



# Variations in mid-ocean ridge CO<sub>2</sub> emissions driven by glacial cycles



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## ABSTRACT

The geological record documents links between glacial cycles and volcanic productivity, both subaerially and, tentatively, at mid-ocean ridges. Sea-level-driven pressure changes could also affect chemical properties of mid-ocean ridge volcanism. We consider how changing sea-level could alter the CO<sub>2</sub> emissions rate from mid-ocean ridges on both the segment and global scale. We develop a simplified transport model for a highly incompatible trace element moving through a homogeneous mantle; variations in the concentration and the emission rate of the element are the result of changes in the depth of first silicate melting. The model predicts an average global mid-ocean ridge CO<sub>2</sub> emissions rate of 53 Mt/yr or 91 Mt/yr for an average source mantle CO<sub>2</sub> concentration of 125 or 215 ppm by weight, in line with other estimates. We show that falling sea level would cause an increase in ridge CO<sub>2</sub> emissions about 100 kyrs after the causative sea level change. The lag and amplitude of the response are sensitive to mantle permeability and plate spreading rate. For a reconstructed sea-level time series of the past million years, we predict variations of up to 12% in global mid-ocean ridge CO<sub>2</sub> emissions.

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## 1. Introduction

Glacial cycles transfer  $\sim 5 \times 10^{19}$  kg of water between the oceans and ice sheets (Tushingham and Peltier, 1991), leading to accumulation and ablation of kilometres of ice on the continents and sea-level change of  $\sim 100$  m. In Iceland, for example, the pressure change associated with melting of the ice sheet since the last glacial maximum had well-documented consequences for the volcanic activity (Sigvaldason et al., 1992; Jull and McKenzie, 1996; Maclennan et al., 2002) and lava geochemistry (Maclennan et al., 2002). More broadly, continental volcanism in both the northern and southern hemispheres shows increased activity associated with the last deglaciation (Gardeweg et al., 1998; Jellinek et al., 2004; Huybers and Langmuir, 2009). Huybers and Langmuir (2009) and Lund and Asimow (2011) hypothesised that the pressure variations caused by changing sea level during glacial cycles would affect mid-ocean ridge (MOR) volcanism. Crowley et al. (2015) documented variations of bathymetry near the Australian–Antarctic ridge that are possible evidence of such glacial effects.

A simple argument shows that variations in crustal thickness and sea-floor relief should be expected to result from sea-level variation. The melting rate of a parcel of mantle beneath a MOR is proportional to its depressurisation rate. As the parcel upwells, it depressurises due to the decreasing height of rock above it. The

rate of change of pressure due to upwelling is the gravitational acceleration  $g$  times the mantle density times the upwelling rate ( $\sim 3$  cm/yr). Sea-level variation can modify this depressurisation rate: the pressure change due to varying sea level is the product of  $g$ , water density and the rate of change of sea level (up to 100 m in 10 kyr or 1 cm/yr). Water is about one third the density of the mantle and sea-level changes can be equivalent to one third the mantle upwelling rate, implying that sea-level changes can modify depressurisation rates, and hence melting rates, by up to  $\pm 10\%$ . Crowley et al. (2015) apply a paleo-sea-level reconstruction to a simulation of MOR melting and melt transport, with melting rates varying according to the variable pressure exerted by sea level. This leads to varying melt flux at the ridge, predicting variations in crustal thickness consistent with bathymetric observations of sea-floor relief.

Given this evidence for glacial cycles affecting MOR melt production, it is reasonable to consider if, as in Iceland (Maclennan et al., 2002), the chemistry of the lavas is also affected. To investigate this we develop a model of the transport of a highly incompatible element from the asthenosphere through the melting region to the MOR. Highly incompatible elements partition strongly into the melt, rather than remaining in the residual solid. Approximating this as complete incompatibility creates useful simplifications in modelling. For instance, a completely incompatible element's path through the melting region is entirely determined by the motion of the melt, without any need to consider that element in the solid or partitioning between phases. Furthermore, for small perturbations to the melting rate (such as those caused by sea-level change) the

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mass-flow rate of the element through the MOR is constant (see Appendix A.4).

In a simple model of melting beneath a mid-ocean ridge, a parcel of mantle upwells adiabatically beneath the ridge axis, cooling slightly due to its expansion. The pressure-dependent solidus temperature of that parcel decreases as it ascends; at some depth (or, equivalently, pressure), the temperature of the parcel is equal to its solidus temperature. This depth, thought to be around 60 km, is called the depth of first silicate melting. With further upwelling, the parcel's temperature exceeds the solidus and it partially melts. As soon as the first increment of melt is produced, 100% of the completely incompatible element that was locally present in the solid mantle is transferred to the melt. Because the mantle is permeable and the melt is less dense than the residue, the melt ascends faster than the solid, segregating from its source. Melt segregation and transport of incompatible elements thus begins at a pressure-dependent depth. More specifically, melt segregation begins at a fixed pressure, but the depth corresponding to this pressure can change. We assume that there is no isostatic rebound associated with sea-level change and hence mantle upwelling is constant. Variations in sea level will therefore cause the depth of first silicate melting (and initiation of melt segregation) to rise and fall. The rate at which mantle crosses this boundary and delivers its content of incompatible elements to the melting region is the mantle upwelling rate minus the rate of upward motion of the boundary. So in this model, variations in the depth of first silicate melting cause variations in the flux of an incompatible element. As sea level falls, the depth of first melting increases, upwelling mantle crosses into the melting region faster, and the flux of incompatible element increases; the reverse is true for sea-level rise. Any perturbation to the melting rate within the melting region does not alter the mass of the incompatible element in the melt, it only dilutes (or concentrates) the element. Variations in melt-transport rate associated with melting perturbations are a secondary effect and are not considered in detail here (though see Appendix A.4).

A more nuanced view of melting may disagree with this simple story in some of the details, especially with the inclusion of volatile elements that are present in small concentrations in the mantle. Experimental evidence suggests that CO<sub>2</sub>-rich melt forms at ~250 km depth (Dasgupta et al., 2013) and has a low viscosity that rises sharply with silica content at shallower depth (Kono et al., 2014). If such carbon-rich melts can segregate from the solid mantle it would complicate the role of the transition to silicate melting at around 60 km. However, it remains an open question whether oxygen fugacity allows such melts to form and, if they do form, whether such tiny melt fractions can segregate from the solid mantle. Dasgupta et al. (2013) suggests carbonatite melt fractions reach ~0.03 wt% deep in the mantle below ridges, which is at the lowest limit of carbonatite melt interconnectivity of 0.03–0.07 wt% in ~0.05 mm olivine grains (Minarik and Watson, 1995). The additional presence of water might increase the melt fraction to 0.06–0.1 wt% (Dasgupta et al., 2013) by 150 km depth, but the threshold for interconnectivity of such melts is not known. In our calculations, we assume that these melt fractions do not segregate from the solid mantle until the onset of volatile-free peridotite melting at ~60 km raises the melt fraction, creating an interconnected, permeable network of pores.

