Aquifer-eustasy as the main driver of short-term sea-level fluctuations during Cretaceous hothouse climate phases

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Abstract: A review of short-term (<3 myr: *c.* 100 kyr to 2.4 myr) Cretaceous sea-level fluctuations of several tens of metres indicates recent fundamental progress in understanding the underlying mechanisms for eustasy, both in timing and in correlation. Cretaceous third- and fourth-order hothouse sea-level changes, the sequence-stratigraphic framework, are linked to Milankovitch-type climate cycles, especially the longer-period sequence-building bands of 405 kyr and 1.2 myr. In the absence of continental ice sheets during Cretaceous hothouse phases (e.g. Cenomanian–Turonian), growing evidence indicates groundwater-related sea-level cycles: (1) the existence of Milankovitch-type humid-arid climate oscillations, proven via intense humid weathering records during times of regression and sea-level lowstands; (2) missing or inverse relationships of sea-level and the marine $\delta^{18}O$ archives, i.e. the lack of a pronounced positive excursion, cooling signal during sea-level lowstands; and (3) the anti-phase relationship of sea and lake levels, attesting to high groundwater levels and charged continental aquifers during sea-level lowstands. This substantiates the aquifer-eustasy hypothesis. Rates of aquifer-eustatic sea-level change remain hard to decipher; however, reconstructions range from a very conservative minimum estimate of 0.04 mm a^{-1} (longer time intervals) to 0.7 mm a^{-1} (shorter, probably asymmetric cycles). Remarkably, aquifer-eustasy is recognized as a significant component for the Anthropocene sea-level budget.

For Michael E. Schudack (1954–2016), a dedicated palaeontologist, geologist, and mentor. He would have enjoyed discussing and contributing ideas to this topic.

Today's sea-level rise, anthropogenically induced by global warming and climate change, is a major concern for our society, because sea-level drives major shifts in the landscape and thus constitutes a crucial boundary for humanity. The causes, processes, rates and consequences of global climate change as well as ideas for counteracting it, such as planetary stewardship and geo-engineering, are the subjects of highly controversial debates among scientists, policymakers, industrial lobbyists, and environmental activists and organizations.

Climate change and fluctuating sea-level are natural phenomena, and these processes have been working throughout Earth's history. The ongoing accelerated global warming is superimposed on the natural warming from the glacial icehouse of the Pleistocene, some 20 000 years ago, into a warm interglacial phase of the equable Holocene, starting 11 700 years ago. Anthropogenically introduced atmospheric greenhouse gases, rising continuously and significantly from the beginning of the Industrial Revolution in the later part of the eighteenth century, have resulted in a rapid and so far uncontrolled runaway warming into a greenhouse to hothouse world (Church *et al.* 2013; Steffen *et al.* 2018). These accelerations, the visible switchover on our planet and the vivid signs already recorded in the stratigraphic archives warrant a new epoch of the Geological Timescale (Crutzen 2002), as also suggested by the stratigraphic Working Group on the Anthropocene (Waters *et al.* 2016; Zalasiewicz *et al.* 2019). Earth System scientists who report on the path to major

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planetary boundaries tend to see the Earth System as currently shifting outside of its orbitally driven glacial–interglacial climate cycles of *c.* 100 kyr of the recent past, and instead moving into a new system phase of a future hothouse state (Steffen *et al.* 2015, 2016, 2018).

The processes, rates and consequences of such a fundamental and global system change can only be studied by exploring past greenhouse phases of the Earth as natural greenhouse laboratories. The Cretaceous Period, a long-term greenhouse phase, provides such a test laboratory to investigate, understand and simulate the processes and consequences of a future hothouse world (e.g. Hay & Floegel 2012; Hay 2017).

Rising global temperatures result in the melting of mountain glaciers and the continental ice sheets in Antarctica and Greenland. Although happening along a natural warming trend that exhibited significant natural variations even during the stable Holocene (e.g. the Medieval Warm Period compared with the Little Ice Age up to *c.* 1850 CE; Cronin *et al.* 2003; Mann *et al.* 2009), today's rate of warming seems to be rising quickly, leading to extreme rates of sea-level rise (e.g. Church *et al.* 2013). Measurements show a distinct acceleration of sea-level and global temperature rise since the 1990s with the globally warmest years all concentrated in the last 20 years, and the last four years (2015–18) being the hottest ever recorded (WMO 2019). Although various factors such as global dimming and solar activity may influence warming trends and give rise to debates, the consequent sea-level rise and its acceleration in recent years is undisputed (Milne *et al.* 2009; Hay, C.C. *et al.* 2015; Treuer *et al.* 2018; Khan 2019) and already poses a threat to islands, megacities and coastal zones worldwide.

Sea-level constitutes a crucial geographic boundary, a critical zone, for humans and societies. Sea-level changes resulting from global change drive major shifts in the landscape with tremendous impacts on mankind, economically as well as societally, even at the current scale of 3.2 ($\pm$0.4–1.4) mm a^{-1} for 2002–2014 (Church *et al.* 2013; Dangendorf *et al.* 2017). These impacts are particularly important for, but not restricted to, vulnerable coastal areas (e.g. El Raey *et al.* 1999; Leatherman 2001; Chust *et al.* 2010; Nicholls 2010; Nicholls & Cazenave 2010; Caffrey & Beavers 2013; Graham *et al.* 2013; Mimura 2013; Brammer 2014; Cazenave & Le Cozannet 2014; Le Cozannet *et al.* 2014; Sarkar *et al.* 2014; Moosdorf & Oehler 2017; Cui *et al.* 2018; Gonneea *et al.* 2019). These trends additionally involve changes in Earth's major ocean circulation systems, such as the weakening Atlantic meridional overturning circulation (e.g. Smeed *et al.* 2014; Rahmsdorf *et al.* 2015*a*, *b*; Caesar *et al.* 2018), which are the main motors for global climate as they redistribute heat on our planet.

During about the past two to three decades satellite altimetry and, more recently, satellite gravimetry (e.g. Gravity Field and Steady-state Ocean Circulation Explorer – GOCE 2009–13; Gravity Recovery and Climate Experiment – GRACE 2002–17) have improved the accuracy and precision of measurements of today's global and regional sea-level changes, and enhanced our knowledge of the distribution and exchange of water mass between oceans and continents (e.g. Tapley *et al.* 2004; Rovere *et al.* 2016). The combination of altimetric datasets (ground and sea-level) with gravimetric (mass distribution and variability) observations now facilitates the monitoring of minute eustatic sea-level fluctuations (down to *c.* 1 mm) and continental water storage changes and fluxes (surface and subsurface) with high temporal (seasonal to monthly) and spatial (hundreds of kilometres) resolution (e.g. Tapley *et al.* 2004; Veit & Conrad 2016). Consequentially, together with 'classic' local measurements from tide gauges, we now have the instruments to better estimate and quantify intensity changes for the hydrological cycle. In particular, we can quantify the land-water contribution to eustatic sea-level, including aquifer charge and discharge rates as well as anthropogenic contributions, such as land water storage (which lowers sea-level, and thus dampens the rate of ongoing glacio-eustatic sea-level rise) and groundwater depletion through human groundwater management (resulting in intensified sea-level rise; e.g. Konikow 2011; Eicker *et al.* 2016; Reager *et al.* 2016; Veit & Conrad 2016; Wada 2016; Wada *et al.* 2017; Rodell *et al.* 2018, and references in all these).

These new observations now allow evidence-based studies of the detailed interplay of ocean water, non-ocean water (also inland or land water, or continental water, separated into glacial, groundwater and other volumes, see Fig. 1, and the second section 'Earth's "surface" water resources and their distribution') and the (terrestrial) hydrological cycle in the context of its interrelationships with natural and anthropogenic climate change. One primary aim of current studies is to close the disparity in today's budget between mean eustatic sea-level change observed with satellite altimetry and the sum of the estimated magnitudes of the processes that contribute to it, the main factors of which are glacio-eustasy, thermo-steric change (also thermo-eustasy, i.e. thermal expansion of water masses) and hydro-eustasy (Rovere *et al.* 2016), or aquifer-eustasy as it is more frequently termed in the geological sciences and for the geological past (see the section 'Aquifer-eustasy' for details). Another primary aim is the unambiguous identification and separation of naturally occurring climate-driven variability in

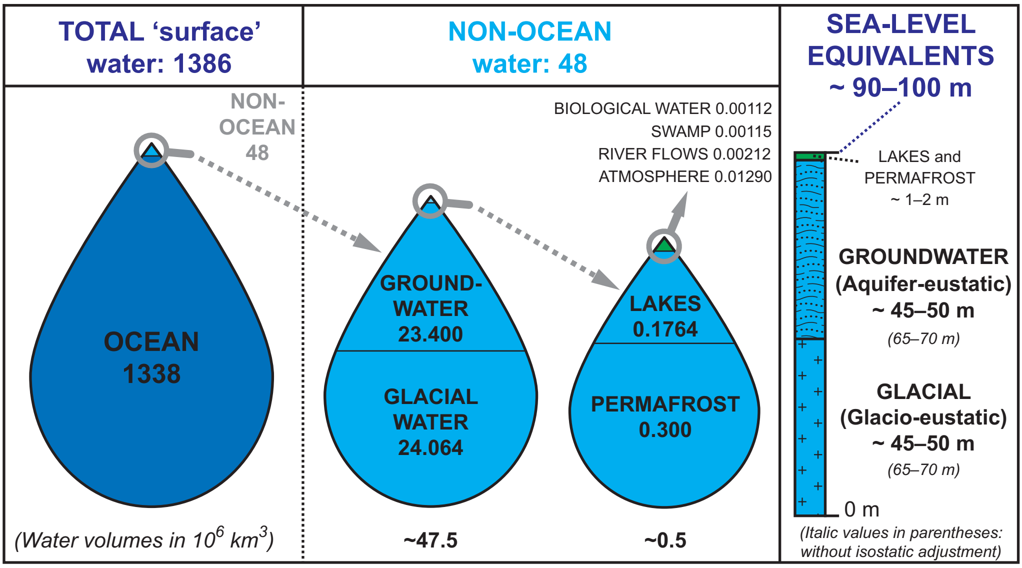

Fig. 1. Earth's total 'surface' water volumes and volume relations in today's Earth system, in millions of cubic kilometres, as well as their sea-level equivalents (in metres) stored in glaciers, groundwater, lakes and permafrost (based on and modified from Hay & Leslie 1990, and references therein; Shiklomanov 1993, especially table 2.1 therein; Eakins & Sharman 2010; Conrad 2013; Sames *et al.* 2016, fig. 2). Excluded are water volumes stored in hydrated, but also 'nominally anhydrous', minerals within the Earth's mantle. Note that the sea-level equivalents are volume-, not process-related values, that simply sum up, i.e. glacio- and aquifer-eustasy interact and often counteract in their net effect on seawater. Earth's total (surface) water estimated with 1.386×10^6 km^3, thereof $1.335–1.338 \times 10^6$ km^3 total ocean water (oceans, seas and bays), and around 48×10^6 km^3 non-ocean water. The latter volume equals a eustatic sea-level of *c.* 146 m without, and *c.* 96 m with, isostatic adjustment, i.e. about 3.04 m without, or 2 m with, isostatic adjustment per 1.0×10^6 km^3 (based on calculations Hay & Leslie 1990; Conrad 2013). Based on these values, the relevant sea-level equivalents of the total glacial and groundwater volume contingents of today's Earth have been deduced. Non-ocean water is distributed over glacial ice (surface cryosphere, i.e. polar ice caps, continental ice sheets, glaciers, and permanent snow) and groundwater (fresh and saline, also including soil moisture of 0.0165×10^6 km^3), the latter two making up about 99% of non-ocean water, as well as permafrost (subsurface cryosphere), lake water (fresh and saline waters), soil moisture, water stored in the atmosphere, swamp water, river flows, as well as 'biological water', i.e. water stored in all organisms on Earth (Shiklomanov 1993). Note: sea-level equivalents for glacial volume contingents are considered to have been considerably higher, up to 250 m, during Phanerozoic icehouse mode and glaciation periods, but probably also groundwater volume contingents might have been somewhat higher, up to 80 m, during greenhouse mode and especially hothouse phases (cf. fig. 3 and discussion in Sames *et al.* 2016; and Fig. 2 herein).

land-water storage (low-frequency) from the anthropogenic trend (high-frequency) in sea-level fluctuation (e.g. Hamlington *et al.* 2017), both elements of which can either dampen or add to the general trend of continuously rising sea-level in today's warming climate. Consequently, future sea-level rise must be modelled based on estimates and expectations of new states for the Earth System (e.g. Hu & Bates 2018).

The process of aquifer-eustasy has recently come into focus as a potential driving factor of short-term (so-called third- to fourth-order cyclicities of the following timescales: fourth-order – a few tens of thousands to about 405 000 years; third-order – 405 000 years up to 3–5 myr, see Haq 2014; Sames *et al.* 2016) eustatic sea-level fluctuations during greenhouse phases in Earth history. This is especially the case for warm greenhouse to hothouse climate mode phases (*sensu* Kidder & Worsley (2012), when the presence of large continental ice sheets and, thus, glacio-eustasy as main driving factor for short-term sea-level fluctuations is unlikely. Herein, we use the climate phase classification of Kidder & Worsley (2012) and Hay & Floegel (2012) to distinguish between *icehouse* (extended polar ice sheets present on the planet, relates to glacials in the Quaternary), *cool greenhouse* (some polar ice and mountain glaciers, relates to interglacials and the current state of the planet), *warm greenhouse* (very little polar ice) and *hothouse* (no ice, more short-lived up to 3 myr, oceanographic conditions favour hypoxia).

The new insights evolving from recently published and upcoming research based on integrated altimetric and gravimetric satellite data facilitate improved studies on the multiple interrelationships of (both natural and anthropogenic) climate change, eustatic sea-level fluctuations and the variability in land-water storage on multi-decadal scales (e.g. Reager *et al.* 2016). However, especially with respect to the latter, these new insights also enable us to (1) constrain the non-ocean water budget, its continental sources (glacial v. groundwater), and their respective volume and rate contributions to eustatic sea-level changes, and (2) facilitate projections of these for larger timescales into the near future and into the geological past. Therefore, on the one hand the present provides keys to the geological past, facilitating a better understanding the interplay of climate, water budget and sea-level. On the other hand, studies of Earth's past are invaluable for understanding climate and sea-level changes over timescales beyond a few decades and provide important contributions for thinking through and modelling possible near-future (hundreds of years scale) scenarios of a warming Earth with rapidly rising greenhouse gas (mainly CO_2, CH_4) levels (e.g. Hay *et al.* 1997; Hay 2011).

