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Review: Short-term sea-level changes in a greenhouse world — A view from the Cretaceous

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ABSTRACT

This review provides a synopsis of ongoing research and our understanding of the fundamentals of sea-level change today and in the geologic record, especially as illustrated by conditions and processes during the Cretaceous greenhouse climate episode. We give an overview of the state of the art of our understanding on eustatic (global) versus relative (regional) sea level, as well as long-term versus short-term fluctuations and their drivers. In the context of the focus of UNESCO-IUGS/IGCP project 609 on Cretaceous eustatic, short-term sea-level and climate changes, we evaluate the possible evidence for glacio-eustasy versus alternative or additional mechanisms for continental water storage and release for the Cretaceous greenhouse and hothouse phases during which the presence of larger continental ice shields is considered unlikely. Increasing evidence in the literature suggests a correlation between long-period orbital cycles and depositional cycles that reflect sea-level fluctuations, implying a globally synchronized forcing of (eustatic) sea level. Fourth-order depositional sequences seem to be related to a ~405 ka periodicity, which most likely represents long-period orbital eccentricity control on sea level and depositional cycles. Third-order cyclicity, expressed as time-synchronous sea level falls of ~20 to 110 m on ~0.5 to 3.0 Ma timescales in the Cretaceous, are increasingly recognized as connected to climate cycles triggered by long-term astronomical cycles that have periodicity ranging from ~1.0 to 2.4 Ma. Future perspectives of research on greenhouse sea-level changes comprise a high-precision time-scale for sequence stratigraphy and eustatic sea-level changes and high-resolution marine to non-marine stratigraphic correlation.

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1. Introduction

Global warming and associated global sea-level rise resulting from steady waning of continental ice shields and ocean warming have become issues of growing interest for the scientific community and a concern for the public. Sea level constitutes a basic geographic boundary for humans and sea-level changes drive major shifts in the landscape. A global sea-level rise even on the scale of a meter or two could have major impact on mankind, particularly in vulnerable coastal areas and oceanic island regions (e.g. El Raey et al., 1999; Nicholls, 2010; Nicholls and Cazenave, 2010; Caffrey and Beavers, 2013; Church et al., 2013; Cazenave and Le Cozannet, 2014). Adaption strategies for vulnerable regions have thus become major concerns for maritime nations worldwide. Identified drivers of recent sea-level rise initiated by global warming are mainly (1) accelerated discharge of melt water from continental ice shields into the oceans; (2) thermal expansion of seawater (e.g. Cazenave and Llovel, 2010; Church et al., 2010); and (3) potential oceanic forcing of ice sheet retreat on ice shelves (e.g. as for parts of Antarctic and Greenland and ice sheets, see Alley et al., 2015).

However, the processes and feedback for sea-level change are highly complex. For example, the increasing temperature of the oceans and increased freshwater discharge into the oceans through melting ice shields can lead to disruptions and changes in the thermohaline ocean circulations (such as the shutdown or slowdown of the Gulf stream, e.g. Rahmstorf et al., 2015; Robson et al., 2014; Velinga and Wood, 2002) that are among the main drivers of global climate (e.g. Hay, 2013). At the same time, the magnitude of future sea-level rise remains highly uncertain (e.g. Nicholls and Cazenave, 2010; Church et al., 2013), and ocean circulation and climate models (coupled atmosphere–ocean general circulation models) are open to non-unique interpretations, making the topic controversial not only within the scientific community and its opinion leaders, but also among policy makers and the media. In addition, regional, non-climate related components of relative sea-level fluctuations (such as tectonically-induced and anthropogenic subsidence, isostatic compensation of increasing water load) further add to the complexity of the matter (e.g. Syvitski et al., 2009; Conrad, 2013).