Among the highly incompatible elements, we focus on carbon despite its active role in the thermodynamics of melt production because variations in CO<sub>2</sub> emissions from the solid Earth are potentially important to understanding past variation of the climate. The solid Earth contains 10<sup>10</sup>–10<sup>11</sup> Mt carbon (Dasgupta and Hirschmann, 2010), orders of magnitude more than the atmosphere (0.6 × 10<sup>6</sup> MtC; Solomon et al., 2007) and the oceans (4 × 10<sup>7</sup> MtC; Solomon et al., 2007). Solid-Earth carbon emissions

from MORs are estimated as ~25 MtC/yr (Coltice et al., 2004; Cartigny et al., 2008; Marty and Tolstikhin, 1998) and from arc volcanoes ~20 MtC/yr (Coltice et al., 2004). As the largest reservoir, the solid Earth's carbon budget is known to control atmospheric carbon on multi-Myr timescales; geological ages show a correlation between volcanic activity and atmospheric CO<sub>2</sub> concentration (Budyko et al., 1987). Hence there is evidence for both MOR volcanism being affected by glacial cycles and for the effect of volcanic CO<sub>2</sub> emissions on atmospheric CO<sub>2</sub> concentration. While we focus on CO<sub>2</sub> in our model, the same theory applies equally to other highly incompatible elements such as U, Th, Nb, Ba, and Rb.

The model is developed under the guiding principle that it should be simple enough that the connections between the assumptions and the outputs are readily traceable. The full model is assembled from independent, decoupled parts that capture the key physics with minimal complexity. Mantle flow is modelled by the passively-driven corner-flow solution (Batchelor, 1967; Spiegelman and McKenzie, 1987); lithospheric temperature structure and thickness is computed with a half-space cooling model (Turcotte and Schubert, 2002). To quantify melt generation and transport we use one-dimensional compaction columns (Ribe, 1985; Hewitt, 2010) that are based on conservation of energy, mass, and momentum at steady state in a homogeneous mantle. The outline of the melting region is given by a parameterised solidus (Katz, 2008). A focusing width is applied such that melt focused to the ridge produces a maximum crustal thickness of 7 km. A detailed discussion of the assumptions made in deriving the model is presented below.

To summarise the results, the model predicts that a section of MOR spreading at 3 cm/yr half-rate will see a change in the rate of efflux of highly incompatible elements (e.g., CO<sub>2</sub>) of ~8% for a linear sea-level change of 100 m in 10 kyrs. For reconstructed sea level data and the present distribution of plate spreading rates, the model predicts global MOR emissions to deviate from the mean by up to ±6%. These results are sensitive to the permeability of the mantle, which is a primary control on the rate of melt transport. There are good constraints on how permeability scales with porosity, but its absolute value at a reference porosity (1% here) is uncertain. We consider a broad range of values that includes the most extreme estimates.

Section 2 details the model used to predict CO<sub>2</sub> emissions for a section of mid-ocean ridge; parameter values are stated in Table 1. The behaviour of the model is demonstrated for simple scenarios of sea-level variation in Sections 3.1–3.3; the model is applied to the global MOR system under a reconstructed sea-level history in Sections 3.4 and 3.5. The results are discussed in Section 4 and the key conclusions stated in Section 5.

## 2. The model

Our goal is to develop a method to compute the CO<sub>2</sub> emission rate  $E_{\text{CO}_2}$  (mass per unit time per unit length of ridge) from a segment of ridge. To achieve this we require a model of CO<sub>2</sub> flux into the melting region and also of its transport to the ridge. We approximate the behaviour of CO<sub>2</sub> as perfectly incompatible, and hence there is no exchange of CO<sub>2</sub> between phases during melt transport. The rate of ridge emission of CO<sub>2</sub> can then be quantified by integrating the mass flux into the base of the melting region  $f_{\text{CO}_2}$  (mass/area/time) and using the travel time from the base of the melting region to the ridge. This is formulated as

$$E_{\text{CO}_2}(t) = 2 \int_0^{x_f} f_{\text{CO}_2}(t_s, x, U_0) dx, \quad (1)$$

where  $x$  is the horizontal distance from the ridge axis,  $x_f$  is the maximum distance over which melt is focused to the ridge axis,  $U_0$

**Table 1**  
Parameter values for calculations.

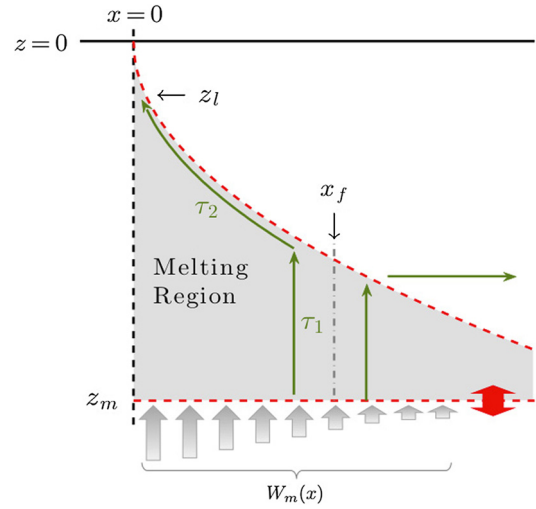
Parameter	Value	Parameter description
$c$	1200	J/kg/K Specific heat
$C_{\text{CO}_2}$	0.375	kg/m <sup>3</sup> CO <sub>2</sub> mass per m <sup>3</sup> of mantle (derived from 125 ppm by weight)
$g$	10	m/s <sup>2</sup> Gravitational acceleration
$K_0$	$10^{-13}$ – $10^{-11}$	m <sup>2</sup> Permeability at 1% porosity
$K$	$K_0(\phi/\phi_0)^n$	m <sup>2</sup> Permeability
$L$	$4 \times 10^5$	J/kg Latent heat of the mantle
$L_{\text{MOR}}$	61 000	km Total length of the mid-ocean ridge system
$n$	3	– Porosity exponent in the permeability relation
$S$	[various]	m Sea level, expressed as deviation from long term mean
$\dot{S}$	[various]	cm/yr Rate of change of sea level with respect to time
$\tilde{T}$	1648	K Potential temperature of upwelling mantle
$T_0$	273	K Ocean floor temperature
$T_{\text{Sref}}$	1554	K Reference solidus temperature
$U_0$	$\leq 8$	cm/yr Plate half-spreading rate
$x_f$	10–70	km Width of region, at $z_m$ , from which melt is focused to the ridge
$x_w$	10–350	km Width of melting region
$z_m$	60	km Depth of first melting
$\alpha$	$3 \times 10^{-5}$	K <sup>-1</sup> Thermal expansion coefficient for the mantle
$\gamma$	$60 \times 10^{-9}$	K/Pa Clausius–Clapeyron slope of the mantle
$\eta_f$	1	Pa s Mantle melt viscosity
$\kappa$	$10^{-6}$	m <sup>2</sup> /s Thermal diffusivity
$\Pi$	0.01	kg/m <sup>4</sup> Adiabatic melt productivity, kg of melt per m <sup>3</sup> of mantle per metre of upwelling
$\rho$	3300	kg/m <sup>3</sup> Mantle density
$\rho_c$	2900	kg/m <sup>3</sup> Oceanic crust (mean) density
$\rho_w$	1000	kg/m <sup>3</sup> Freshwater density
$\Delta\rho$	500	kg/m <sup>3</sup> Density difference between liquid and solid mantle
$\phi_0$	0.01	– Reference porosity (volume fraction)

is the half-spreading rate, and  $t$  is time. A parcel of melt arriving at the ridge axis at time  $t$  was produced by mantle that crossed into the melting region at time  $t_s$ . The travel time of melt from the base of the melting region to the ridge is represented as  $\tau$ , which varies with lateral distance  $x$  from the ridge axis. Hence the source time is  $t_s(x) = t - \tau(x)$ . The factor of two in eqn. (1) arises from the symmetry of the melting region across the ridge axis. A sketch of half the melting region is shown in Fig. 1.