Although comparison of deep-time climate trends with today's global change still suffers from scaling problems, recent rates of change measured for decades and modelled for hundreds of years into the future increasingly approach the (tens of) millennia resolution of deep-time studies (such as sub-Milankovitch periodicities, e.g. Boulila *et al.* 2009; Hilgen *et al.* 2014), and we can use data (timescales/frequencies, magnitudes and rates of change) from today's global change for estimations and model tests of deep-time records and interpretations (see the sections 'Short-term sea-level cycles, eustasies and their controls', 'Aquifer-eustasy', 'Evidence for and impact of aquifer-eustasy in Earth history' and 'Rates of eustatic sea-level change and the scaling problem' for details). The recent and ongoing immense improvement of the Geological Time Scale is resulting in an increasingly precise and accurate numerical timescale – especially through the application of geochronology with precise numerical dating methods such as zircon U/Pb dating (e.g. Kuiper *et al.* 2008; Hilgen *et al.* 2014) and cyclostratigraphy (or astrochronology) based on Milankovitch climate cycles linked to orbital cycles with frequencies of *c.* 20, *c.* 40, *c.* 100 and 405 kyr, and their multiples, which control solar insolation (Hinnov & Hilgen 2012; Hinnov 2013, 2018; Hilgen *et al.* 2014; Laskar *et al.* 2011). Thus, observational timescales and, consequently, rates of change deciphered from the geological record are becoming more precise, reliable and comparable with the Anthropocene (see the sections 'Aquifer-eustasy', 'Evidence for and impact of aquifer-eustasy in Earth history' and 'Rates of eustatic sea-level change and the scaling problem' for details). This trend is giving new dimensions, precision and significance to the results of high-resolution deep-time studies from the Cretaceous (e.g. Gale *et al.* 2002; Sageman *et al.* 2006, 2014; Wilmsen 2007; Wu *et al.* 2009, 2013, 2014; Meyers *et al.* 2012; Thibault *et al.* 2012, 2016*a*, *b*; Voigt *et al.* 2012; Wendler *et al.* 2014; Batenburg *et al.* 2016; Laurin *et al.* 2016; Huang 2018; Wolfgring *et al.* 2018 and references therein).

This paper focuses on Cretaceous short-term sea-level changes, and provides evidence for mechanisms for eustasy and approaches to their recognition and correlation. In that, we elaborate mainly on a relatively new hypothesis for an additional major factor controlling sea-level and contributing to short-term sea-level fluctuations at different, climate-mode-dependent scales: aquifer-eustasy (Hay & Leslie 1990; Wendler *et al.* 2011, 2014; Föllmi 2012; Wagreich *et al.* 2014, Wendler & Wendler 2016; Li *et al.* 2018; Ray *et al.* 2019). Here we discuss the growing evidence for this process occurring during hothouse climate periods of Earth history, such as those within the Cretaceous and the Triassic. In the following, we establish ties from observations of the Earth's greenhouse past to modern observations (see above). Finally, we discuss some of the consequences of aquifer-eustasy processes for both greenhouse periods of the past, and the overall Earth System in today's global warming epoch, the Anthropocene. Thereby this paper supplements and substantiates the recent review paper by Sames *et al.* (2016) as well as the very recent study on Cretaceous sea-level by Ray *et al.* (2019).

The Cretaceous greenhouse laboratory and its fluctuating sea-level

The Cretaceous period (145–66 myr ago) is the youngest prolonged greenhouse interval in Earth history, characterized by high global mean temperatures (e.g. Hay & Floegel 2012; Holz 2015; Huber *et al.* 2018) and a very high mean global sea-level, up to 250 m above today's sea-level (Conrad 2013; Haq 2014). Only a fraction of this higher sea-level was caused by a lack of glaciated regions during this warmer climate; most was caused by slow geodynamic processes associated with changes in plate tectonics. In particular, the breakup of Pangea is linked to high activity of the mid-ocean ridges, widening them and displacing seawater upward. During this period, climate was influenced by greenhouse gases from the high magmatic-volcanic activity and several interwoven feedback mechanisms (e.g. Jenkyns 2010), leading to long greenhouse and hothouse episodes. However, evidence for climate change during the Cretaceous period, such as cold snaps and extreme warmth superimposed on the general greenhouse climate phase, is also ubiquitous (e.g. Jenkyns 2003; Föllmi 2012; Hu *et al.* 2012; Huber *et al.* 2018), whereas evidence for continental glaciation is extremely rare. There is only one piece of unequivocal evidence for continental glaciations from the Early Cretaceous (Valanginian–Hauterivian, Aptian) of South Australia (Alley & Frakes 2003; Alley *et al.* 2019) and some evidence for polar ice is reported for the later part of the Late Cretaceous (Campanian–Maastrichtian, e.g. Bowman *et al.* 2013).

Although sea-level was generally high compared with today (Conrad 2013), fluctuating within tens of millions of years (the second-order curves of sequence stratigraphy models, e.g. Haq 2014), we also identify shorter superimposed fluctuations with amplitudes of *c.* 10–40 m (sea-level change magnitude category 'modest' of Ray *et al.* 2019). Such fluctuations are observed not only during cool greenhouse conditions (Kidder & Worsley 2010; Hay & Floegel 2012), when ice on Earth was still conceivable (e.g. Miller *et al.* 2005*a*, *b*), but were also present during the warm greenhouse and hothouse phases of Kidder & Worsley (2010, 2012; or 'Cretaceous Hot Greenhouse' of Huber *et al.* 2018) in the mid-Cretaceous, from *c.* 125 to 90 Ma (Aptian–Turonian). This was a time when there was apparently no ice at the poles during protracted intervals of millions of years (e.g. Rich *et al.* 2002; Flögel *et al.* 2011) and cool-temperate climate zones reached the polar regions instead of giving way to deciduous vegetation (Hay & Floegel 2012). In contrast to some probably diagenetically altered oxygen isotope data (e.g. Bornemann *et al.* 2008), results from stable oxygen isotope records from excellently preserved glassy foraminifera (Moriya *et al.* 2007; MacLeod *et al.* 2013) and other concurrent temperature proxies like TEX86 (e.g. O'Brien *et al.* 2017) do not show any inferred ice-induced oxygen isotope shifts or significant cold periods for Cenomanian–Turonian times of the Cretaceous Thermal Maximum (including OAE 2 in the latest Cenomanian). This renders the presence of even ephemeral ice sheets extremely unlikely, a conclusion that is also supported by newer numerical simulations (e.g. Flögel *et al.* 2011; Ladant & Donnadieu 2016). Maximum mean annual sea-surface temperatures are considered to have been up to about 37°C during the late Cenomanian–Turonian (O'Brien *et al.* 2017).

The inconsistency between the presence of short-term sea-level fluctuations during the mid-Cretaceous warm greenhouse period and the existence of large continental ice sheets, which should have been very improbable or impossible during hothouse phases, has been subject to debate among researchers during the last few decades. This inconsistency, however, also became the key issue in calling for the consideration of a major control factor for sea-level changes other than glacio-eustasy. During the last decade, and particularly within the scope of UNESCO-IUGS IGCP project 609 'Climate-environmental deteriorations during greenhouse phases: Causes and consequences of short-term Cretaceous sea-level changes' (2013–18), there have been major steps towards gaining a better general and specific understanding of the interplay between global climate modes (greenhouse–icehouse) and states (dominantly arid or humid), orbital control over the dynamics of the hydrological cycle, and associated short-term sea-level fluctuations. These cyclicities must be reconciled with the behaviour of various interdependent proxies, as well as with respect to evidence of aquifer-eustasy in the geological record for the Cretaceous and Triassic, respectively (e.g. Jacobs & Sahagian 1993; Föllmi 2012; Wagreich *et al.* 2014; Wendler *et al.* 2014, 2016; Wendler & Wendler 2016; Li *et al.* 2018; Ray *et al.* 2019). In the advancing twenty-first century, right in the middle of the Anthropocene, we have been and are confronted by the consequences of a rapidly warming Earth, quickly waning glaciers and continental ice sheets, continuously rising global sea-level and the prospect that mankind is probably facing an anthropogenic greenhouse world in the very near future (within a few centuries) that will be largely ice-free. Against this background, the combination of our insights from greenhouse intervals of Earth's past with new insights derived from integrated satellite altimetry and gravimetry brings aquifer-eustasy into the scientific focus as an important driver of short-term sea-level changes. Cretaceous climate and sea-level history can serve as a natural laboratory to investigate and model the Earth under different climate conditions, and to infer the causes and consequences of climate extremes, including the (ongoing) shift between (interglacial) icehouse and greenhouse climate modes, for example. Before we explore and review the mentioned progress in respective Cretaceous research and aquifer-eustasy (the section 'Aquifer-eustasy' et seq.), we outline relevant fundamentals and scientific state-of-the-art in the following sections.

Earth's 'surface' water resources and their distribution

All estimations of short-term eustatic sea-level fluctuations need to especially consider the non-ocean 'surface' water volumes on Earth: how and where these are distributed, the available storage spaces and their volumes, and the hydrological cycle that links these water volumes with the ocean water. They should also consider the processes and factors controlling the intensity of the hydrological cycle, which is the rate at which water is removed from the oceans to the continents or the other way around.

There seems to exist a broad consensus that Earth's 'surface' water totals 1.386×10^6 km^3, with $1.335–1.338 \times 10^6$ km^3 representing ocean water (oceans, seas and bays), and around 48×10^6 km^3 representing water outside of the oceans (see Fig. 1; Hay & Leslie 1990, and references therein; Shiklomanov 1993, and references therein; Eakins & Sharman 2010). Here we refer to 'surface' water as water that exists within the Earth's surface environment, including oceans, ice and aquifers. This distinguishes surface water from water stored in hydrated (but also 'nominally anhydrous') minerals within the Earth's deep mantle. Mantle water volumes are debated as they are difficult to estimate, and recent constraints suggest that several ocean masses of water are probably stored within the Earth's mantle (e.g. Hirschmann & Kohlstedt 2012; Conrad 2013; Tschauner *et al.* 2018, and references in these). This water enters the mantle via subduction of hydrous minerals, and is eventually restored to the surface environment via volcanic outgassing at mid-ocean ridges, back-arcs and hotspots. Any imbalance between these water fluxes into and out of the mantle results in a change in the volume of surface water, and therefore a change in sea-level, and may produce more than 100 m of sea-level change during a supercontinental cycle (Karlsen *et al.* 2019), and even more during Earth's history (Fig. 2). Water cycling with the deep mantle thus occurs too slowly to be important on timescales shorter than first or second order (at least tens of millions of years).

Therefore, 'surface' water designates all non-mantle water of the system Earth, on and above the Earth's crust, and we use quotation marks with 'surface' to indicate that this includes water below the actual ocean or land surface. Earth's 'surface' water is distributed over (Fig. 1) glacial ice (surface cryosphere, i.e. polar ice caps, continental ice sheets, glaciers, plus permanent snow) and groundwater (fresh and saline waters), the latter two making up about 99% of non-ocean water, as well as permafrost (subsurface cryosphere), lake water (fresh and saline waters), soil moisture, water stored in the atmosphere, swamp water, river flows and 'biological water', i.e. water stored in organisms on Earth (see Shiklomanov 1993).

Of the Earth's total 'surface' water, present-day continental ice sheets contain the major proportion equivalent to *c.* 66 m of sea-level equivalent ('*c.* 66.1 m' after Vaughan *et al.* 2013) without isostatic compensation, and roughly 45 m with isostatic compensation (cf. Conrad 2013; and Fig. 1 herein). Oceanic floating ice (e.g. today's northern polar regions) and floating glaciers peripheral to the continental ice sheets (e.g. ice shelfs of Antarctica) are not relevant for (glacio-)eustatic seal-level fluctuations as these are in hydrostatic equilibrium with the ocean, i.e. they have already displaced ocean water equal to the volume of water that would be created by their melting. The water volumes relevant to and, just as important, *available for*, short-term sea-level fluctuations in the context of operative timescales (10^4 to 10^5 or <0.01 myr, see Sames *et al.* 2016, fig. 3, for overview) are glacial ice and groundwater. Changes to continental water storage, and associated sea-level change, can occur as the waxing and waning of continental ice sheets or the charge and discharge of continental aquifers (Hay & Leslie 1990; Jacobs & Sahagian 1993, 1995). The main insight here, fundamentally based on the work of Hay & Leslie (1990), was that present day Earth's estimated pore space volume within the upper 1 km of the average elevation of the continents above sea-level is *c.* 25×10^6 km^3, and – if it could be filled with (or emptied of) groundwater completely (groundwater that is 'available', i.e. for changing sea-level through ocean water volume change) – is approximately equivalent to the total water volume currently stored in glacial ice on the continents today.

