cm-thick slices for micropaleontological investigation. Each of these samples was dried, weighed and further treated with $H_2O_2$ and sieved with 125, 250 and 500 µm