Equation (1) requires an expression for  $f_{\text{CO}_2}$ . This is a product of the rate at which mantle material crosses the depth of first silicate melting  $z_m$  and the CO<sub>2</sub> concentration in that material. For generality, we consider an expression that allows for volatile-enriched incipient partial melting beneath the depth of first silicate melting, though we will later exclude this scenario from consideration. Thus,  $f_{\text{CO}_2}$  is written as

$$f_{\text{CO}_2}(t_s, x, U_0) = \left( W_m(x, U_0) - \frac{dz_m(t_s)}{dt} \right) (1 - \phi) C_{\text{CO}_2}^{\text{solid}} + \left( w_m - \frac{dz_m(t_s)}{dt} \right) \phi C_{\text{CO}_2}^{\text{melt}}, \quad (2)$$

where  $W_m(x, U_0)$  is the upwelling rate of the mantle,  $w_m$  is the upwelling rate of incipient melt,  $C_{\text{CO}_2}$  is a mass concentration of CO<sub>2</sub>, and  $\phi$  is the volume fraction of melt; all of these are evaluated at depth  $z_m$  and distance  $x$  from the ridge axis. The first term in parentheses on the right-hand side of the equation is the rate at which mantle crosses into the melting region. The concentrations and melt fraction may be considered steady-state, constant values as long as  $w_m \geq W_m \geq \max(\dot{z}_m(t))$ . This ensures that the



**Fig. 1.** Sketch of the melting region. Two example melt streamlines are shown in green. Mantle upwelling rate into the base of the melting region  $W_m$  is represented by grey arrows, the size of which shows the decreasing magnitude of  $W_m$  with distance from the ridge axis. The red arrow indicates the variability of  $z_m$  with respect to time, expressed in equation (6) (all other boundaries are steady state). The melt streamlines on either side of the maximum focusing distance  $x_f$  show melt flow to the ridge or frozen into the lithosphere. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rate at which material crosses the depth of first silicate melting is always positive or zero. Even the fastest sea-level changes on record, meltwater pulses during the last deglaciation, satisfy these conditions for most MORs: 20 m sea level change in 500 yrs gives  $\dot{z}_m = 1.3$  cm/yr. However, meltwater pulse events are not resolved in the reconstructed sea-level series that we consider in this paper (Siddall et al., 2010), so the conditions  $w_m \geq W_m \geq \max(\dot{z}_m(t))$  are true with only occasional exceptions for the slowest spreading ridges. With these conditions satisfied and assuming that either  $\phi(z_m) = 0$  or that  $w_m = W_m$ , equation (2) can be simplified to

$$f_{\text{CO}_2}(t_s, x, U_0) = \left( W_m(x, U_0) - \frac{dz_m(t_s)}{dt} \right) C_{\text{CO}_2}. \quad (3)$$

Here we should interpret  $C_{\text{CO}_2}$  as the mass concentration of CO<sub>2</sub> in the solid mantle plus co-moving incipient melt, if it is present. This model could be modified to accommodate more complicated situations, but this is not given further consideration at present.

The flux of CO<sub>2</sub> in equation (3) depends on the solid mantle upwelling rate at the depth of first silicate melting. Approximating this as passive (plate-driven) flow of isoviscous rock, mantle upwelling is given by the corner flow solution (Batchelor, 1967; Spiegelman and McKenzie, 1987). The vertical component of this solution, evaluated at  $z = z_m$ , can be written as

$$W_m(x, U_0) = \frac{2U_0}{\pi - 2\alpha_c - \sin 2\alpha_c} \left( \frac{1}{1 + \frac{x^2}{z_m^2}} - \sin^2(\alpha_c) \right), \quad (4)$$

where the lithosphere is represented as a wedge with angle  $\alpha_c$  to the horizontal. We follow Spiegelman and McKenzie (1987) in computing the wedge angle to approximately match the plate thickness at a specified distance from the axis. We use  $\alpha_c = \tan^{-1}(z_l/x_w)$ , such that the wedge intersects the upper boundary of the melting region  $z_l$  at the maximum width of melting region  $x_w$  (see Appendix A.3 for details). This definition of the wedge angle ensures that the lithospheric wedge does not overlap with the melting region, and that the upwelling rate is small but non-zero at the extreme width of the melting region ( $0 \leq W_m(x_w) \ll U_0$ ).

An expression for the depth of first melting  $z_m$  is needed in equations (3) and (4). Taking decompression as the only influ-

ence on local mantle temperature prior to melting, we model the depth of first melting as the intersection between an adiabatic temperature profile and the solidus temperature profile. We approximate both profiles as linear with respect to depth (details in Appendix A.1) to obtain

$$z_m = - \left( \frac{\tilde{T} - T_{S_{\text{ref}}}}{\gamma \rho g - \frac{\alpha g \tilde{T}}{c}} \right) + \frac{\rho_w}{\rho} S, \quad (5)$$

where  $\tilde{T}$  is the mantle potential temperature,  $T_{S_{\text{ref}}}$  is the solidus temperature at reference mantle composition and surface pressure,  $\gamma$  is the Clausius–Clapeyron slope for the mantle,  $\rho$  is the mantle density,  $\alpha$  is the coefficient of thermal expansion,  $c$  is the specific heat capacity,  $S$  is the sea-level deviation from a long-term mean, and  $\rho_w$  is the density of water. The first term in equation (5) is the dry peridotite melting depth of  $\sim 60$  km, and the second term is the shift in melting depth due to sea-level. The only time dependent variable in equation (5) is the sea level  $S$ , so differentiating gives

$$\frac{dz_m}{dt} = \frac{\rho_w}{\rho} \frac{dS}{dt}. \quad (6)$$

These equations state that silicate melting begins at a fixed pressure, but the depth corresponding to this pressure varies as sea level rises and falls.