For the given volume of *c.* 25×10^6 km^3 of groundwater (somewhat less, i.e. *c.* 23.4×10^6 km^3 following other estimations by Shiklomanov 1993), global sea-level equivalents of about 76 m without and 45–50 m with isostatic adjustment have been calculated (see, Hay & Leslie 1990; Conrad 2013, and references therein). Consequently, this equals a eustatic sea-level change of about 3.04 m without, or 2 m with, isostatic adjustment per 1.0×10^6 km^3, and for the estimated total of the current 48×10^6 km^3 of non-ocean 'surface' water equals a eustatic sea-level of *c.* 146 m without, and *c.* 96 m with, isostatic adjustment (herein, Fig. 1). It is essential to note that this *c.* 96 m just refers to a volume-related, not process-related, value. The simple summation of the sea-level equivalents for groundwater and glacial water, of course, is not realistic since glacio- and aquifer-eustasy generally interact and often counteract in driving sea-level in opposite directions. Given the very similar volumes of glacial water and groundwater calculated for today's Earth, their net effects on glacio- and aquifer-eustasy could completely cancel out each other in theory, e.g. in a temporal snap-shot of a humid, hot greenhouse ('hothouse') world with no continental ice sheets (corresponding to *c.* 50 m sea-level rise) and completely filled aquifers (corresponding to *c.* 50 m sea-level fall). However, the Earth's climate system is neither static nor simply dualistic, but dynamic and very complex instead (see below and Fig. 2):

(1) The climatic cyclicities controlling glacio-eustasy and aquifer-eustasy and the relative scales of their effects on short-term

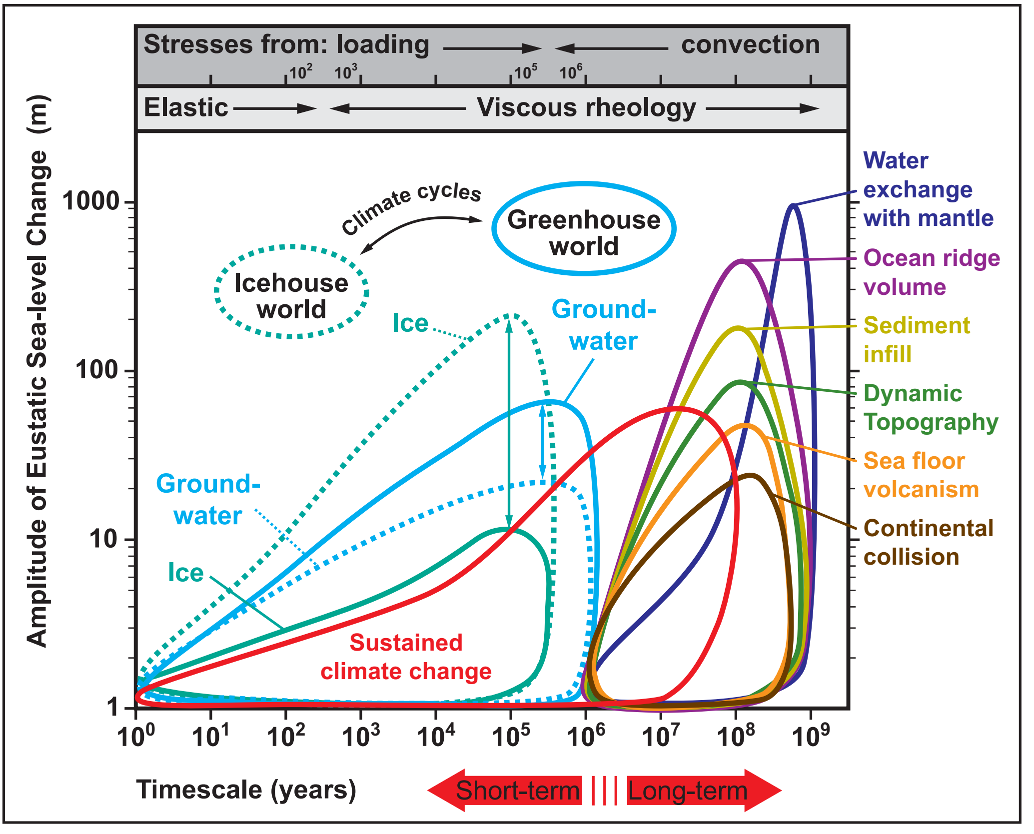

Fig. 2. Log-scale diagram of the timing and amplitudes of major geological mechanisms driving eustatic sea-level fluctuations, considering cyclic climate change for both icehouse and greenhouse modes (adapted from Miller *et al.* 2005*a* based on data and sketches from various authors including, among others, Hay & Leslie 1990; Jacobs & Sahagian 1993; Wendler & Wendler 2016; Sames *et al.* 2016; J. Wendler, unpublished). The curves have been fitted to appropriate timescales and amplitudes, in contrast to earlier versions (Miller *et al.* 2005*a*; Sames *et al.* 2016). Note that this diagram is a rough sketch giving minimum and maximum amplitudes and timescales to illustrate (1) eustatic sea-level change efficacy (amplitude) of selected factors relative to each other in the two different main climate regimes – 'icehouse world' with extensive continental ice masses and 'greenhouse world' with only minor continental ice (i.e. generalized end members of the climate phase classifications and subdivisions); and (2) ranges of their main relevance in the geological record (timing v. amplitude), i.e. at short-term scales (fourth- to third-order order cycles and higher – left side of the diagram) or long-term scales (second- to first- order cycles up to the scale of supercontinental cycles – right side of the diagram). These are intended to show the important dimensions of mechanisms and processes, not to be read as a true graphical representation of measured or calculated data (in which case all components also would have to start at the point of origin). For the longer-term cycles (first- and second-order, right half of the diagram), sea-level is influenced by tectonic and volcanic processes associated with mantle dynamics. These include continental collision (a decrease in the area of the continents causes sea-level drop), seafloor volcanism (which takes up space in the ocean basin, raising sea-level) and changes to the average dynamic topography, sediment infill and mid-ocean ridge volume (all of which can change the average depth of the seafloor, thus changing sea-level). For a detailed discussion of these processes, see Conrad (2013). Imbalances in the deep mantle water cycle, in which seawater is lost to the mantle down subduction zones but is restored by outgassing at mid-ocean ridges can change the volume of water in the oceans during supercontinental cycles and also during Earth's long-term evolution (Karlsen *et al.* 2019). For short-term cycles (third- and fourth-order, left half of the diagram), climate changes dominate sea-level change by cycling water between the oceans and continental ice (glacio-eustasy) and/or continental aquifers (aquifer-eustasy). Here the arrows of the climate mode shift between icehouse (dotted lines) and greenhouse modes (solid lines) and the associated shift between the dominance of glacio-eustasy and the dominance of aquifer-eustasy as the governing factor for short-term sea-level fluctuations. Only one mechanism, sustained climate change, operates across all timescales and causes sea-level change not associated with third- and fourth-order cycling. This mechanism represents sustained changes in the total volume of glacial and aquifer reservoirs on the continents, as well as thermal expansion or contraction of seawater ('thermo-eustasy' or 'steric sea-level change'), as caused by a long-term shift between climate modes (e.g. a shift from warm greenhouse to icehouse, or vice-versa).

sea-level changes operate on different timescales (glacio-eustasy, 100 000 years; aquifer-eustasy, 405 000 years) and exhibit different patterns of relative rates of resulting sea-level rises and falls.

(2) The interrelation of the effects of continental ice and groundwater to sea-level change depends on the principal global climate mode (icehouse or greenhouse), their intrinsic variations or sub-modes (icehouse with glacials and interglacials – greenhouse mode with cool greenhouse intervals punctuated by cold snaps, and warm to hot greenhouse, or ‘hothouse’, intervals with few or no continental ice sheets, respectively), as well as the climate state, i.e. the predominance of humid or arid conditions on a global scale.

(3) In contrast to water stored in continental ice sheets, which can completely melt and drive sea-level rises, only a proportion of the water volume stored in relevant continental aquifers (‘available groundwater’ to affect sea-level changes, see the following paragraph) has a net effect on sea-level rises as aquifers cannot be completely emptied.

(4) Depending on the climate mode and interval of Earth history under consideration, when the volume of continental ice was much higher than today, the volume of ‘available’ groundwater depends on relevant volumes of aquifers (see right below) and could have been much higher than today (both considered in Fig. 2).

It follows that with respect to aquifers and groundwater storage and release, although only a proportion of the corresponding water volume is considered to effectively result in eustatic sea-level changes, this proportion is significantly above 10 m (Hay & Leslie 1990; Wendler *et al.* 2016). This is particularly important when considering various palaeogeographic settings in Earth history that are more or less different from today (especially different topographies, i.e. lower average elevations and, thus, considerably higher ‘available’ pore space and groundwater volumes, as has been suggested for the Cretaceous for example, see the ‘Continental elevation problem’ of Hay 2011, 2017; Hay *et al.* 2018, and references therein) and an almost totally ice-free, warm greenhouse to ‘hothouse’ world (e.g. during the mid-Cretaceous). In this case and including the minor component of thermo-eustasy, aquifer-eustasy would be the main and sole mechanism to be considered for changing sea-level on short timescales. Moreover, such settings would result in even higher aquifer volumes of ‘available’ groundwater because the widespread or total lack of continental ice sheets and permafrost areas would increase the aquifer-accessible land area (Hay 2011; Föllmi 2012; Hay *et al.* 2018). Therefore, depending on the climate mode of the Earth as well as the climate state, that is the presence of predominantly arid or predominantly humid conditions, both the allocation of water volumes between glacial water and groundwater on the one hand, and the respective operative water volumes processed by the hydrological cycle on the other hand, can vary considerably (mainly regarding the transfer of water from the oceans to continents and in reverse, and enhanced water transfer from low to high latitudes, e.g. Hay & Leslie 1990; Jacobs & Sahagian 1993; Kidder & Worsley 2010, 2012; Föllmi 2012; Wendler & Wendler 2016). Consequently, the distribution of the proportions of the main drivers of short-term sea-level fluctuations is equally variable with respect to their eustatic sea-level equivalents (Figs 1 & 2; Sames *et al.* 2016). The insight that these variations are and were climatically, and thus ultimately orbitally, controlled, is supported by evidence from the geological record and has led to considerable progress in cyclostratigraphy. In turn, the presence of cyclic sequences during hothouse times where larger continental ice sheets were absent (see the section ‘Evidence for and impact of aquifer-eustasy in Earth history’) provides evidence for short-term sea-level fluctuations during these time intervals and has called for explanations other than glacio-eustasy as the main driving factor for these (e.g. Hay & Leslie 1990; Jacobs & Sahagian 1993, 1995; Föllmi 2012; Wagreich *et al.* 2014; Wendler *et al.* 2014, 2016; Wendler & Wendler 2016; Ladant & Donnadieu 2016).

Short-term sea-level cycles, eustasies and their controls

Short-term cyclic sea-level fluctuations during Earth history translate into intervals of a few tens of thousands to about 405 000 years (fourth-order) and 405 000 years up to 3–5 myr (third-order) (Haq 2014; Sames *et al.* 2016), in contrast to ‘long-term’ second-order (*c.* greater than 5 to *c.* 20 myr and longer) to first-order (*c.* 100–*c.* 200 myr) sea-level fluctuations controlled by ‘solid-Earth’ contributions (e.g. Conrad 2013; Sames *et al.* 2016; see also Fig. 2 herein for overview). Sequence stratigraphy hierarchies indicate the presence of third- to fourth-order cycles during most of the Phanerozoic (e.g. Haq 2014). These changes can be reconstructed from shifting fossil shorelines that form repeating sedimentary sequences, the classical sequence stratigraphy method (e.g. Haq *et al.* 1987; Simmons 2012).

Short-term global sea-level fluctuations with amplitudes on the order of metres to tens of metres (potentially above 100 m up to 250 m, e.g. Cloetingh & Haq 2015, table 1; but see also revision in Sames *et al.* 2016, fig. 3) can be the result of various processes, essentially controlled either by geodynamic–geophysical mechanisms (the changes in the volume of ocean basins – changing capacity or 'container-volume') or by climate-related processes (changes in the ocean's water volume) (e.g. Conrad 2013; Sames *et al.* 2016, chapter 2 for overview, especially figs 2–5 therein). Miscellaneous overviews on these 'solid earth contributions' to sea-level have been published in recent years (e.g. Milne & Mitrovica 2008; Conrad 2013; Cloetingh & Haq 2015; Sames *et al.* 2016; Karlsen *et al.* 2019), and the reader is referred to these publications, especially with respect to rates and amplitudes of local to regional sea-level or sea-level change ('eurybatic' sea-level or sea-level change of Haq 2014) resulting from processes such as dynamic topography and tectonic stresses. These processes lead to regional continental uplift and subsidence resembling actual sea-level fluctuations in the geological record (local absolute sea-level rises or falls measured or reconstructed for the past). In this context it must be recalled that all measurements of amplitudes of sea-level or sea-level changes (recent and past rises and falls measured or reconstructed in millimetres to metres) in any given region are always local, even when there is a strong overlying global signal (e.g. Haq 2014). Therefore, global (eustatic) sea-level amplitudes and changes cannot be measured directly from the geological record – these would be averaged global estimates of eustatic changes in relation to a fix-point, the Earth's centre for example. Modern-day satellite measurements can now accurately measure eustatic sea-level change in the modern ocean, but this is not possible from geological observations.

As mentioned above, sea-level stands and fluctuations always represent a mixed signal of solid-Earth contributions ('container volume') and climate-controlled contributions (ocean water volume changes). With respect to the cyclic, short-term eustatic sea-level fluctuations of our focus, especially those in time intervals around and below 1 myr, solid-Earth processes are (almost) negligible as their contribution to sea-level amplitudes is minimal on these timescales and therefore mostly below detectability in the geological record considering amplitude and available stratigraphical resolution (Fig. 2; cf. Sames *et al.* 2016, p. 396 et seq.). The major group of processes controlling cyclic short-term sea-level fluctuations are, thus, ocean water volume changes, and in particular continental ice sheet growth and decay (glacio-eustasy), and continental groundwater storage and release (aquifer-eustasy of Wendler *et al.* 2011, 2014). All of these processes are climatically controlled, and thus can be related to the Earth's orbital dynamics.

Climate change that is sustained across periodic climate cycles (Fig. 2) can be associated with transfer of water between the continents and the oceans and thermal expansion or contraction of seawater (thermo-steric sea-level change, thermo-eustasy). For example, the change in climate mode from a generally warm greenhouse in the Cretaceous to the icehouse of the Pleistocene was associated with both a cooling of the oceans and a net loss of continental ice mass that was probably not fully balanced by an accompanying change in aquifer mass. This probably led to a net sea-level drop during the Cenozoic of up to 60 m (Conrad 2013). On shorter timescales, recent anthropogenic climate change is also not associated with climate cycles, and may cause metres of sea-level change over centuries. Intermediate amplitudes of such 'sustained' sea-level are likely on second to third order timescales (Fig. 2).

Although glacio-eustatic sea-level change during Pleistocene glacial–interglacial cycles is obvious, there is still discussion on the *per se* existence of global eustatic short-term sea-level fluctuations and cyclicities during greenhouse times (e.g. Zorina *et al.* 2008), and some authors argue against any correlatable global transgressions and regressions, putting solely regional geophysical processes into the game (e.g. Moucha *et al.* 2008; Petersen *et al.* 2010). The lack of definite demonstration that the *majority* of short-term Cretaceous sedimentary cycles are eustatic in nature, and thus a response of climate changes, remains indeed a big issue depending on the availability of stratigraphic resolution and global correlation on timescales equal to or below the duration of sea-level changes (see Ray *et al.* 2019). However, there is growing evidence for climatically driven, short-term eustasy in the Cretaceous rock record and beyond (see the section 'Evidence for and impact of aquifer-eustasy in Earth history' and Ray *et al.* 2019).

