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Climate-environmental Deteriorations in a Greenhouse Earth System: Causes and Consequences of Short-Term Cretaceous Sea-Level Changes (a Report on IGCP 609)

Michael WAGREICH[1,*], Benjamin SAMES[1] and HU Xiumian[2]

[1] *University of Vienna, 1090 Vienna, Austria*
[2] *Nanjing University, School of Earth Sciences and Engineering, 210023 Nanjing, China*

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Anthropogenic global warming and resulting sea-level rise in response to enhanced atmospheric greenhouse gases and melting of the Earth's continental ice shields have become issues of continuously growing interest for the scientific community as well as the public, pointing to threads of societies in a future greenhouse Earth System. As the sea level constitutes a fundamental boundary for (human) life on our planet and sea-level changes drive not only major shifts in the landscape but endanger also the greater part of big cities of the world, a global sea-level rise even on the scale of a few meters has major impact on mankind. Main drivers of recent short-term (on a geological time frame) sea-level rise initiated by greenhouse global warming are accelerated discharge of melt water from continental ice shields and mountain glaciers into the oceans and thermal expansion of seawater and potentially the oceanic forcing of ice sheet retreat on ice shelves as well. The processes and coherences behind are highly complex, and coupled feedback mechanisms of global warming are considered to affect global climate and, thus, the whole continents as well.

The Cretaceous greenhouse period provides a deep-time view on greenhouse phase Earth System processes and planetary boundaries (e.g. Hu et al., 2012; Hay, 2017), and provides invaluable data for a better understanding of the causes and consequences of global (eustatic) short-term sea-level changes over a very long-time interval with different, intermittently 'extreme' climates. In that, the Cretaceous greenhouse, especially the mid-Cretaceous (Aptian to Turonian, ca. 126–66 Ma) hothouse periodserves as a natural laboratory to learn for a future greenhouse Earth System out of the glacial-interglacial cyclicity of the Pleistocene.

IGCP 609 (Li et al., 2016) addressed correlation, causes and consequences of significant short-term (cycles of 3rd and 4th order, i.e. about 0.5–3.0 Ma and a few tens of thousands to 0.5 Ma, respectively) sea-level changes which are recorded in Cretaceous sedimentary sequences worldwide. Such cyclic sea-level changes and corresponding sequences are usually explained by the waxing and waning of continental (polar) ice sheets. However, though Cretaceous eustasy involves processes like brief glacial episodes for which evidence has been given (and resulting glacio-eustasy models, e.g. Miller et al., 2005) the presence of continental ice sheets during the Cretaceous is still disputed, and remains particularly enigmatic for the mid-Cretaceous hothouse episodes and global average temperature maxima during the Cenomanian to Turonian (Hu et al., 2012). IGCP 609 placed emphasis on the causes and mechanisms of short-term eustatic sea-level changes in the mid-Cretaceous hothouse during which the presence of continental ice sheets was highly improbable and, thus, other mechanisms have to be taken into consideration to explain significant short-term eustatic changes.

Major progress within the last six years 2013–2018 concern: (1) Cretaceous sequence stratigraphy put into a numerical time frame (e.g., Haq, 2014; Haq and Huber, 2017). Major mechanisms for global and regional sea-level changes have been quantified, and regional, tectonically induced, versus global mechanisms for sea-level change were discussed and quantified (Wagreich et al., 2016; Sames et al., 2016; see Fig. 1). (2) Various proxy correlations, such as oxygen and carbon isotopes, and interpretations for sea-level reconstructions in the Cretaceous were challenged and feedback mechanisms were evaluated in detail (e.g. Wendler and Wendler, 2016). 3) Orbital forcing in the (long) Milankovitch band was identified as the main driver of sea-level cycles also during greenhouse times (e.g. Wendler et al., 2014, 2016a) pointing to climate control of continental water storage. (4) Processes and triggering mechanisms of short-term sea-level fluctuations during greenhouse periods remain controversial, but evidence is growing for the revival of the 'aquifer-eustasy' (Fig. 1) and'limno-eustasy' hypotheses (Hay and Leslie, 1990; Föllmi, 2012).(5) Against the background that short-term cyclic sea-level changes are climate driven and, thus, ultimately orbitally controlled – and that, besides the characteristic remnant magnetization, this is the only signal potentially recorded in contemporaneous non-marine deposits as well – the stratigraphic application of short-term climate cycles more and more comes under scrutiny as promising tool for non-marine to marine correlations (e.g. Sames, 2017). (6) Case studies within the project came from various regions of the world; published studies include, e.g., Austria (Neuhuber et al., 2016; Wolfgring et al., 2018b), China (Xi et al., 2016; Wu et al., 2017; Li et al., 2018), Egypt (Fathy et al., 2018), Tanzania (Wendler et al., 2016a), Jordan (Wendler et al., 2016b), Pakistan (Iqbal et al., 2019), Spain (Socorro et al., 2017), Turkey (Yilmaz et al., 2018; Wolfgring et al., 2018a), NW Europe (Hart et al., 2016), Russia