The source time  $t_s$  used in equations (1) and (3) depends on the travel time of melt to the ridge from any point  $x$  along the base of the melting region. For simplicity, we consider melt flow as following a vertical path from the base to the top of the melting region, then following a high porosity channel along the impermeable top of the melting region to the ridge axis, as illustrated by streamlines  $\tau_1$  and  $\tau_2$  in Fig. 1. This is a reasonable approximation of numerically modelled streamlines for homogeneous mantle (e.g., Katz, 2008), where buoyancy forces drive vertical fluid flow in the majority of the melting region, with the compaction pressure only becoming large enough to deflect melt flow from the vertical within a few kilometres of melt-impermeable boundaries (Sparks and Parmentier, 1991). We consider flow along the high porosity channel as instantaneous, motivated by the high flow rates expected there, as compared to vertical flow rates in the rest of the melting region (Katz, 2008). To compute the travel time from the base of the melting region to the base of the lithosphere, we use a 1D compaction column from Hewitt (2010). This model assumes Darcy flow and thermodynamic equilibrium for a two-component, homogeneous mantle with a constant Clausius–Clapeyron slope. Following the reduced model of Crowley et al. (2015), we assume that small variation in melting rates due to sea-level change do not significantly affect melt velocity or travel time. Furthermore, in computing  $\tau$  we take  $z_m$  as constant, because changes in  $z_m$  due to sea level are only tens of metres, changing  $\tau$  by  $\ll 1\%$ . This gives a travel time

$$\tau(W_m, z_l, z_m) = \phi_0 \left( \frac{\eta_f}{K_0 \Delta \rho g} \right)^{\frac{1}{n}} \left( \frac{\rho}{\Pi W_m} \right)^{1-\frac{1}{n}} \left[ n (z_l - z_m)^{\frac{1}{n}} \right], \quad (7)$$

where  $\eta_f$  is the mantle melt viscosity,  $K_0$  is the permeability of the mantle at the 1% reference porosity  $\phi_0$ ,  $\Delta \rho$  is the density difference between the solid and melt,  $n$  is the porosity exponent in the permeability relation ( $n \approx 2.7 \sim 3$ , Miller et al., 2014),  $z_l(x, U_0)$  is the depth of the upper boundary of the melting region, and  $\Pi$  is the adiabatic melt productivity (kg of melt produced per  $\text{m}^3$  per m upwelling). This productivity is given by Hewitt (2010) as a ratio of thermodynamic parameters, and we retain the same parameter values here.

To close the model we need an expression for the upper boundary of the melting region  $z_l(x)$ . This boundary is located where the local temperature equals the solidus temperature, which is controlled by the thickness of the conductively cooled boundary layer that forms the lithosphere. Crowley et al. (2015) also included the effects of adiabatic decompression and latent heat removal, but this leads to an expression for  $x_l(z)$  that cannot be inverted. However, as shown in Appendix A.2, the depth of this melting boundary is approximated by an isotherm of the half-space cooling model, which can be expressed as  $z_l(x)$ . This isotherm is hotter than the low-pressure solidus, but the temperature difference compensates for the change in solidus temperature with respect to depth. We use

$$z_l(x, U_0) = 2 \sqrt{\frac{\kappa x}{U_0}} \operatorname{erfc}^{-1} \left( \frac{\tilde{T} - T_l}{\tilde{T} - T_0} \right), \quad (8)$$

where  $T_l$  is the temperature of the upper boundary of melting region, assumed to be constant.  $T_0$  is the temperature of the ocean floor, and  $\kappa$  is the thermal diffusivity of the mantle. Note that although we have neglected adiabatic decompression and latent heat of melting in equation (8), these are accounted for in the melting calculations.

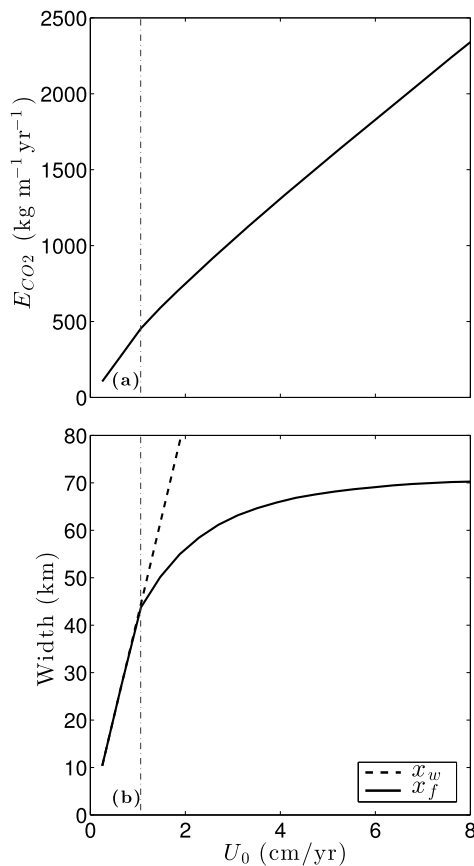
### 3. Results

Below we demonstrate the behaviour of the model by a series of examples, then consider global  $\text{CO}_2$  emissions for reconstructed sea level. We begin by modelling a unit length of mid-ocean ridge in the absence of sea-level change. This defines the baseline state of the model that we compare against when applying sea-level forcing. The first dynamic example is a single, linear sea-level change, which illustrates key characteristics of the model and emphasises the importance of the melt travel time. The emissions curve for this example approximates the Green's function for the model: the response to a step-change in sea level. We next consider simple, periodic sea level curves, demonstrating the system's response to an oscillatory forcing as a function of the frequency of that forcing. We then compute the model's response to a reconstructed Pleistocene sea-level record.

Building on these calculations for a single section of mid-ocean ridge, we calculate predictions for a global model, created by summing sections with appropriate spreading rates over the full MOR system. We demonstrate this composite model by considering the global emissions response to a single sea-level change and then to the reconstructed Pleistocene sea-level curve.

#### 3.1. Constant sea level & baseline emissions

Baseline emissions are defined as the steady-state emission rate of  $\text{CO}_2$  from the MOR for constant sea level. This represents the background state, which is disturbed after sea-level change. Fig. 2 shows baseline emissions as a function of plate spreading rate and demonstrates that, in the absence of changing sea level,  $\text{CO}_2$  emissions per metre of ridge are approximately proportional to the half-spreading rate  $U_0$ . A faster spreading rate drives faster mantle upwelling, bringing more  $\text{CO}_2$  into the melting region. Faster spreading rates also increase the width of the melting region (see Appendix A.3), leading to more melt and more  $\text{CO}_2$  being focused to the ridge axis. However, not all melt produced is focused to the MOR; at some lateral distance, melts are frozen back into the lithosphere, rather than travelling to the ridge axis (e.g., Katz, 2008). We incorporate this detail by enforcing a maximum focusing width  $x_f$  such that melt focused to the MOR will produce crust  $\leq 7$  km thick in steady state, consistent with observations (White et al., 1992; Bown and White, 1994). Crustal thickness is calculated as the volume flow rate of melt to the ridge axis ( $\text{kg m}^{-3}$



**Fig. 2.** (a) Ridge CO<sub>2</sub> emissions for constant sea level, and (b) focusing width  $x_f$  and full width  $x_w$  of the melting region; all shown for varying half-spreading rate. Focusing width is equal to the width of the melting region when crustal thickness is less than 7 km ( $U_0 \leq 1$  cm/yr), and is otherwise limited such that crustal thickness does not exceed 7 km. The switch between these behaviours is marked by the grey dotted line at 1 cm/yr.  $E_{CO_2}$  is computed with CO<sub>2</sub> concentration in the mantle of 125 ppmw.

per metre along MOR axis) times the density ratio of basaltic melt to oceanic crust, divided by the half-spreading rate. At half-rates  $U_0 \geq 1$  cm/yr, the focusing width is smaller than the width of the melting region. With the imposition of this limit on melt focusing, there is a slight change in the slope of the baseline emission curve at  $U_0 = 1$  cm/yr (Fig. 2).