Three main arguments provide evidence of eustasy during greenhouse climates without ice, and all are enhanced and strongly supported by the ever-improving numerical timescale especially of the Mesozoic:

(1) Short-term sea-level fluctuations during greenhouse times are clearly cyclic and show regular and periodic transgressions and regressions, from the undisputed glacio-eustatic Quaternary with its ice/temperature-based Marine Isotope Stages measured by oxygen isotopes (Raymo *et al.* 2006; Miller *et al.* 2011) down to the Miocene cycles, and still identifiable by oxygen isotopes in the Cretaceous (Stoll & Schrag 1996; Haq 2014) down to clear-cut cycles in the Jurassic and Triassic (e.g. Kent *et al.* 2004).

(2) These cycles follow Milankovitch orbital cyclicity as proven by now for nearly the whole Phanerozoic greenhouse intervals including the Paleozoic (Eriksson *et al.* 2019)

and Mesozoic (Boulila *et al.* 2011; Wendler *et al.* 2014).

(3) Correlation of individual short-term sea-level cycles based on astrochronology is by now precise and accurate, and therefore can be tested and thus approved or falsified. For instance, sea-level synchronicity can be proven in the Milankovitch band around major synchronous Earth history events such as the Paleocene–Eocene Thermal Maximum, the K/Pg boundary (Cretaceous–Paleogene impact-related mass extinction), and the OAEs (oceanic anoxic events) of the mid-Cretaceous (e.g. Voigt *et al.* 2006; Batenburg *et al.* 2016). Even rather small events such as the middle/late Turonian sea-level fall event (Haq & Huber 2017) can be precisely correlated using the global negative carbon isotope excursion, the Hitch Wood event of Jarvis *et al.* (2006).

Thus, we conclude that short-term sea-level fluctuations during greenhouse times of the Cretaceous are present, global and cyclic in the mainly longer Milankovitch bands (405 kyr, 1.2 myr and 2.4 myr). Their amplitudes are hard to decipher given the randomness and incompleteness of the stratigraphic record in general (e.g. Sadler 1981) and the inevitable regional modification owing to geodynamic and tectonic processes. In addition, different established sea-level curves and magnitudes of short-term sea-level change for the Cretaceous are debated (for details see Ray *et al.* 2019, introduction and fig. 1 therein). Ray *et al.* (2019) provide new constraints and categories for amplitudes of Cretaceous sea-level changes based on extensive review and integrated geological and statistical analysis of available records. Hothouse episodes like the Cenomanian–Turonian fall into their 'modest' (10–40 m of sea-level change) category.

Sequence stratigraphic studies, especially around passive margins, and the growing number of case studies from all over the world, have resulted in greenhouse sea-level fluctuations with magnitudes of up to tens of metres (e.g. Ray *et al.* 2019 and references therein). In comparison with icehouse glacial–interglacial cycles, amplitudes during greenhouse may be significantly lower but are still in a range (*c.* 10–40 m of Ray *et al.* 2019) that was hitherto only explainable by waning and waxing of continental ice sheets (e.g. Miller *et al.* 2005*a*, *b*). This calls for an alternative climate-controlled non-glacial driver that reduces the water mass in the oceans – called 'hydro-eustasy' (e.g. Gornitz 2006; Rovere *et al.* 2016) or 'aquifer-eustasy' based on the source of the major water volume that contributes (see Fig. 1; and Hay & Leslie 1990; Jacobs & Sahagian 1995; Wendler *et al.* 2011, 2014; and Sames *et al.* 2016), as discussed in the following chapters.

Aquifer-eustasy

Definitions and overview

Aquifer-eustasy describes groundwater-driven, short-term (third- to fourth-order and higher cycles) eustatic sea-level fluctuations (changes in ocean basin water volume) caused by climate-driven land water storage owing to shifts in the hydrological cycle's dynamic balance towards charging (via precipitation) or discharging (via evapo-transpiration and runoff) of continental aquifers. These cycles are governed by (palaeo-)climate change (cf. Föllmi 2012; Wagreich *et al.* 2014; Wendler & Wendler 2016; Li *et al.* 2018), and are analogous to climate cycles of ice-driven glacio-eustasy associated with the waxing and waning of continental ice sheets.

Aquifer-eustasy is a pervasive process in interplay with glacio-eustasy and, to minor extent, with thermo-eustasy (eustatic effect resulting from the thermal expansion of seawater, also termed the 'thermo-steric effect', e.g. Sames *et al.* 2016, p. 400). It mainly operates on timescales between 10^4 and 10^6 years (Fig. 2), where 10^4–10^5 years is the time presumed by Hay & Leslie (1990) for aquifer/groundwater reservoirs to adjust after changes to the global hydrological cycle, and 10^5–10^6 years is the timescale for these adjustments to be manifest as eustatic sea-level fluctuations (e.g. Sames *et al.* 2016; Wendler & Wendler 2016). We estimate the rate of aquifer-eustatic sea-level change to be in the range of about 0.7 mm per year (=7 m/1000 years = 140 m/20 000 years; deduced from Reager *et al.* 2016, who give climate driven land water storage as −0.71 mm per 1 year). Depending on the climate mode, aquifer-eustasy will be either outpaced by glacio-eustasy (during an icehouse) or the dominant process (in a hothouse phase) that controls cyclic short-term sea-level fluctuations (Figs 2 & 3). A minor component of thermo-eustasy is always present. For detailed review of the aquifer-eustasy hypothesis we refer to Föllmi (2012), Wendler & Wendler (2016) and Sames *et al.* (2016 and references therein), as well as to sections 'Earth's "surface" water resources and their distribution', 'Recent progress on aquifer-eustasy' and 'Evidence for and impact of aquifer-eustasy in Earth history'.

Originally, the idea that charging and discharging aquifers could considerably contribute to eustatic sea-level fluctuation was brought forward by Hay & Leslie (1990) and Jacobs & Sahagian (1993), although these authors did not mention eustasy. The term 'aquifer-eustasy' itself was coined much later by Jens Wendler (Wendler *et al.* 2011, 2014) to denote the major reservoir of continental rock pore space that can be filled by (ground)water and thus affect global sea-level by changing the ocean water volume (Figs 1 & 2). The global water mass of groundwater that today can be potentially stored in those aquifer systems is estimated to be at least equivalent to the water mass currently stored in the Earth's 'permanent' continental ice (glacial ice, *c.* 24.064 × 10^6 km^3, Fig. 1), corresponding to 65–70 m sea-level equivalent without, and 45–50 m sea-level equivalent with, isostatic adjustment (Fig. 1). It must be noted again (see also the section 'Earth's "surface" water resources and their distribution') that these numbers refer to the considered maximum storage/pore volume of aquifers, although only a proportion of this corresponding water volume is 'available', i.e. can be discharged and thus considered to effectively result in eustatic sea-level changes. This 'available' proportion is the water stored in aquifers sufficiently above the particular sea-level (see Fig. 4 and legend to Figs 4–6), and it is significant today (about 50 m sea-level equivalent according to Hay & Leslie 1990; see also Fig. 1 herein). The available water volume should have been even larger during greenhouse intervals such as the Cretaceous, which had an enhanced hydrological cycle, with the absence of permafrost, and more 'available' pore space given different palaeogeographic settings such as lower global average elevations, leading to increased aquifer-accessible 'flat' land area, as has been suggested by Hay (2011, 2017) and Hay *et al.* (2018, and references therein).

Aquifer-eustasy is a subcategory of the superordinate concept of 'hydro-eustasy' (Fig. 3; e.g. Gornitz 2006; Rovere *et al.* 2016), which denotes all non-ice-related changes in the volume of the world's ocean water as a consequence of water redistribution between different hydrological reservoirs such as groundwater, snow, surface-runoff water, river flows, soil moisture, organisms (biological water) and permafrost (Fig. 1). The use of this term is, thus, ideal for applications today and through the Anthropocene, since it (1) also covers anthropogenic land-water storage and groundwater depletion and (2) works on very short timescales (seasonal to decadal) and with very small water volumes, resulting in minor eustatic sea-level fluctuations observable through satellite altimetry and gravimetry technology today (see introductory section above). Aquifer-eustasy is by far the most dominant of the hydro-eustatic processes (this excludes glacio-eustatic water by definition) with respect to operating (ground)water volumes (Fig. 1), and is considered to have been even more dominant in greenhouse intervals. Aquifer-eustatic sea-level equivalents, i.e. eustatic sea-level rises and falls, are much higher on longer timescales (tens to hundreds of thousands of years, Fig. 2) and thus get into the range of values that are detectable ('measurable') in the geological record (above 10 m, 'modest' category of Ray

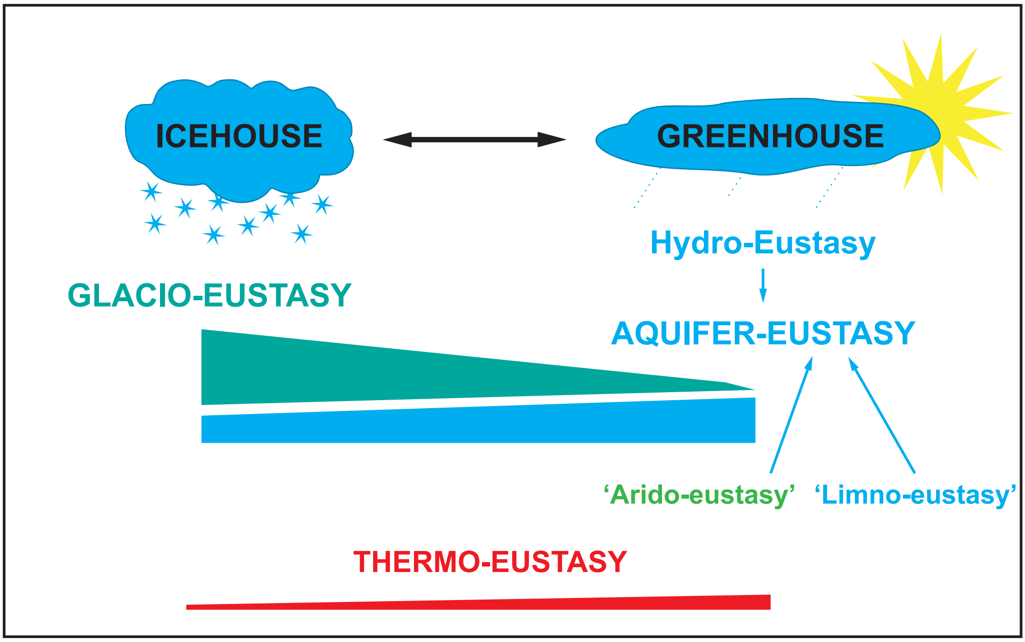

Fig. 3. Overview of relational hierarchy and terminology of eustasy models relevant for short-term sea-level fluctuations as well as relative contributions of the three main factors during icehouse (left) and greenhouse (right) modes. The dominance of either glacio-eustasy or aquifer-eustasy and the available active water volumes depend on the climate mode and state (see also Fig. 2, and text for details).