To study sea-level changes over time, both today and in the sedimentary record, the main focus is on the globally synchronous changes, i.e. so-called eustatic sea-level changes — in contrast to relative or regional sea-level changes (termed *eurybatic* shifts by Haq, 2014, see Section 2.1 for details). The term *eustasy* goes back to the Austrian geologist Eduard Suess in 1888 who introduced the term "eustatic movements" for the globally synchronous sea-level changes preserved in the stratigraphic record, which is how it is used in the modern sense (for details see Wagreich et al., 2014; Şengör, 2015). In the context of eustatic sea-level change, terms such as "glacio-eustasy" or "glacio-eustatic sea-level changes" (eustatic sea-level changes caused by the waxing and waning of continental ice shields that lead to an increasing or decreasing water volume in the oceans), thermo-eustatic sea-level changes, tectono-eustatic sea-level changes etc., have subsequently been coined. However, all measures of sea-level change amplitude (rises and falls measured in meters) in any given region of the globe are always local ('regional' or 'relative' sea-level changes, see Conrad, 2013; Haq, 2014; Cloetingh and Haq, 2015), even when there is a strong underlying global signal since they are a product of both local vertical movements (solid-Earth factors) and eustasy (changes in ocean water volume and/or the volume of ocean basins, i.e. ocean capacity or "container volume", respectively; refer to Section 2 for details). Consequently, eustatic sea-level amplitudes cannot be measured directly; quantitative estimates for amplitudes of past sea-level changes thus rely on averaged global estimates of eustatic changes in relation to a fix point, e.g. the Earth's center (see Haq, 2014).

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 archives worldwide are addressed by the UNESCO-IUGS IGCP project 609 "Climate–environmental deteriorations during greenhouse phases: Causes and consequences of short-term Cretaceous sea-level changes" (http://www.univie.ac.at/igcp609/; lasting from 2013–2017). The project serves as a communication and collaboration platform bringing together specialists and research projects from around the world (from universities and other research facilities, from the industry and from stratigraphic consulting companies).

The Cretaceous (145–66 million years ago) was different from our present world in many respects, including climatic conditions (greenhouse world in general, with potential episodic glaciations, particularly during the Early Cretaceous), climate change patterns, oceanographic conditions and generally high global (eustatic) sea level. It was a time of enormous evolutionary changes, particularly on land, and critical to the origin and development of modern continental ecosystems. As the youngest prolonged greenhouse interval in Earth history, the Cretaceous constitutes a well-studied period in these respects (e.g. Hay, 2008; Hay and Floegel, 2012; Hu et al., 2012; Wagreich et al., 2014). The Cretaceous greenhouse period provides a suitable laboratory for better understanding of the causes and consequences of global short-term sea-level changes over a relatively long time interval with different (intermittently extreme) climates that may have important relevance for predictive models of future sea levels (e.g. Hay, 2011; Kidder and Worsley, 2012).

Our views of Cretaceous climates have changed during the last decades, from a warm, equable Cretaceous greenhouse to a Cretaceous that is subdivided into 3–4 longer-term climate states: a cooler Early Cretaceous greenhouse with the possibility of "cold snaps", a very warm greenhouse mid-Cretaceous ("Supergreenhouse") including short-lived 'hothouse' periods with widespread anoxia and a possible reversal of the thermohaline circulation (HEATT episodes of 'haline euxinic acidic thermal transgression', see Kidder and Worsley, 2010; Hay and Floegel, 2012), and a Late Cretaceous warm to cool greenhouse evolution (e.g. Skelton, 2003; Kidder and Worsley, 2010, 2012; Föllmi, 2012; Hay and Floegel, 2012; Hu et al., 2012). Moreover, an increasing number of short-term climatic events within the longer-term trends are also reported (e.g. Jenkyns, 2003; Hu et al., 2012).

Cyclic sea-level changes and corresponding depositional sequences and sedimentary cycles are usually explained by the waxing and waning of continental (polar) ice sheets. However, though Cretaceous eustasy involves brief glacial episodes, for which there is evidence at least in the Early and the latest Cretaceous (e.g. Alley and Frakes, 2003; Price and Nunn, 2010; Föllmi, 2012), the presence of continental ice sheets