* Corresponding author. E-mail: michael.wagreich@univie.ac.at

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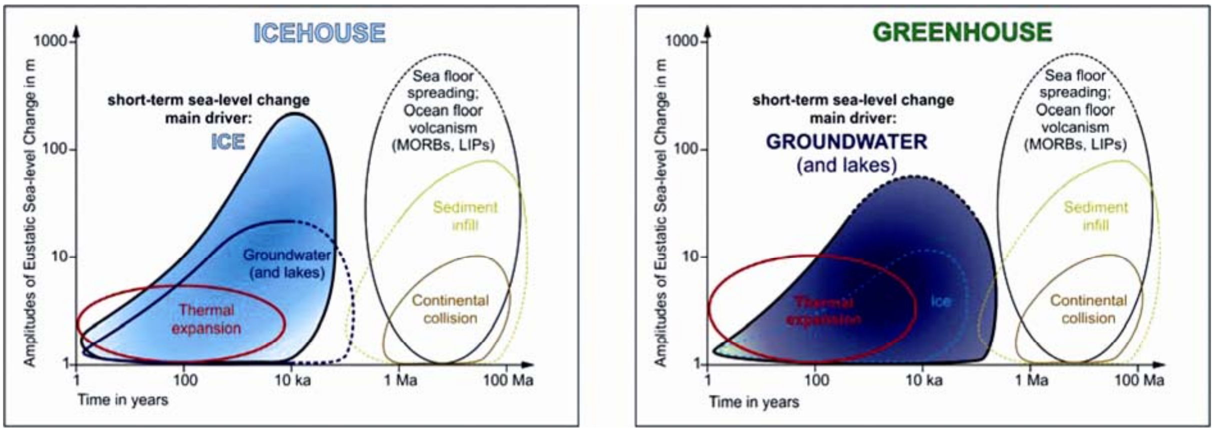

Fig. 1. Log-scale diagram sketches of the timing and amplitudes of major geologic mechanisms for driving eustatic sea-level changes during icehouse (left) and greenhouse (right) climate phases of the Earth System (modified from Miller et al., 2005 and Sames et al., 2016）.

Glacio-eustasy is the main driver during icehouse times, whereas aquifer eustasy is suggested as the main driver during greenhouse times with no continental ice shields on Earth.

(Zorina, 2016; Zorina et al., 2017) and USA (Ross et al., 2017).

Tests on Cretaceous hothouse eustasy cycles showed theoretically predicted out-of-phase relationships between sea- and lake-level changes in the mid-Cretaceous on 1.2 Ma Milankovitch scales (Wagreich et al., 2014). Evidences for humid-arid climate cycles on Milankovitch scales also support the aquifer eustasy hypothesis (Wendler et al., 2014, 2016b). We suggest the following scenario for sea-level fluctuations during a greenhouse ice-free world: Stronger humid conditions result higher storage in groundwater reservoirs and higher lake levels, thus filling up the continental aquifers as discharge into the ocean cannot keep up; this lowers sea level during times of lake-level highstands; vice-versa more arid conditions result in lower aquifer storage and low lake levels, and thus a rise in sea level. Such increased climate-driven land water storage is also reported from today's satellite measurement (Reager et al., 2016).In addition, the thermo-eustatic effect of water expansion due to warming may add a few more meters to such a mechanism, if warming occurs during times of aridity.

In addition, the revision of fundamental aspects in the context of recent and Cretaceous global sea-level shifts and its application, has led to different ideas and approaches. All measurements of amplitude of sea-level changes (rises and falls measured in meters) in any given region are always local (‘regional’ or ‘relative’), even when there is a strong underlying global signal, since they are a product of both local vertical movements (solid-earth factors) and eustasy, or the change of ocean water volume and volume of ocean basins (‘container volume’), respectively. Eustatic sea-level amplitudes cannot be measured, these are averaged global estimates of eustatic changes in relation to a fixed point, e.g. the Earth’s center. Regarding the reconstruction of sea levels and sea-level changes from the geologic record, the differentiation of relative (regional, eurybatic) and eustatic (global) sea-level changes and the respective proportion of each signal at a given locality or region is a critical issue (Haq, 2014; Sames et al., 2016), the disregard of these factors can lead to strong over- or underestimations of respective amplitude estimates. In recent years, a complex of solid-earth processes and feedbacks under the label of ‘dynamic topography’ have become a stronger focus of attention since they affect local measurements of sea level and past reconstructions (Cloetingh and Haq, 2015). We have learned that some of the processes mentioned above can refashion landscapes only regionally, and that solid-earth processes are responsible for retaining lithospheric memory and its surface expressions. Moreover, and in contrast to previous perceptions that considered solid-earth processes to be operative at long-term (way beyond 5 Ma) scales, IGCP 609 provided evidence that it is essential to take these processes into consideration since they affect local measures of sea level, and thus, estimated eustatic sea levels and sea-level changes on short-term scales as well (Sames et al., 2016).

Key words: sea-level change, greenhouse, Cretaceous

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About the first author (also corresponding author)

Michael WAGREICH, male, born in 1960 in Badennear Vienna, Austria; PhD; grduated from the University of Vienna; professor at the Department of Geodynamics and Sedimentology, University of Vienna, Austria. He is interested in sedimentology and stratigraphy, working mainly on Mesozoic and Cenozoic palaeoclimate and geological events including the Anthropocene. Email: michael.wagreich @univie.ac.at; phone: +43-1- 4277-53404.