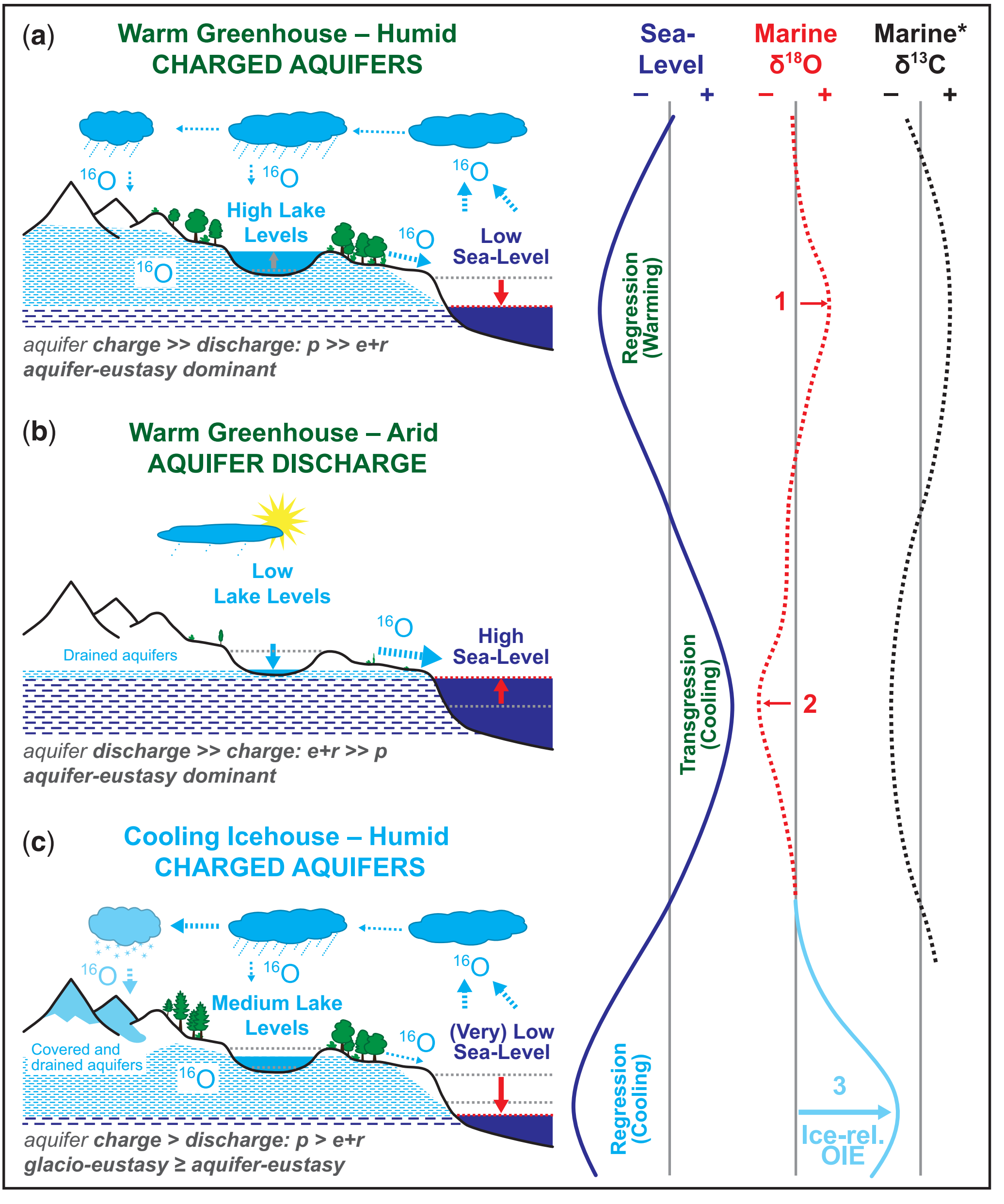

Fig. 4. Relationship between climate mode and state, aquifer charge, eustatic sea-level, oxygen isotope ratio ($\delta^{18}O$) of ocean water and the marginal (*) marine carbonate rock record. For explanation refer to Figure 7. (**a**)–(**c**) Simple sketches of the aquifer-eustasy model in (a) warm (warming) greenhouse humid and (b) greenhouse (cooling) arid state, as well as (c) (cooling) icehouse humid state. These illustrate the dynamic balance of aquifer charge v. aquifer discharge, principally resulting in anti-phased relationships of eustatic sea-level stands and lake-level stands as well as the oxygen isotope ratio ($\delta^{18}O$) of ocean water (marine carbonate rock record), and marginal (proximal basin) marine (*) carbon isotope ratio ($\delta^{13}C$) (newly combined and supplemented as based on e.g. Suarez *et al.* 2011; Föllmi 2012; Wagreich *et al.* 2014; Sames *et al.* 2016; Wendler & Wendler 2016; Laurin *et al.* 2019). The thicknesses of dotted arrows indicate relative intensities of ^{16}O transfer (small arrow, low transfer; large arrow, high transfer). With respect to $\delta^{18}O$ and $\delta^{13}C$ values, these indicate relative trends – higher (+) and lower (−) and not necessarily actual (positive or negative) values. Note that in greenhouse phases with aquifer-eustasy being the dominant process, regressions are caused by warming (charging aquifers), whereas in icehouse phases regressions are caused by cooling (waxing of

et al. 2019) at the maximum stratigraphic resolution available. Therefore, the term 'aquifer-eustasy' is preferred in the Earth sciences since it emphasizes the measurable major contribution of groundwater to eustatic sea-level fluctuation on geological timescales.

Wagreich *et al.* (2014, p. 121) coined the term 'limno-eustasy' (Fig. 3) based on the practice that in limnology the term 'limnic' covers the study of all inland-waters (surface and underground) and – as outlined and tested in that paper – suggests that lake-level and sea-level fluctuations should be in an out-of-phase relationship. As lakes and aquifers are connected, and because we cannot well measure aquifer stands in the geological record, major lake-level fluctuations can be used as a proxy for charged (lake-level highstand, eustatic sea-level lowstand, Figs 4 & 6) or discharged (lake-level lowstand, eustatic sea-level highstand, Figs 4 & 6) aquifers, especially during hothouse phases of Earth history such as the Turonian. However, Wendler & Wendler (2016) pointed out that the term 'aquifer-eustasy' – besides referring to the major non-glacial hydro-eustatic water volume contribution – should be preferred for the reason that etymological confusion might provoke an association with surface waters generally, thus disregarding subsurface aquifers as the principle storage medium available to force short-term eustatic sea-level fluctuations. The two current authors that then were involved in the Wagreich *et al.* (2014) article (BS and MW) have accepted these objections, and we here restrict the term 'limno-eustasy' to a subcategory of aquifer eustasy (Fig. 3) in the narrower sense of being a proxy for palaeoaquifer stands and, thereby, aquifer-eustatic sea-level fluctuations in an inversely phased relationship.

Similarly, the rationale for the new term 'arido-eustasy' (Brikiatis 2019), and its logical relationship with other terms such as glacio-, aquifer- and thermo-eustasy, must be considered. The 'arido-eustasy model' (Brikiatis 2019) is based on an anti-covariation pattern in the geochemical record of marine organic and marine carbonate carbon isotopes (using different markers), resulting from orbitally controlled climate-state shifts from extremely humid ('wet') to arid climate states and vice versa, on short-term timescale shifts during greenhouse phases of the last 200 myr (but see also the section 'Carbon isotope evolution and the carbon cycle', and Laurin *et al.* 2019). Brikiatis (2019, p. 29) states that 'the model proposes that sea-level changes [sic!] during greenhouse periods are triggered and forced by arid/wet climate modes. Hence, it may be referred to as an arido-eustatic, in contrast to a glacio-eustatic, model of sea-level change'.

However, with respect to the term chosen, and while considering the restriction of the meaning of 'limno-eustasy' above, we have some objections:

(1) We cannot follow Brikiatis' (2019) opinion of 'arido-eustasy' as a process to force short-term sea-level fluctuations because the term and definition of this model do not include any water volume that can actually be released into or removed from ocean water. Thus, the arido-eustasy model is not a eustatic process but instead refers to a proxy (as does limno-eustasy, see above) to identify aquifer-eustatic sea-level fluctuations controlled by humid–arid climate state shifts during greenhouse (supergreenhouse/hothouse) phases.

(2) This is to say, the term 'arido-eustasy' itself includes 'arid', referring to a climate state instead of the water storage and release, plus 'eustasy, which is misleading and does not at all have the same quality or rank to be related – or put in contrast to – glacio-eustasy,

Fig. 4. *Continued.* continental ice sheets). Aquifer charge is inversely related to eustatic sea-level, i.e. aquifer highstands result in eustatic sea-level lowstands (a) and vice versa (b). The relationship between the $\delta^{18}O$ values of ocean water and aquifer-eustasy during greenhouse phases (A + B) is more complex and a function of the temperature-related intensity of the hydrological cycle. (a) A relatively strong $\delta^{18}O$ positive shift (no. 1) is present during humid climates and charging aquifers, involving effects of high global mean temperature and lower degree of Earth's latitudinal temperature gradient and low presence or absence of ice – all of which have different combinations of effects on the degree of oxygen fractionation connected with the number of precipitation steps (for details see text, particularly the section 'Aquifer-eustasy'; Wendler *et al.* 2016, and table 4 therein; and Kidder & Worsley 2010, 2012; Föllmi 2012). (b) A relatively strong $\delta^{18}O$ negative shift (no. 2) occurs during warm arid climates resulting from discharging aquifers that lead to a high ^{16}O transfer into the sea, as well as low lake levels and rising sea-level and transgressions. In an icehouse world (c), the cumulated effects of high latitudinal temperature gradient and polar ice result in an extremely strong positive $\delta^{18}O$-excursion (ice related OIE in light blue, no. 3). The carbon isotope record – $\delta^{13}C_{org}$ = marginal (proximal basin) marine (*) carbon isotope ratio during greenhouse phase – is relatively high during humid state and relatively low (negative?) during arid state (based on Föllmi 2012; Laurin *et al.* 2019). Abbreviations: p, precipitation; e, evaporation; r, surface runoff; OIE, (ice-related) oxygen isotope excursion; $\delta^{18}O$, oxygen isotope ratios of ocean water and marine carbonate; $\delta^{13}C$, marginal (proximal basin) marine (*) carbon isotope ratio; 1, considerable posititve $\delta^{18}O$-shift during humid greenhouse climate and charging aquifers; 2, relatively low $\delta^{18}O$ values of ocean water owing to reflux of ^{16}O enriched groundwater (aquifer discharge) that also leads to higher eustatic sea-levels during arid greenhouse climate; 3, ice related, very strong positive $\delta^{18}O$ excursion during icehouse mode).

aquifer-eustasy, or thermo-eustasy. (Finally, as the focus of the model is related to extremely humid ('wet') greenhouse climate, we wonder why the more logical term 'humido-eustasy' was not used.)

Consequently, it remains to be discussed, whether or not the term 'arido-eustasy' (not the theoretical model behind it) is useful. At the moment and for the reasons given above, we place the term and model of 'arido-eustasy' as equivalent to 'limno-eustasy', as being a subcategory for aquifer-eustasy (Fig. 3). We also consider arido-eustasy a geochemical proxy model for orbitally controlled greenhouse humid–arid climate state shifts in the context of aquifer-eustatic sea-level fluctuations, and especially as proxy for extremely wet (monsoon) climate intervals resulting in eustatic sea-level falls/regressions and strong perturbations of the carbon cycle leading to negative δ^{13}C-excursions in the (marginal/proximal) marine organic carbon-isotope record as these contain terrestrial organic matter (e.g. Föllmi 2012; Brikiatis 2019).

Recent progress on aquifer-eustasy

During about the last two to three decades, there has been progressively growing evidence that climatically – and, thus, ultimately orbitally controlled (Milankovitch cyclicity) – short-term (third- to fourth-order) sea-level fluctuations were present not only during icehouse times but also during greenhouse times (e.g. Boulila *et al.* 2011; Eriksson *et al.* 2019). However, the new insight is that (1) not only a differentiation between the principal global climate modes, icehouse or greenhouse, but (2) also the respective intrinsic variations ('climate sub-modes', i.e. icehouse mode with glacials and interglacials; greenhouse mode with cool greenhouse intervals punctuated by cold snaps, and warm to hot greenhouse, or hothouse, intervals with few or no continental ice sheets, respectively) as well as the respective climate state (predominance of humid or arid conditions on a global scale) are fundamental for interpreting the main driving factors, processes and feedback mechanisms for short-term sea-level fluctuations, particularly when dealing with the Cretaceous (e.g. Föllmi 2012; Sames *et al.* 2016; Wendler & Wendler 2016; Wendler *et al.* 2016; Ray *et al.* 2019; and references in these).

Therefore, in the context of the main climate-related (thus orbitally controlled) processes governing short-term fluctuations in the ocean water volume, i.e. cyclic eustatic sea-level fluctuations, the fundamental new insights of the last decade of research are (see below for details):

(1) In general, including thermo-eustasy as minor component, today and in Earth's history there always is (and was) an interplay of glacio- and aquifer-eustasy (e.g. Wendler & Wendler 2016), except during warm greenhouse to hothouse, ice-free phases of greenhouse times, presumably (but see item 4 below).

(2) During the icehouse climate mode – with large continental ice sheets present – the main contributing factor to short-term sea-level fluctuations in terms of amplitude (volume) is glacio-eustasy whereas during the greenhouse climate mode – with only small or no continental ice sheets present – the main water volume contribution is through aquifer-eustasy (e.g. Wendler & Wendler 2016; and Fig. 2 herein).

(3) In contrast to glacio-eustasy, aquifer-eustasy is a pervasive process in both major climate modes – icehouse and greenhouse (e.g. Wendler *et al.* 2016), including all subordinate modes of these and both climate states. A minor component of thermo-eustasy is always present, but it is stronger in the greenhouse mode (global sea-level equivalent up to 10 m in the greenhouse mode in contrast to less than 5 m in the icehouse mode, cf. Sames *et al.* 2016 figs 4 & 5, and references given therein).

(4) Particularly when dealing with the 'mid-Cretaceous hothouse state' (also 'Cretaceous supergreenhouse', Cenomanian–Turonian), the controversy of whether continental glaciation, i.e. large, long-term continental ice sheets, existing for thousands of years and beyond (not local glaciers!) was present during this time interval or not (e.g. Price 1999; Fluteau *et al.* 2007; Bornemann *et al.* 2008; Huber *et al.* 2018, see also the section 'Short-term sea-level cycles, eustasies and their controls') fundamentally refers to the availability of relevant water volumes (i.e. sufficient global sea-level equivalents of more than 10 m that could be reconstructed from the geological record) for glacio-eustatic sea-level changes of recognizable amplitude.

(5) Based on the new insights gained from the GOCE and GRACE missions (see introductory chapter above and the section 'Recent land water storage trends supporting the aquifer-eustasy hypothesis') and what we know from Earth history, especially from recent results on the Cretaceous (sections 'The Cretaceous greenhouse laboratory and its fluctuating sea-level' and 'Evidence for and impact of aquifer-eustasy in Earth history'), we can now conclude with certainty what Jacobs & Sahagian (1995) and Wendler *et al.* (2016) 'only' assumed: that aquifer-eustasy is a pervasive process and has been present throughout Earth history, or at least throughout the Phanerozoic interval. Consequently, glacio-eustasy may

not entirely have been a pervasive process as it is considered to be a minor player in warm greenhouse phases but was potentially not even active at all during hothouse intervals when continental ice-sheets were absent.

(6) There is a considerable relative difference in the oxygen isotope fractionation between greenhouse and icehouse climate modes on the one hand, but also between humid and arid greenhouse climate states on the other hand, which is presumed to lead to respective relative differences in marine $\delta^{18}O$ values, which impacts their interpretations (see Föllmi 2012; Wendler & Wendler 2016 and fig. 1 therein; and the section 'Oxygen (and carbon) isotopes' and Fig. 4 herein).

(7) The glacio-eustatic and aquifer-eustatic effects may counteract each other in various ways (Wendler & Wendler 2016): (a) in that the strength of aquifer-eustatic sea-level forcing is delimited by glacio-eustasy and vice versa; and (b) in their relation to climate mode and state and the resultant effect on eustatic sea-level and marine $\delta^{18}O$ values (see Fig. 4). In the greenhouse phase with (globally dominantly) humid climate, regressions are caused by warming (enhanced hydrological cycle and dominant aquifer-eustasy resulting in falling sea-level through strong continental groundwater storage – see also the section 'Oxygen (and carbon) isotopes') whereas in icehouse phases, regressions are caused by cooling (glacio-eustasy dominant, falling global temperatures lead to waxing of continental ice-sheets and falling eustatic sea-level). In addition, thermo- and aquifer-eustasy also counteract in their inverse effects on sea-level. In greenhouse climates aquifer-eustasy leads to water storage on land and falling sea-level while the increased ocean-water volume leads to higher sea-levels, whereas the contrary is true in icehouse times.