For the range of  $U_0$  on Earth of up to 8 cm/yr, Fig. 2(a) shows baseline emissions of up to 2300 kg m<sup>-1</sup> yr<sup>-1</sup>. This is calculated using 0.38 kg CO<sub>2</sub> per m<sup>3</sup> of upwelling mantle (125 ppm CO<sub>2</sub> by weight, hereafter ppmw), based on an average of MOR source mantle of 50–200 ppmw (Dasgupta, 2013; Cartigny et al., 2008; Saal et al., 2002; Marty and Tolstikhin, 1998; Salters and Stracke, 2004). These source mantle CO<sub>2</sub> concentrations are inferred by four methods: (i) Cartigny et al. (2008) start with Nb concentration in MORBs, use Nb/C ratios, and assume an average degree of melting to calculate a CO<sub>2</sub> concentration in the source mantle. (ii) Saal et al. (2002) use MORB melt inclusions to measure CO<sub>2</sub> concentrations in the erupting mantle immediately prior to degassing, then assume an average degree of melting to calculate a CO<sub>2</sub> concentration in the source mantle. (iii) Marty and Tolstikhin (1998) use <sup>3</sup>He concentrations in the ocean to infer a <sup>3</sup>He efflux from MORs. Then they apply a He/C ratio to estimate carbon efflux from MORs, which is matched to a CO<sub>2</sub> concentration in the erupting mantle using a (completely degassed) crustal formation rate of 21 km<sup>3</sup>/yr. CO<sub>2</sub> in the source mantle is then calculated by assuming an average degree of melting to generate MORB. (iv) Salters and Stracke (2004) start from major elements in the mantle and use a chain of

element ratios to derive a CO<sub>2</sub> concentration in the depleted mantle. For all these approaches, CO<sub>2</sub> concentration in the mantle is derived using several assumptions and has large uncertainties. The global MOR efflux of CO<sub>2</sub> is calculated using fewer assumptions and has less uncertainty. An alternative constraint on mantle CO<sub>2</sub> content is to match the global baseline emissions of the model to the estimated global MOR efflux by choosing a concentration of CO<sub>2</sub> in the source mantle of 215 ppmw (Section 3.5). This is effectively substituting our average degree of melting into other's calculations, and gives a result slightly higher than prior estimates of  $C_{CO_2}$ . For simplicity, we use a generally accepted 125 ppmw  $C_{CO_2}$  throughout this paper, but restate key results for the 215 ppmw value. This changes CO<sub>2</sub> emissions by a factor of 1.7, as emissions scale linearly with  $C_{CO_2}$  (see eqn. (3)).

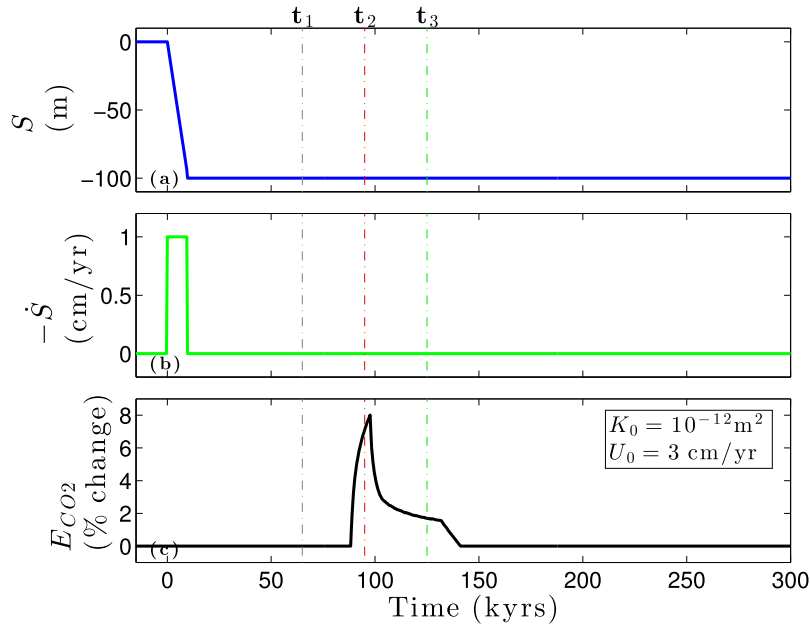
Subsequent sections present scenarios of changing sea-level. In these sections, plots depict emissions in terms of percentage difference from baseline emissions for the appropriate half-spreading rate; these percentage values apply to all highly incompatible elements and for any  $C_{CO_2}$ . Percentage results can be converted to CO<sub>2</sub> mass via Fig. 2. The deviations from the baseline emission rate are a consequence of non-zero  $\dot{z}_m$  in equation (3). By definition, total emissions are equal to this deviation summed with baseline emissions.

