

Solar influence of decadal- to millennial-scale climate variability in the mid-Cretaceous Supergreenhouse: Insights from a Mongolian lacustrine record

*Hitoshi Hasegawa¹, Hisao Ando², Nagayoshi Katsuta³, Yasushi Muraki⁴, Niiden Ichinnorov⁵, Masafumi Murayama⁶, Koshi Yamamoto⁷, Tohru Ohta⁸, Takashi Hasegawa⁹, Masanobu Yamamoto¹⁰, Noriko Hasebe¹¹, Ulrich Heimhofer¹², Masayuki Ikeda¹³, Shoji Nishimoto¹⁴, Koichi Yamaguchi¹⁵, Fumio Abe⁴, Ryuji Tada¹⁶

1. Faculty of Science and Technology, Kochi University, 2. Department of Earth Sciences, Faculty of Science, Ibaraki University, 3. Faculty of Education, Gifu University, 4. Institute for Space-Earth Environmental Research, Nagoya University, 5. Institute of Paleontology and Geology, Mongolian Academy of Sciences, 6. Faculty of Agriculture and Marine Sciences, Kochi University, 7. Department of Earth and Environmental Studies, Nagoya University, 8. Faculty of Education and Integrated Arts and Sciences, Waseda University, 9. Faculty of Science, Kanazawa University, 10. Faculty of Environmental Earth Science, Hokkaido University, 11. Institute of Nature and Environmental Technology, Kanazawa University, 12. Institut für Geologie, Leibniz Universität Hannover, 13. Institute of Geoscience, Shizuoka University, 14. Nagoya City Science Museum, 15. Nagoya Municipal Industrial Research Institute, 16. Department of Earth and Planetary Science, the University of Tokyo

Climatic oscillations on multidecadal- to millennial- time scales are widely recognized in the Holocene and last glacial paleoclimatic records. Given the marked correlation with cosmogenic radionuclide production rates, changes in solar activity are proposed to cause the observed climatic oscillations (e.g., ~210-year de Vries cycle, ~1000-year Eddy cycle, and ~2300-year Hallstatt cycle; e.g., Steinhilber *et al.*, 2012; Adolphi *et al.*, 2014; Moffa-Sanchez *et al.*, 2014; Soon *et al.*, 2014). Evidence of a ~1500-year climate cycle is also reported mainly from North Atlantic and Arctic records (i.e., Bond events in the Holocene and Dansgaard-Oeschger cycles (DOC) in the last glacial), although a causal link of the ~1500-year cyclicity with internal climate variability and external solar forcing remains largely controversial (e.g., Bond *et al.*, 2001; Braun *et al.*, 2005; Debret *et al.*, 2009; Muscheler, 2012; Barker *et al.*, 2015; Buizert & Schmittner, 2015). However, the existence of decadal-millennial climatic cycles and their relationship with solar variations have not been demonstrated prior to the last glacial, except for a Miocene lake record (Kern *et al.*, 2012), essentially due to the lack of appropriate datasets based on reliable proxy and archives.

Here, we present evidence of decadal- to millennial-scale climate variability during the mid-Cretaceous (Early Aptian) from a Mongolian lacustrine record (Shinekhudag Formation). Depositional age of the Shinekhudag Formation is defined as between 123.8–118.5 Ma based on the radiometric age constraints (Hasegawa *et al.*, 2018). Strata of the formation is composed of rhythmically alternating beds of dark grey shale and light grey dolomite, interpreted to reflect orbital-scale precipitation changes. Based on seasonally-resolving analyses of the varve record present in the shale beds by using a fluorescent microscope, we reconstructed changes in algal organic matter flux, most probably reflecting changes in lake surface productivity controlled by strength of summer insolation, for a 5.5 cm thick interval (corresponding to ca. 1090 yr duration). The algal organic matter flux proxy shows periodicities of ca. 3–5, 11, 35–40, 90–120, 220, and 360–400 years. The obtained cyclicities seem to correspond to the well-documented solar activity cycles (11 year Schwabe cycle, 88–105 year Gleissberg cycle, and ~210 year de Vries cycle). Particularly, changes in algal productivity appear to reflect a pronounced 11 year Schwabe cycle, which is not so obvious in Holocene record (e.g., Czymik *et al.*, 2016; Novello *et al.*, 2016).

We further performed decadal-resolving elemental composition analyses for a 20 m thick core interval (corresponding to ca. 200 ky duration) by using a μ XRF core scanner (COX, ITRAX), in order to reconstruct centennial- to millennial-scale climatic variability in the mid-Cretaceous. The precipitation proxy (Ca/Ti) record shows periodicities of ca. 400–500, 1000, 1400–1450, 2000–2300, and 3500–4000 years. The 1000 and 2300 years' cyclicities are corresponding to Eddy and Hallstatt cycles of invoked long-term solar activity change. Thus, our finding suggests that a solar influence of decadal- to millennial-scale climatic oscillations existed during the mid-Cretaceous "Supergreenhouse" period. In addition, the variation pattern of the 1400–1450 years' cycle observed in the Mongolian lake record appears to be similar to the DOC of the last glacial. Many studies (e.g., Barker *et al.*, 2015; Buizert & Schmittner, 2015) excluded a solar forcing origin of ca. 1500 year' climate variability of DOC and interpreted the DOC to be triggered by internal variability of either polar iceberg calving or oceanic circulation changes in the North Atlantic and Arctic oceans. However, lake records of both the Miocene (Kerns *et al.*, 2012) and the mid-Cretaceous (this study) revealed that existence of similar periodicities of climate oscillations, although polar-ice volume and land-ocean distribution settings in both periods are largely different compared with the last glacial. Therefore, our finding supports the idea of persistent external pacing of 1400–1500 year' s climate variability (Bond *et al.*, 2001; Braun *et al.*, 2005). As noted by Muscheler (2012), although 1500 year cyclicity is not observed in spectral characteristics of solar variation records in the Holocene, it may be still premature to rule out solar forcing altogether. Our findings further suggest the existence of another climate stability mode which strengthened millennial-scale climate oscillations in the mid-Cretaceous "Supergreenhouse" world, not only in the glacial mode (Barker *et al.*, 2011).

Keywords: decadal-scale, millennial-scale, Climate variability , Lacustrine varve, Cretaceous, Solar activity