(8) The inverse relationship of aquifer-eustatic sea- and lake-level stands, the 'limno-eustatic effect' or 'limno-eustasy' of Wagreich *et al.* (2014), can be applied to cyclostratigraphic marine to non-marine correlations when sufficient stratigraphic resolution is available, especially with regard to the non-marine successions.

Evidence for and impact of aquifer-eustasy in Earth history

Humid–arid weathering cycles in carbonate platforms and desert systems

The first empirical evidence for the existence of aquifer-eustasy processes in deep-time greenhouse archives came from weathering products within low-latitude carbonate platforms. Wendler *et al.* (2011, 2014) described million-year-scale third-order sea-level cycles from the Levant Platform (Jordan), related those to climate cycles, and looked in detail at detrital material (Wendler *et al.* 2016) and the terrigenous mineral assemblages in the carbonate succession. These authors demonstrated a correlation between changes in precipitation, continental weathering intensity and evaporation. Sea-level falls and lowstands were associated with products of intense chemical weathering such as clays, indicating a wet climate phase. In contrast, preservation of weathering-sensitive minerals such as feldspars and epidotes in the sediments of sea-level rises and highstands reflects decreased continental weathering owing to dryer arid climate phases. Thus, aquifer charge during wet phases with an enhanced hydrological cycle results in land-water storage and falling sea-level, whereas dry to arid phases lead to aquifer discharge and high sea-level (Fig. 5; Wendler *et al.* 2016). A similar conclusion was drawn from a study on fine-grained marine siliciclastics in Tanzania, where lowstands of Turonian climate/sea-level cycles are pinned down by increasing grain size, enhanced organic carbon flux, faunal assemblage changes and foraminiferal $\delta^{18}O$ minima (Wendler *et al.* 2015). Warmer sea-water during regressions and a minor surface-water salinity decrease led the authors to favour aquifer-eustasy as the main process controlling these sea-level fluctuations. Evidence for desertification and related coeval sea-level highs was also put forward by Wu *et al.* (2017) based on mid-Cretaceous aeolian and evaporite sedimentation in China.

Lake-level cycles and the limno-eustasy hypothesis

A second test and proxy for the existence of aquifer-eustasy is the 'limno-eustasy' idea (Wagreich *et al.* 2014; see the section 'Definitions and overview' herein for details), i.e. the fact that large permanent lakes are connected to the aquifers and thus lake-level stands mirror aquifer-level stands. This is an important proxy for recognizing climate-driven aquifer charge and discharge (Jacobs & Sahagian 1995), and the resulting aquifer-eustatic sea-level fluctuations during greenhouse phases of Earth's history, because we cannot well 'measure' aquifer stands in the geological record (lacking available direct proxies for aquifer levels in the rock record). During humid times, which are related to high groundwater levels and thus filled aquifers, lakes are deep and large whereas during dry periods, lakes become smaller and shallower as aquifer discharge to the oceans affects the existence and water depth of large lakes. The reasoning that follows is that major 'limno-eustatic' lake-level fluctuations would be a proxy for charged aquifers (lake-level highstand, eustatic sea-level lowstand) or discharged aquifers (lake-level lowstand, eustatic sea-level high-stand) and the corresponding aquifer-eustatic sea-level fluctuations in an inversely phased relationship (Figs 4 & 6; Wagreich *et al.* 2014). As aquifer charge is not necessarily a globally synchronous and equally strong process – when, for example, during a precession cycle the Northern Hemisphere becomes more humid, more arid conditions would be expected on the Southern Hemisphere (an effect also strongly variable as depending on the varying relative continent distribution over both hemispheres through the Phanerozoic) – global means are considered.

Wagreich *et al.* (2014) looked on lake depths and lake anoxic events of the Songliao Basin, a long-living and large Cretaceous lake archive in NE China, to test the 'limno-eustatic' lake-level proxy idea. Here, a high-resolution record of Upper

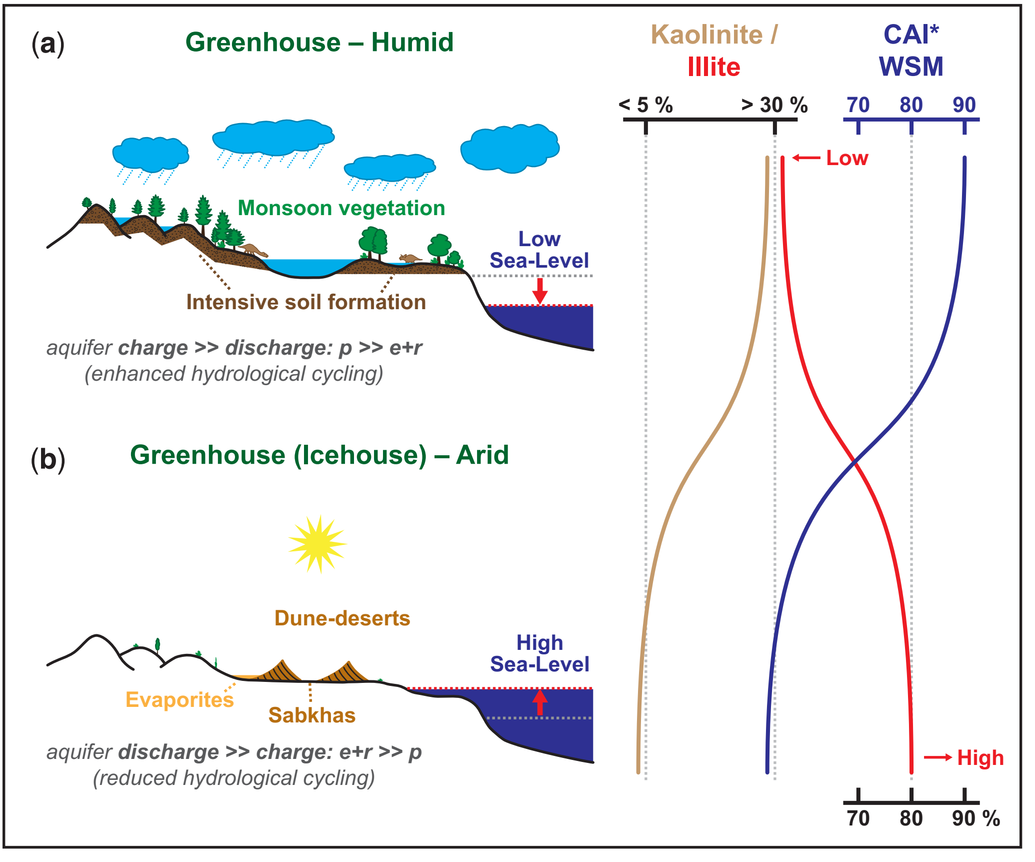

Fig. 5. Schematic illustration of the general global relationship of (**a**) humid and (**b**) arid cycles under greenhouse conditions, surface processes, and eustatic sea-level base on Cretaceous evidence (combined after Föllmi 2012; Wagreich *et al.* 2014; Wendler *et al.* 2016; Laurin *et al.* 2019). For explanation refer to Figure 7. Note that the lower average continental relief that is presumed for the Cretaceous (Hay *et al.* 2018, and references therein; see also the section 'Earth's "surface" water resources and their distribution'), in contrast to Figures 4 & 6. The cyclic variation in distribution patterns of weathering sensitive minerals with focus on the clay minerals kaolinite and illite, and weathering intensity expressed by the Chemical Index of Alteration (Nesbitt & Young 1982, based on analysis of weathering-sensitive mineral of whole-rock geochemical data) are used as proxies for aquifer-eustasy for Wendler & Wendler (2016). The reasoning is that the shift between a predominantly humid climate state (a), enhanced hydrological cycling, to predominantly arid climate state (b), reduced hydrological cycling, is also connected with a change from dominantly chemical weathering (relatively high kaolinite component in the siliciclastic assemblage) to dominantly physical weathering (relatively high illite component in the siliciclastic assemblage). Abbreviations: p, precipitation; e, evaporation; r, surface runoff; WSM, weathering-sensitive minerals with focus on clay minerals (cf. Wendler *et al.* 2016); CAI*, Chemical Index of Alteration (Nesbitt & Young 1982) of weathering sensitive minerals of whole-rock geochemical data.

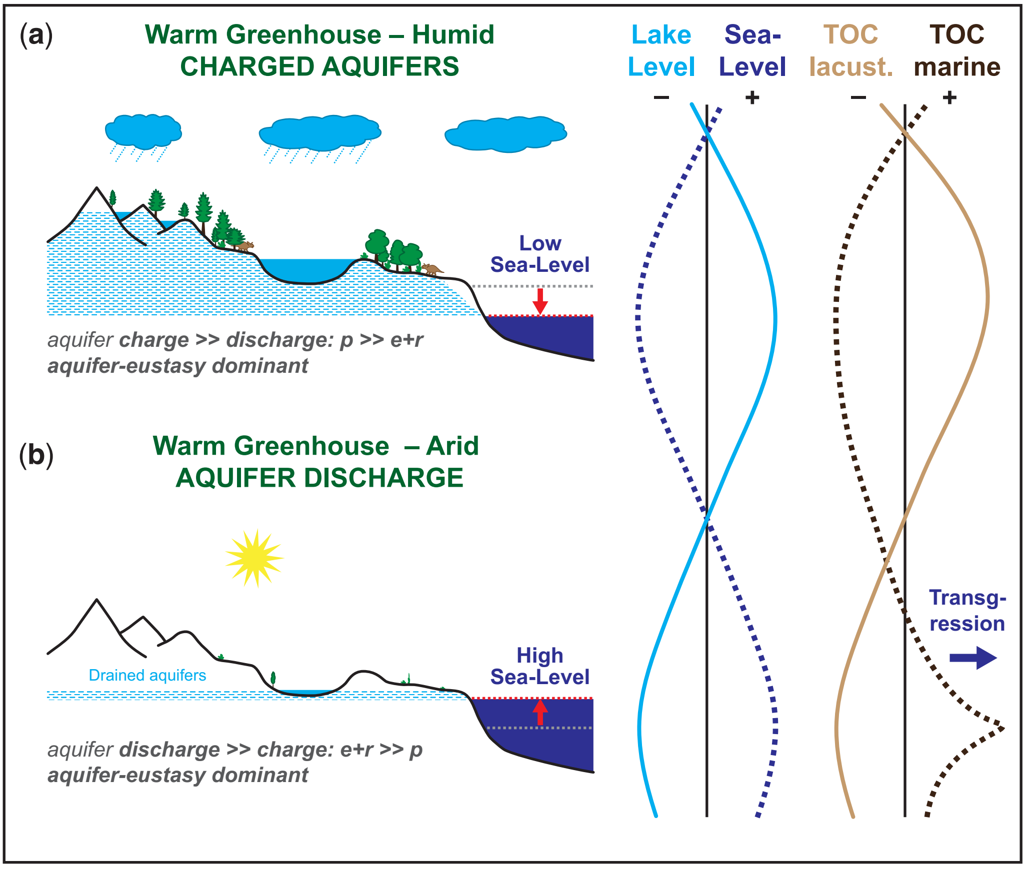

Fig. 6. Sketch-illustration of the anti/out-of-phase relationship between lake level and eustatic sea-level under humid (**a**) and arid (**b**) greenhouse climate conditions in relation relative variations in total organic carbon (TOC) content of respective lacustrine and marine sedimentary rocks (combined after Föllmi 2012; Wagreich *et al.* 2014; Wendler *et al.* 2016; Laurin *et al.* 2019). For explanation refer to Figure 7. (a) Under predominantly humid climate, the TOC content of lacustrine deposits is high owing to lake highstands/lake anoxic events producing a stratified lake with oxygen deficiency in bottom waters (Xi *et al.* 2011; Jia *et al.* 2013), but no TOC anomalies in proximal marine deposits. (b) Predominantly arid conditions lead to low lake levels with predominant mixing of lake waters and oxygenation of lake bottom sediments throughout (Wagreich *et al.* 2014), whereas during transgressive phases, and high sea-level, organic matter may be concentrated in condensed sections (Haq 1991) forming TOC-rich marine sediment layers. Abbreviations: p, precipitation; e, evaporation; r, surface runoff.

Cretaceous lacustrine and terrestrial sediments was dated by geochronology (U/Pb zircon dates) and astrochronology (Wu *et al.* 2013; Xi *et al.* 2018, 2019). Two events of deep and extensive lake sedimentation (so-called lake anoxic events, during lake-level highstands and organic-rich sedimentation) could be correlated to sea-level lowstands in the late Turonian and in the Santonian (sea-level curve of Haq 2014) within a Milankovitch-band precision (Wagreich *et al.* 2014; Xi *et al.* 2018, 2019; Yang *et al.* 2018), thereby supporting the limno-eustatic hypothesis. Further tests which rely strongly on sufficient dating, stratigraphic resolution and marine to non-marine correlations, as well as different sea-level curves applied and their interpretations (i.e. whether the sequences reflect eustasy or not), remain to be conducted.

Oxygen (and carbon) isotopes

Föllmi (2012) and Wendler & Wendler (2016) discuss the evolution of stable isotopes during aquifer-eustasy cycles, and Wendler *et al.* (2016) speculate on the carbon cycle and carbon isotope evolution. Whereas the carbon isotopes of marine carbonates depend on various factors that hinder a straightforward interpretation, e.g. the terrestrial area, vegetation density and the balance of terrestrial to marine

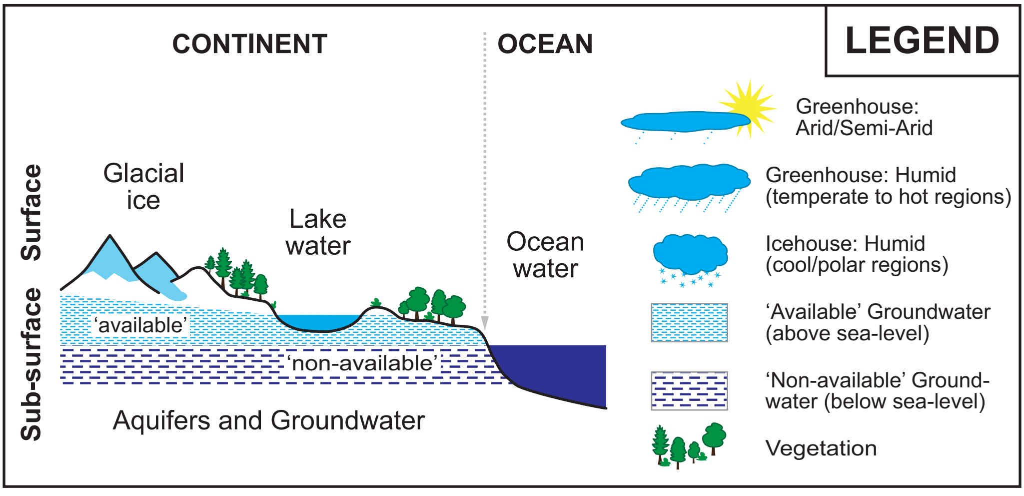

Fig. 7. Graphic legend to Figures 4–6. 'Available' groundwater refers to the proportion of groundwater stored in aquifers above respective actual eustatic sea-level stands, which contributes to aquifer-eustatic sea-level fluctuations. 'Non-available' groundwater refers groundwater partially at and below the respective actual sea-level which does not contribute to aquifer-eustatic sea-level fluctuations. It is also important to note that a significant flow of groundwater directly entering the ocean does not interact directly with the climate system and is, thus, not included in respective climate models (Hay *et al.* 2018).

burial during a sea-level cycle, the interpretation of oxygen isotopes seems more straightforward.