### 3.2. Single sudden change in sea level

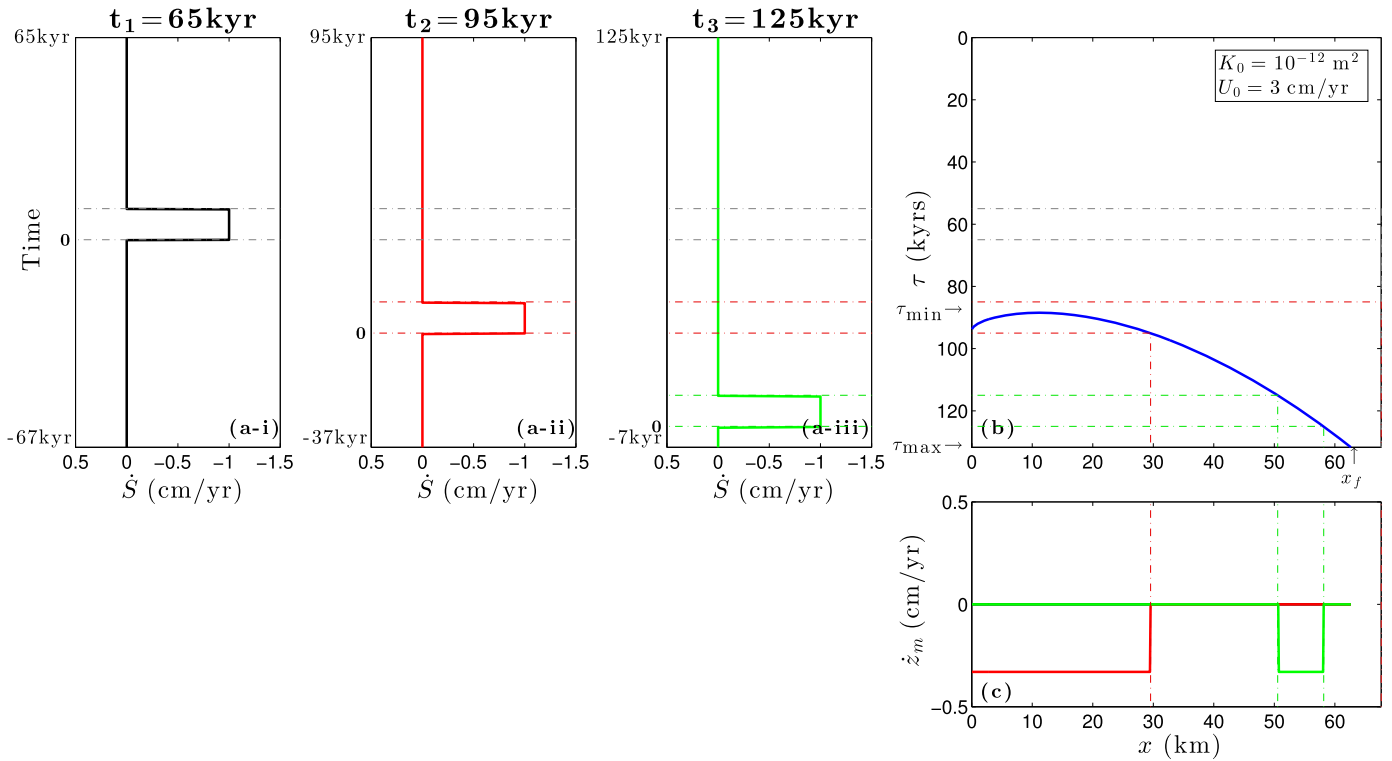
Imposition of a sudden sea-level change exposes the behaviour of the model. We use a steep, linear ramp, which gives a box function in  $\dot{S}$ . Fig. 3 shows the predicted MOR CO<sub>2</sub> emission rate  $E_{CO_2}$  resulting from this sea level forcing. CO<sub>2</sub> emissions remain at the baseline level for ~90 kyrs after the change in sea level and then there is a sharp rise in  $E_{CO_2}$ , representing an 8% increase in emission rate. This delayed response is due to the travel time of CO<sub>2</sub> from the base of the melting region to the ridge. After the 8% peak,  $E_{CO_2}$  falls sharply to about 3%, followed by a slow decay until 130 kyrs, after which there is a linear drop back to the baseline level over the duration of the box-pulse in  $\dot{S}$ . The origin of this emissions pattern in Fig. 3(c) is explored in Fig. 4.

Fig. 4 demonstrates how the shape of the emission response curve in Fig. 3(c) is a consequence of the travel time  $\tau$  and its variation with respect to distance  $x$  from the ridge axis. This travel time, shown in Fig. 4(c), ranges between  $\tau_{min}$  for melts originating in the mantle beneath the ridge axis and  $\tau_{max}$  for distal melts that are focused laterally. The mixture of melts that arrives at the ridge at time  $t$  contains CO<sub>2</sub> that was transported in melts that initiated along the base of the melting region at all  $x < x_f$ . These deep melts formed and began to segregate from their source at times in the past  $t - \tau(x)$ . The CO<sub>2</sub> content of the segregated melt is different to the baseline case according to the  $\dot{S}$  value at  $t - \tau(x)$ . Therefore, we can calculate the deviation from the baseline by considering the rate of sea-level change (alternatively,  $\dot{z}_m$ ) acting on the melting region when each element of melt first segregated. This is represented in Fig. 4(c), and the integral of this plot with respect to  $x$  is directly proportional to  $E_{CO_2}$  in Fig. 3.

The  $E_{CO_2}$  response is clarified by again considering a sharp, linear drop of sea level that occurs over the interval  $0 \leq t \leq 10$  kyrs. The drop in sea level causes the depth of the base of the melting region to increase, importing additional CO<sub>2</sub> into the melting regime. In panels (a-i), (a-ii), and (a-iii) of Fig. 4 we see the box pulse receding into the past as time progresses over  $t_1 < t_2 < t_3$  (Fig. 3c shows  $E_{CO_2}$  at these times). The start and end times of the pulse are projected onto  $\tau(x)$  in panel (b). At  $t_1$ , the projection lines do not intersect  $\tau(x)$ , meaning that the CO<sub>2</sub> perturbation generated by  $\dot{S}$  has not yet reached the ridge axis. Therefore the emissions curve in Fig. 3(c) remains at the baseline level. At  $t_2$ , the projection lines span  $\tau_{min}$ ; the shallow slope of  $\tau(x)$  near  $\tau_{min}$



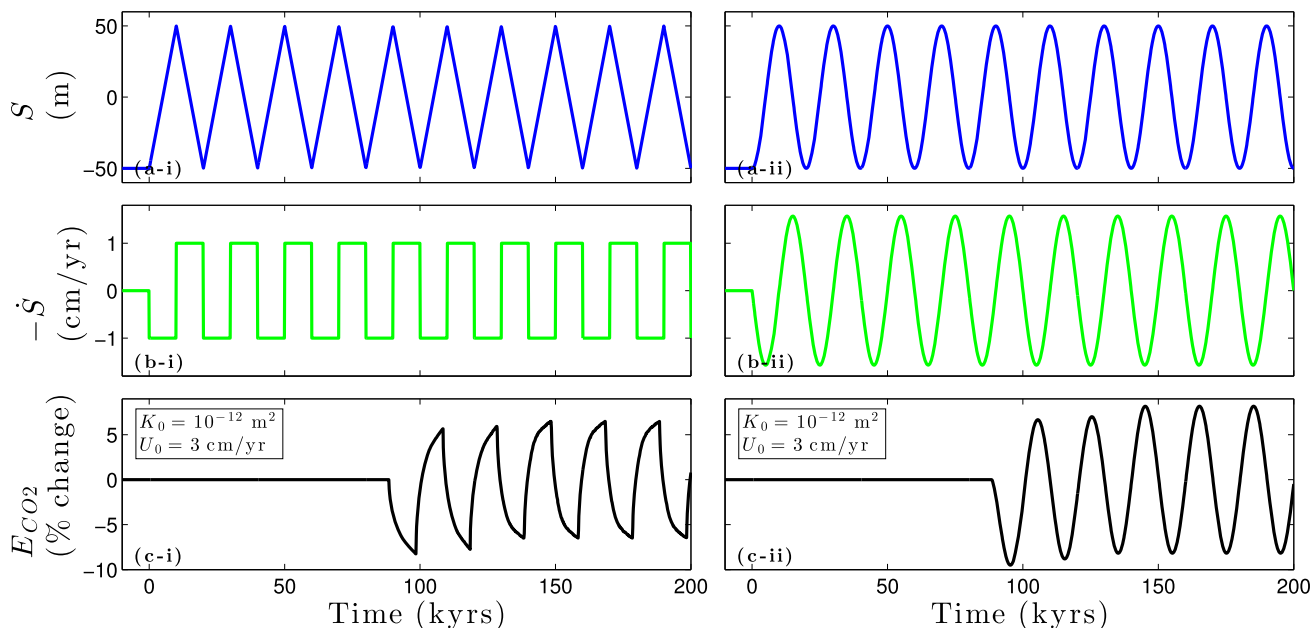
**Fig. 3.** Single step change in sea level. Plots show (a) sea-level change, (b) the negative rate of sea-level change, and (c) CO<sub>2</sub> emissions from a section of mid-ocean ridge, measured as percentage change from baseline emissions. The plate half-spreading rate and the permeability constant at 1% porosity are  $U_0$  and  $K_0$ , respectively. The three times marked on the plots correspond to (a–i, ii, iii) in Fig. 4. Negative  $\dot{S}$  is plotted so that peaks in  $\dot{S}$  and consequent peaks in  $E_{CO_2}$  point in the same direction.