Several parameters and processes such as ice proportion, temperature, evaporation and precipitation, and diagenesis influence marine calcite oxygen isotope fractionation (the number and intensities of fractionation steps), often measured on foraminiferal calcite (e.g. Miller *et al.* 2011). The oxygen-isotope fractionation process during different climate modes differed significantly (Fig. 4). Wendler & Wendler's (2016) case study uses the Turonian $\delta^{13}C$ records (Pewsey positive carbon isotope event of Jarvis *et al.* 2006; Wendler *et al.* 2014) where the oxygen isotope maximum correlates to a transgression that is in contrast to glacio-eustasy processes in which cooling and ephemeral ice shield build-up (e.g. Miller *et al.* 2005*b*) should result in a regression and sea-level low associated with a coeval $\delta^{18}O$ maximum (Fig. 4). Wendler & Wendler (2016) thus applied an aquifer-eustasy model for this sea-level cycle.

An enhanced hydrological cycle (e.g. during Late Cretaceous Anoxic Event 2 (OEA2), *c.* 94 Ma; van Helmond *et al.* 2014) with increased precipitation on the continents may lead to heavier $\delta^{18}O$ values of sea surface water, because of warmer temperatures and higher evaporation, resulting in ^{18}O-depleted continental precipitation and ^{18}O-enriched ocean surface waters (e.g. Suarez *et al.* 2011). Föllmi (2012) also gave evidence for the existence of 'freshwater lids', i.e. less saline surface waters owing to a high influx of freshwater during humid intervals, leading to lighter $\delta^{18}O$ values and short negative $\delta^{18}O$ excursions superimposed on longer-term positive trends.

In general (see Fig. 4), a combination of cooler temperatures and large continental ice sheets results in the very strong, maximum positive $\delta^{18}O$ excursions and the glacio-eustatic sea-level lowstands as seen in the Pleistocene (e.g. Lisiecki & Raymo 2005; Raymo *et al.* 2006). In contrast, warm temperatures and land-based aquifer and lake water storage cause a relatively strong positive $\delta^{18}O$ excursion, but much less than under icehouse conditions during aquifer-eustatic sea-level highstands (Wendler & Wendler 2016).

Carbonate clumped isotope (^{13}C–^{18}O) thermometer studies of Cretaceous greenhouse intervals (Dennis *et al.* 2013; Price & Passey 2013) further support the ice-free hypothesis for Cretaceous warm greenhouse intervals.

Carbon isotope evolution and the carbon cycle

Wendler *et al.* (2016) speculate on the carbon cycle and carbon isotope evolution during greenhouse aquifer cycles. The carbon isotopes of marine pelagic carbonates depend on various factors and feedback processes that may hinder a straightforward interpretation, e.g. the terrestrial area, vegetation density and the balance of terrestrial to marine burial during a sea-level cycle. However, a significantly different short-term terrestrial carbon storage cycle process may influence hothouse marginal-marine carbon isotope ratios as recently put forward by Laurin *et al.* (2019) for the OAE 2 interval. In marginal marine settings such as the Western Interior Seaway, negative $\delta^{13}C$ peaks show orbital control on obliquity and short eccentricity scales (80–120 kyr). The link between such atmospheric carbon-cycle perturbations and metre-scale sea-level change on the 100 000 year timescale was interpreted by Laurin *et al.* (2019) by invoking an aquifer-eustasy model. Humid hothouse phases with a strong positive precipitation–evaporation balance and a megamonsoon climate led to short-term groundwater aquifer charge, enhanced terrestrial biomass production and a short-term positive $\delta^{13}C$ shift owing to enhanced terrestrial carbon burial such as that interpreted for lake anoxic events (Xi *et al.* 2018). In contrast, aquifer discharge during drier climate phases weakened terrestrial carbon burial and induced carbon remineralization, leading to a negative $\delta^{13}C$ shift in marginal marine settings (Fig. 4). These negative excursions in the terrestrial-sourced $\delta^{13}C_{org}$ are subsequently linked to short-term and initial marine transgressions (Laurin *et al.* 2019).

Brikiatis (2019) proposes the 'arido-eustasy model' which, based on palaeoenvironmental information from carbon isotope record variations, produces anti-covariation patterns of marine organic (wood) and carbonate carbon-isotope records to identify and explain 'non-glacial' (i.e. aquifer-eustatic, short-term) sea-level fluctuations >10 m during greenhouse periods of the last 200 myr. This model interrelates orbitally driven intervals of an extremely humid (wet) climate with environmental crises, (aquifer-eustatic) sea-level falls and carbon-cycle perturbations 'during which negative excursions in the marine organic carbon-isotope record of sediments containing matter from terrestrial vegetation should be understood as a proxy reporting periods of high precipitation rather than changes in the global carbon reservoir' (Brikiatis 2019, p. 25). The model is demonstrated by several Mesozoic examples, regarding the Cretaceous (Brikiatis 2019, see especially supplementary material therein), including the late Cenomanian (OAE 2), or Bonarelli-Event, and three late Aptian Events. The main limit for an application of this model to larger intervals of the Mesozoic is the lack of sufficient qualitative and quantitative resolution of the geochemical record (Brikiatis 2019). As stated above (in the section 'Definitions and overview') we here consider 'arido-eustasy' as a subcategory of aquifer-eustasy (cf. Fig. 2) and as a geochemical proxy model for orbitally controlled greenhouse humid–arid climate state shifts in the context of aquifer-eustatic sea-level fluctuations, and especially as proxy for extremely wet (monsoon) climate intervals resulting in eustatic sea-level falls/regressions and strong perturbations of the carbon cycle leading to negative $\delta^{13}C$-excursions in the (marginal/proximal) marine organic carbon-isotope record as these contain terrestrial organic matter (e.g. Föllmi 2012; Brikiatis 2019).

Other Phanerozoic evidences for aquifer-eustasy

Compared with the Cretaceous, the Triassic was a time of a completely different palaeocontinent configuration, remarkably a supercontinent world with the existence of Pangaea and Panthalassa. However, based on case studies from the late Triassic, Jacobs & Sahagian (1993, 1995) were among the first to work out a detailed hypothesis that includes land-based groundwater and lake water storage and an enhanced hydrological cycling involving a 'supermonsoon' atmospheric circulation (i.e. the so-called 'Pangean megamonsoon', cf. Parrish 1993), mainly from the equatorial Tethys Gulf into partly landlocked basins of Pangaea. Jacobs & Sahagian (1995) concluded that climatically driven changes in non-ice-related continental water storage can produce significant sea-level changes and Milankovitch frequency eustatic fluctuations during periods of Earth's history that lacked continental-scale ice sheets. By comparing the early Holocene pluvial period with the late Triassic, they found that this effect is especially significant if large internally drained areas are involved in the monsoonal precipitation (i.e. convection and precipitation associated with continental heating) which forms lakes and increases water storage in aquifers. Applying those ideas to the Holocene results in a potential sea-level change of 4–8 m (Jacobs & Sahagian 1993, 1995).

Li *et al.* (2018) further addressed eustatic sea-level variations during an Early Triassic hothouse phase using a modelling approach and orbitally forced sequences of 1–2 myr duration. For the early Triassic, Li *et al.* (2018) recognized an anti-phase relationship of sea-level cycles as identified in southern China deeper-water sections and continental water storage variations in the land-locked terrestrial Germanic Basin; the variable precipitation intensity of long-period obliquity cycles controlled variations in aquifer storage volume in the Germanic Basin, with 1.2 myr obliquity nodes associated with reduced poleward flux of heat, moisture and precipitation, and 1.2 myr obliquity maxima related to intensified precipitation.

Other testable evidences not observed yet or purely speculative

Hay *et al.* (2018) and Hay & Floegel (2012) indicated that, during the Cretaceous, continental palaeoelevations were smaller than they are today ('Continental elevation problem') and speculated that there were more extensive terrestrial wetlands like lakes and meandering rivers with oxbow lakes and swamps. Coupled climate model sensitivity runs for the mid-Cretaceous by Hay *et al.* (2018) used eight times the preindustrial CO_2 level and 50–75% water surfaces on land, providing water vapour as an additional greenhouse gas. Modelling results show reduced meridional temperature gradients and conditions compatible with the palaeontological and stratigraphic record. During greenhouse times precipitation rates over land were higher than they are today, but evaporation rates were also higher. Because of the reduced seasonality, precipitation rates would have been more constant over the year.

Hypothetical diagenetic cycles and processes of aquifer charge/discharge

Cyclic charging of the pore space of aquifers by meteoric water and removal by delayed discharge may result in significant meteoric diagenesis, karst phenomena and cement formation, especially on carbonate platforms which were exposed during sea-level lowstands. Thus, dating of carbonate cements and applying clumped isotope temperature analysis may lead to a more detailed diagenesis evolutionary history and the recognition of cycles in diagenesis related to aquifer-driven sea-level cycles. Pioneer work in this direction is reported by Gázquez *et al.* (2018) on tracking palaeoaquifer changes such as water-table position on karst-related speleothems during the past 600 ka by age dating and stable isotope compositions. A case study from a Paleozoic carbonate unit relating diagenesis to changing sea-level was presented by Dyer *et al.* (2015) for the middle Carboniferous.

Cretaceous intervals dominated by aquifer-eustatic short-term sea-level changes

Short-term climate cycles in the Cretaceous are ubiquitous, and include the longer (100 and 405 kyr) and long (1.2 and 2.4 myr) Milankovitch band. Aquifer-eustasy may have dominated times when no ice shields were present on the planet, i.e. the hothouse ('supergreenhouse') state of Earth's climate of Kidder & Worsley (2012) and Hay *et al.* (2018). The mid-Cretaceous constitutes the main period for a hothouse Earth, with its distinct ocean-wide anoxia that relate to extreme hot climates. However, cold snaps are also present during the Cretaceous, and even subdivide protracted hothouse OAEs into several climate phases on the 100 kyr scale, such as OAE 2 and its Plenus Cold Event (e.g. Jenkyns *et al.* 2016). However, direct evidence for ice shields during the Cretaceous is sparse (Alley *et al.* 2019), and proxy evidence for an ice-free planet is even more rarely presented and strongly discussed (e.g. Bornemann *et al.* 2008; v. MacLeod *et al.* 2013). Supporting evidence for ice-free periods comes mainly from palaeoclimate modelling studies based on temperature reconstructions using various proxies such as TEX68, oxygen isotopes and vegetation reconstructions (e.g. Spicer & Herman 2010; O'Brien *et al.* 2017). Thus, aquifer-eustasy may have played the dominant role for eustatic sea-level changes during hothouse and warm greenhouse times of the Cretaceous, such as the mid-Cretaceous OAEs (1a, early Aptian; 1b–d, early and late Albian; 2, Cenomanian–Turonian boundary interval) and during other times of extremely hot temperatures such as the Weissert Oceanic Event in the early Valanginian, during the Cenomanian–Turonian and the more dubious Coniacian–Santonian OAE 3 (Wagreich 2012) when the hothouse changed to a warm greenhouse climate phase.

Rates of eustatic sea-level change and the scaling problem

Estimating rates of sea-level change of deep-time archives is limited by several drawbacks and large errors. Although precise timing down to 100 or even 20 kyr Milankovitch cycles is possible, rates still suffer from the phenomenon of integration over (too) long time intervals, which renders mean figures too low given the problem of insufficient archives and gaps in the stratigraphic record (e.g. Sadler 1981). However, an increasingly precise timescale reduces this error. Another temporal error stems from the fact that asymmetry of sea-level cycles is seldom recorded from archives older than the Pleistocene. Estimates such as 'fast sea-level rise' and 'slow sea-level fall', e.g. as related in the Quaternary to rapid ice melting, but slow ice build-up (e.g. the asymmetric $\delta^{18}O$ curve of the stack curve; Raymo *et al.* 2006; Shakun *et al.* 2015; Lisiecki & Stern 2016; Spratt & Lisiecki 2016) leave open a wide variety of sea-level change rate estimates.

The other major biases lie in the selection of the sea-level curve used for reference, on the one hand, as these considerably differ in their magnitude estimates (cf. Ray *et al.* 2019, fig. 1 therein) and resolution, and in the regional, eurybatic (Haq 2014) sea-level change to be considered, on the other hand. The regional influence of various non-eustatic, geophysical and geodynamic components render every local measurement unreliable – only the sum of many widely distributed sea-level change archives can give a reliable mean, but this can hardly be achieved in the stratigraphic record (Haq 2014). Admittedly, if we see a regular cyclicity in a particular location, then we can probably infer that this is not caused by geophysical mechanisms since they cannot operate that rapidly. Nevertheless, we use some orbitally tuned and time-controlled case studies from the Cretaceous Thermal Maximum to obtain possible rate magnitudes of changes.