**Fig. 4.** The effect of a linear change in sea level on ridge CO<sub>2</sub> emissions. The three points in time shown in black, red, and green show the state of the system 65, 95, and 125 kyrs after the pulse began. Plots show: (a–i, ii, iii) rate of sea-level change from present into the past, for the three points in time marked in Fig. 3. (b) Travel time of melt from the base of the melting region to the ridge, increasing downwards. Travel time at  $x=0$  is slightly greater than  $\tau_{min}$  because the sharp increase in lithospheric thickness within a few km of the ridge increases the column height; the effect of this increase in height exceeds the effect of faster on-axis upwelling. (c) Rate-of-change of the depth of first melting that acted on the melt currently arriving at the ridge axis, when that melt began to segregate. Dashed lines mark how the travel time converts  $\dot{S}(t)$  to  $\dot{z}_m(x)$ . The integral of a coloured line from 0 to  $x_f$  in panel (c) is directly proportional to  $E_{CO_2}$  at the corresponding time in Fig. 3(c). This is expressed by the integral of  $\dot{z}_m$  with respect to  $x$  in equation (3). A video animating this plot and  $E_{CO_2}$  over time is included in the online supplementary materials. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

means that CO<sub>2</sub> from a broad (30 km) region affected by the  $\dot{S}$  pulse is arriving at the ridge axis at  $t_2$ . This causes the spike in emissions shown in Fig. 3(c). At  $t_3$ , the interval of sea-level change has receded far into the past. The only CO<sub>2</sub> perturbation in melts

arriving at the ridge is in distal melts from the base of the melting region at 50 to 58 km off-axis. The narrowness of this band translates to a reduced (but non-zero) value of  $E_{CO_2}$  at  $t_3$  in Fig. 3(c). As the sea-level drop recedes further into the past, the emission



**Fig. 5.** Sawtooth and sine waves in sea level starting at  $t = 0$ . Plots show (a) sea-level, (b) negative rate of sea-level change, (c)  $\text{CO}_2$  emissions from a section of mid-ocean ridge. Considering the left column, each box-pulse in  $\dot{S}$  produces an emissions peak/trough as in Fig. 3(c) with interference where they overlap, giving the net result seen in (c-i). The steady upward shift in the  $E_{\text{CO}_2}$ -peaks until  $\sim 150$  kyr is due to this overlap. If the first box-pulse in  $\dot{S}$  had been in the opposite direction,  $E_{\text{CO}_2}$  peaks in (c) would be mirrored across  $E_{\text{CO}_2} = 0$ .

rate drops to zero because the very distal melts (from  $x > x_f$ ) are not focused to the ridge axis. This process is animated in a video in the online supplementary materials.

In the limit of vanishing duration of sea-level change, the pulse of  $\dot{S}$  approximates to a Dirac delta function. Hence the  $E_{\text{CO}_2}$  response shown in Fig. 3(c) is an approximation of the Green's function. Conceptually, the emissions response for any sea-level time series could be approximated by convolution with a Green's function approximation like Fig. 3(c).

From this discussion, it is clear that changes to  $\tau(x)$  will alter how MOR emissions respond to changing sea-level. Equation (7) for travel time shows that plate half-spreading rate  $U_0$  and permeability constant  $K_0$  are the key parameters affecting the melt travel-time  $\tau$ . Higher values of either lead to shorter travel times, giving a higher peak in  $E_{\text{CO}_2}$  over a shorter time period, with this peak occurring sooner after the causative sea-level change. This is explored in more detail in the following section.

### 3.3. Oscillating sea level

We now consider oscillatory sea level and discuss the concepts of lag and admittance.

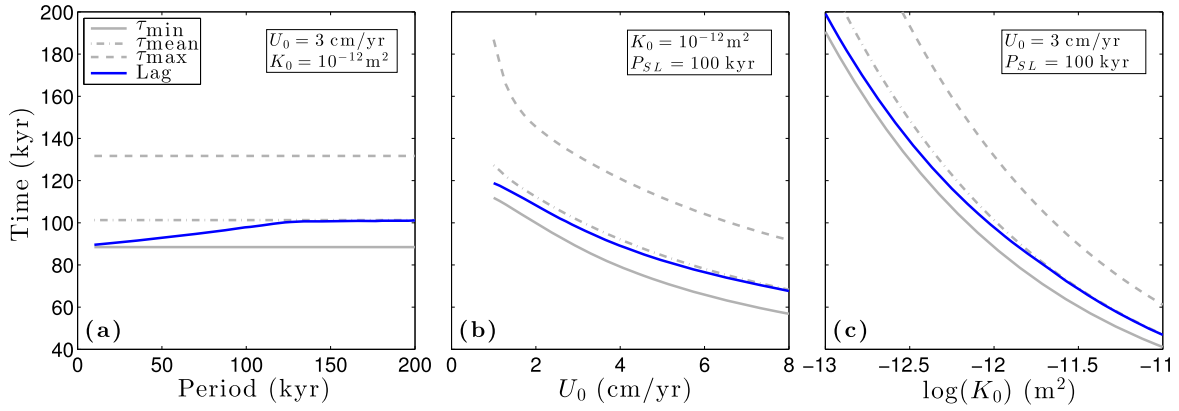
Fig. 5 shows a pair of oscillating sea level scenarios and their predicted  $E_{\text{CO}_2}$  variation. The left column (i) shows a time series of alternating box-pulses in  $\dot{S}$ ; the right column (ii) shows a sinusoidal sea-level variation. Fig. 5(c-i) has an oscillating series of peaks in  $E_{\text{CO}_2}$  resulting from a series of  $\dot{S}$  box-pulses in Fig. 5(b-i). This  $\dot{S}$  series is equivalent to summing single box-pulses from Fig. 3(b), with suitable offset and amplitude. Similarly, the  $\text{CO}_2$  emissions can be represented as a sum of offset emissions spikes from single, linear changes in sea level. The train of emissions peaks in Fig. 5(c-i) and (c-ii) stabilises in amplitude after  $t \approx \tau_{\text{max}}$ ; this transient represents the spin-up time of the model, associated with the tail of excess emissions shown in Fig. 3.