For the Cenomanian two orbitally controlled reconstructions indicate rates up to 1 m/kyr sea-level change (Voigt *et al.* 2006; Gale *et al.* 2008; Cenomanian, 405 kyr cycles, half cycle = 200 kyr, 25 m = 0.125 m ka^{-1} = 125 mm ka^{-1}). Long-term mean estimates from aquifer-eustasy models and the prevailing Milankovitch cyclicity suggest 25 m sea-level rise and fall in 1.2 myr (Wendler *et al.* 2016) for a full cycle. A half-cycle of 25 m sea-level rise results in at minimum a 0.04 mm a^{-1} or 40 mm ka^{-1} rise. These rates would be larger if based on the (debated) magnitude estimates of Haq (2014), which he reports as medium (25–75 m) to major (>75 m) for some of the Cenomanian (e.g. KCe4 sequence boundary at 95.5 Ma) and Turonian KTu4 (91.8 Ma) sequences. Taking Haq's (2014) values in a conservative way (75 m maximum sea-level change amplitude), using minimum estimates for a cycle duration of 405 kyr in the Cenomanian (Gale *et al.* 2008) and the Turonian (Batenburg *et al.* 2016) and applying again a conservative half-cycle estimate for the duration of sea-level fall results in a rate of 0.37 mm a^{-1}. If asymmetry of sea-level cycles is assumed (e.g. Greselle & Pittet 2010, for glacio-eustasy, and Wagreich *et al.* 2014, for aquifer-eustasy), as is known for glacial–interglacial cycles (e.g. Raymo *et al.* 2006), then time intervals down to the short eccentricity band (100 kyr) for the faster part of the cycle result in a doubling of such rates to 0.70 mm a^{-1}.

Although the range of estimated values still has a huge uncertainty both in the temporal and the spatial range, and may be considered speculative thus far, we estimate rates for short-time high-frequency sea-level changes of 0.04–0.70 mm a^{-1}. This compares with the most recent measurements of climate-driven land-water storage of Reager *et al.* (2016) with a 0.71 mm a^{-1} sea-level fall contained in the global sea-level rise of 3.2 ± 0.4 mm a^{-1} during the past two decades (see also the next section). In comparison, the recent human-driven land water storage owing to anthropogenic changes in hydrology sums up to a rather similar, but positive, magnitude of about 0.38 mm a^{-1} additional sea-level rise.

Recent land water storage trends supporting the aquifer-eustasy hypothesis

Recent climate change triggered by global warming owing to excess greenhouse gases results in rising global sea-levels accelerating over the instrumental observational period with a most recent rate of about 3.2 (±0.4–1.4) mm a^{-1} (Church *et al.* 2013; Dangendorf *et al.* 2017). Various terms contribute to this global total value, including the melting ice shields of Greenland and Antarctica as the main component (1.26 mm a^{-1}, Reager *et al.* 2016). Data from the Gravity Recovery and Climate Experiment (GRACE) satellites since 2002 allow the observation of regional and global mass changes for climate-driven groundwater storage, using changes in gravity data. Based on GRACE data, Reager *et al.* (2016) quantified climate-driven changes in land water storage and their impact on global sea-level. Their net land water storage mass gain (equivalent to 0.33 ± 0.16 mm a^{-1} of sea-level drop) and subtracting the IPCC estimate for the anthropogenic component (0.38 ± 0.12 mm a^{-1} sea-level rise, Church *et al.* 2013) results in their estimate of the climate-driven land water storage change of 0.71 ± 0.20 mm a^{-1} sea-level drop, i.e. 0.71 mm a^{-1} water storage uptake that slows down recent sea-level rise (Reager *et al.* 2016).

Furthermore, Reager *et al.* (2016) identified against the background of a seasonal cycling of water from oceans to land the equivalent of 17 ± 4 mm of sea-level cycling, on top of a long-term trend of overall sea-level rise today. They also identified a decadal global water cycle variability that is linked to ocean–atmosphere phenomena and adds further uncertainty to trend estimates. In particular, what happens today is that rising temperatures lead to an increased precipitation over land and a net movement of water from ocean to land, with a corresponding component of eustatic sea-level fall. Decadal changes were interpreted by Hamlington *et al.* (2017) and Wada *et al.* (2017) as related to internal climate variability such as the Pacific Decadal Oscillation and the El Niño Southern Oscillation.

Increases in precipitation over land caused positive storage trends in some regions of the world. Magnitudes can be reconstructed, e.g. a drought followed by an extreme precipitation event in Australia and other areas of the Southern Hemisphere is thought to have resulted in a significant drop in global sea-level of about 7 mm in early 2011, persisting until late that year. Australia's mass anomaly persisted owing to the expansive land-locked basins that hindered runoff from La Niña-related precipitation (Boening *et al.* 2012; Fasullo *et al.* 2013).

Another implication of the recent climate warming is the intensification of the global water cycle by increasing rates of ocean evaporation, terrestrial evapotranspiration and precipitation (Huntington 2006; Trenberth 2011). Warming-induced intensification implies an increase in water flux between ocean, atmosphere, terrestrial, freshwater and cryospheric pools, and is mainly due to two factors: (1) evaporation increases with increasing temperature; and (2) warmer air holds more moisture. Increased amounts of water vapour (itself a major greenhouse gas) in the atmosphere thus provide a positive warming feedback and produce more intense precipitation events. According to Trenberth (2011), this results in dry areas such as the subtropics becoming drier, and wet areas becoming wetter, especially in the mid to high latitudes. This intensification of the terrestrial water cycle owing to greenhouse warming was substantiated by Eicker *et al.* (2016) using GRACE data and a modelling approach.

Thus, intensification of hydrological cycles in general, climate-related changes to atmospheric transport and the delivery of moisture to the continents in particular result in changes in land-water storage owing to climatic change. This is to say that warmer temperatures tend to intensify the hydrological cycle, putting more water on land and leading to an aquifer-eustatic sea-level drop.

At the current state of knowledge a direct translation of the above insights into the Cretaceous remains difficult and highly hypothetical, mainly because of problems of stratigraphic resolution and scaling. Nevertheless, these insights have recently accelerated progress in, and acceptance of, the aquifer-eustasy hypothesis in several respects. One of the main issues leading to the broad rejection of the aquifer-eustasy hypothesis was the disbelief in the existence of processes that would lead to an imbalance of the hydrological cycle strong enough to result in significant (i.e. of recognizable amplitude in the geological record) eustatic sea-level changes on timescales between 100 000 and 3 myr. This particularly refers to the mechanism of increased transfer of water to, and storage on, the continents, as the discharge process should quickly rebalance the system – at least fast enough not to be relevant on the above geological timescales. Although temporal upscaling towards the latter timescales must remain strongly hypothetical, now that we have unequivocal evidence for aquifer-eustasy, we can research its controlling factors and mechanisms, and systematically develop, model and test hypotheses on how these would operate on larger timescales and in different climate modes and states, and how they may have operated during the Cretaceous.

Non-climate related cycles?

One of the main arguments for the recognition of eustatic sea-level changes in deep-time is their cyclic behaviour, i.e. the constant ups and downs at several hierarchical temporal scales that are beautifully displayed by sequence stratigraphy for both icehouse and greenhouse phases of the Earth system (e.g. Haq *et al.* 1987; Haq 2014, 2017*a*, *b*, 2018). This intrinsically gives an argument by itself for a cyclic process. For the Quaternary ice age, the relation to Milankovich cyclicities is straightforward and there is no reasonable argumentation against glacio-eustasy. However, nearly the same cycling becomes debated when identified for greenhouse times, and arguments against its global significance (e.g. Ruban *et al.* 2010) and against climate-control (e.g. Cloetingh & Haq 2015) have been put forward. We consider those arguments as only being valid as long as the time control of the cycles is questionable owing to insufficient dating, which would question the definite relation of short-term sedimentary cycles to climatically driven eustatic sea-level changes, as pointed out by Ray *et al.* (2019), for example. The question whether or not sedimentary cycles are eustatic in nature or have formed independently of climate and eurybatic or eustatic sea-level change (e.g. allocycles) is also a correlate of the fundamental question in cyclostratigraphy, depending on the quality of stratigraphic resolution and correlation: is the succession 'just cyclic' (i.e. not displaying regular frequencies) or is it displaying a 'true' cyclicity with definite, regular frequencies. In the former case it is probably not eustatic in nature, in the latter case it is probably eustatic as it must have been controlled by a mechanism with defined regular frequencies (orbital cyclicities).

The stratigraphic revolution of the last 20 years has been made possible with the application of advanced geochronology based on precise U/Pb zircon and Ar/Ar dates (Kuiper *et al.* 2008; Gradstein *et al.* 2012; Ogg *et al.* 2016; EARTHTIME projects, e.g. Renne *et al.* 2005), the extension of an orbital cyclostratigraphy and astrochronology 250 Ma backward from today (Laskar *et al.* 2011; Gradstein *et al.* 2012) and more reliable global correlation tools like carbon isotope stratigraphy (e.g. Jarvis *et al.* 2006, 2015; Voigt *et al.* 2012; Wendler 2013) and magnetostratigraphy (e.g. Gradstein *et al.* 2012; Wolfgring *et al.* 2018). These advancements have led to a reliable numerical timescale with a general error below 1 myr, and for the Cretaceous an error of one long eccentricity cycle of 405 kyr (Gradstein *et al.* 2012).

Arguments for the existence of the same orbital cycles within the Milankovitch band are now ubiquitous from all of the greenhouse intervals of the Mesozoic (Boulila *et al.* 2011; Wendler *et al.* 2014). There is no argument left that something like a mysterious 'cyclic mantle degassing' (e.g. Cloetingh & Haq 2015) exists, nor that such deep-Earth processes should follow a Milankovitch cyclicity.

However, there is strong and growing evidence that those arguments can be turned around into an Earth System where several near-surface geophysical and geodynamical processes are indeed influenced by climate cycling and the resulting sea-level change. Thus, cyclic sea-water loading on accretionary wedges may influence tectonic activity, as evidenced by the recognition of climate-induced tectonic deformation and fault displacements (e.g. Li & Hampel 2012). Also, volcanic activity may be forced by climate changes such as deglaciation forcing volcanism in the Quaternary (e.g. Kutterolf *et al.* 2018), or farther back in time along mid-ocean ridges (e.g. Crowley *et al.* 2015; Tolstoy 2015). We conclude that, given this evidence, the negation of the existence of climate cycles and their record as cyclic sequences indicating eustatic sea-level cycles during greenhouse times cannot be maintained.

Conclusions

Short-term sea-level fluctuations during greenhouse climate phases, especially during the mid-Cretaceous hothouse (Cenomanian–Turonian), when there was no significant glacial ice, have remained enigmatic for a long time. Evidence assembled in the last three decades allow us to conclude that:

(1) Milankovitch climate cycles were present during greenhouse and hothouse phases of Earth's climate, and governed rises and falls of eustatic sea-level during glacial–interglacial cycles of the last 2.75–0.9 myr. However, there are considerable differences between mainly ice- and mainly aquifer-driven climate cycles, i.e. in the duration of these cycles as well as in the pattern of rates of resultant sea-level rises and falls, respectively. Glacial–interglacial cycles are driven by Earth's orbital precession, modulated by eccentricity in such a way that clusters of unusually high summer insolation maxima occur at 100 000-year intervals resulting in rapid deglaciations. Thus, *ice-sheets build up slowly* during the decrease *and melt rapidly* during the increase of insolation, corresponding *sea-level falls* have a relatively *long duration*, whereas *sea-level rises* are relatively *rapid*. The entire cycle has a 100 000-year duration and resultant sea-level changes are on the order of 100–150 m. Moreover, the sediment supply during the brief sea-level highstands is inadequate to build the continental shelves back to their (Neogene) elevations previous to the growth of the Northern Hemisphere ice sheets, i.e. the continental configuration is changing. In contrast, aquifer-eustatic cycles take place over a longer timescale than glacial–interglacial cycles. Aquifer charge and discharge take place over $\pm$ 400 000 year (405 000 year) intervals. When the long-term envelope of Milankovitch precession cycles is maximal, rainfall is more abundant, global conditions are generally humid and a net transfer of water from the ocean to the continents takes place, resulting in a sea-level fall. When Milankovitch precession cycles are minimal, rainfall is reduced and global conditions are generally more arid, resulting in sea-level rise. These (mainly) aquifer-eustatic sea-level rises and falls are both slow, much slower than the glacio-eustatic ones, and are on the order of 10–40 m (this is the Ray *et al.* 2019, estimate for modest amplitudes during the Cenomanian–Turonian). Sediment supply during humid times (sea-level falls) is adequate to maintain a constant continental configuration.

(2) The dominant process governing eustatic sea-level fluctuations during greenhouse times is aquifer-eustasy, i.e. the charge and discharge of continental aquifers, for which growing evidence can be presented from the Cretaceous and from other greenhouse climate phases of the Phanerozoic. Thus, aquifer-eustasy is a process that induces and modulates sea-level change and is the only significant process to explain sea-level cycles in the range of a few thousand to a few million years during greenhouse episodes with no significant continental ice shields.

(3) In contrast to glacio-eustasy, aquifer-eustasy is and was a pervasive process in both major climate modes – icehouse as well greenhouse of all states, whereas glacio-eustasy cannot be important in the absence of continental ice. This conclusion results from the identification and quantification of land-water storage changes that are active today.

(4) Learning from the past and linking to present climate change and sea-level discussions, absolute values of past eustatic changes (v. regional or eurybatic ones) can be reconstructed with more precision. Evidence comes from both deep-time studies of greenhouse/hothouse phases of the System Earth, but also from calculations of the components of recent sea-level change.

(5) Based on all the evidence published on aquifer-eustasy today and in Earth history, there is no need to invoke (mysterious) continental ice sheets and glacio-eustasy to explain short-term sea-level changes during warm greenhouse to hothouse phases. Consequently, the enigma of how to reconcile the obvious evidence for short-term sea-level fluctuations, present even during extremely warm 'hothouse' ('supergreenhouse') stages such the

Cenomanian–Turonian interval, has been solved. As a consequence, while not excluding that we might find evidence for continental ice sheets with new discoveries and methods in the future, we can state that the controversies pro and contra continental glaciations during 'hot-house' stages just based on the evidence of short-term eustatic sea-level changes are not constructive (as is the almost compulsive search for geological evidence for continental glaciations during these time intervals).

(6) Near-future research should focus on further increasing the stratigraphic resolution and on integrating the different proxies, or developing new ones, within the context of aquifer-eustasy remaining active throughout all phases of the climate system.

(7) Increasing stratigraphic resolution allows us to utilize aquifer-eustasy as a tool for cyclostratigraphic marine to non-marine correlations in the near future.

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