Fig. 5(ii) shows sinusoidal sea level and provides the context to define the lag metric. Lag  $\mathcal{L}$  is the time between a peak in  $\dot{S}$  and the corresponding peak in emissions. Because the time interval around  $\tau_{\text{min}}$  kyrs before  $t$  has the largest influence on  $E_{\text{CO}_2}$  at  $t$ , the  $E_{\text{CO}_2}$  signal should lag  $\dot{S}$  by about  $\tau_{\text{min}}$ . However, the lag

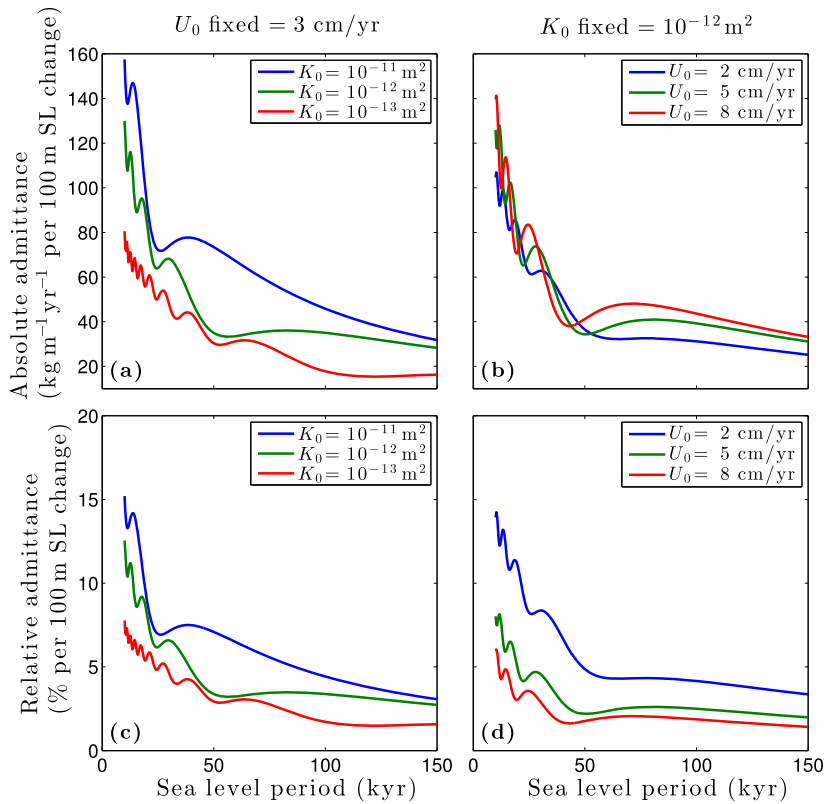
will not be exactly  $\tau_{\text{min}}$ , as the influence of  $\dot{S}$  on  $E_{\text{CO}_2}$  is felt up to  $\tau_{\text{max}}$  years after the change in sea level. Thus the exact value of lag will be slightly greater than  $\tau_{\text{min}}$  and we expect this difference to depend on the period of sea-level oscillation relative to  $\tau_{\text{max}} - \tau_{\text{min}}$ . In particular, when the period approaches and exceeds  $2(\tau_{\text{max}} - \tau_{\text{min}})$ , the lag becomes equal to the mean melt-transport time  $\tau_{\text{mean}}$ . Fig. 6 shows lag,  $\tau_{\text{min}}$ ,  $\tau_{\text{mean}}$ , and  $\tau_{\text{max}}$  for varying half-spreading rate, permeability constant, and sinusoidal sea-level period. We note that  $\tau_{\text{min}} \leq \mathcal{L} \leq \tau_{\text{mean}} \ll \tau_{\text{max}}$  and therefore we assume  $\mathcal{L} \approx \tau_{\text{min}}$  with a small, systematic error.

Sinusoidal variation of sea level also provides a context in which compute admittance. Admittance is the ratio of the response amplitude to the forcing amplitude as a function of the sinusoidal forcing period. We define two versions of admittance: absolute admittance, with units of kilograms  $\text{CO}_2$  per metre of ridge per year per 100 m of sea-level change, and relative admittance, with units of percentage change from baseline emission rate per 100 m of sea-level change. The latter is the absolute admittance divided by the baseline emission rate. Fig. 7 shows absolute and relative admittance and how they vary with changing sea-level period, half-spreading rate, and permeability constant. We discuss both the trends and the oscillations of these curves, starting with absolute admittance.

Absolute admittance (panels (a) and (b) of Fig. 7) depends on the period of sea-level oscillation, the permeability, and to a lesser extent, on the half-spreading rate. We consider these in turn. Shorter periods of sea-level variation at constant amplitude give larger values of  $|\dot{S}|$  and  $|\dot{z}_m|$ , and hence increase the temporal variation of  $f_{\text{CO}_2}$ . This causes increased deviation of ridge emissions from baseline. Increased mantle permeability and spreading rate both reduce the melt travel-time from the base of the melting region. In the melt travel-time model of equation (7), the permeability appears as  $K_0$ , while the spreading rate  $U_0$  is directly proportional to the mantle upwelling rate  $W_m$ . A reduced melt travel-time implies a smaller difference between  $\tau_{\text{max}}$  and  $\tau_{\text{min}}$ , and therefore a focusing of  $\text{CO}_2$  from the base of the melting region to the ridge axis over a shorter interval in time. The uncertainty in mantle permeability translates to a broader spread of the



**Fig. 6.** Lag and travel time for varying (a) sinusoidal sea-level period, (b) half-spreading rate, and (c) permeability constant. The lag is calculated as the time between a peak in  $-\dot{S}$  and the corresponding peak in  $E_{CO_2}$  for sinusoidal sea level.



**Fig. 7.** Absolute and relative admittance for varying half-spreading rate, permeability, and sinusoidal sea-level period. Plots hold either  $U_0$  or  $K_0$  fixed. The magnitude of sea-level change is constant for all periods.

absolute admittance curves than does the range of half-spreading rates considered.

Relative admittance is equal to the absolute admittance normalised by the baseline emissions rate. The baseline depends on half-spreading rate but not on permeability (Fig. 2(a)). We therefore see a difference between absolute and relative admittance in Fig. 7(b) and (d). For slow-spreading ridges, which have a low baseline emissions rate, the normalised variance (and hence the relative admittance) is larger.

The oscillations superimposed on the primary admittance trend are not physically significant, but are readily explained. They arise from variation in the number of sea-level half-cycles that fit into the time interval from  $t - \tau_{max}$  to  $t - \tau_{min}$ ; this is the time interval over which  $\dot{S}(t - \tau)$  can contribute  $CO_2$  emissions at time  $t$ . For oscillatory sea level, each positive or negative peak in  $\dot{S}$  has an

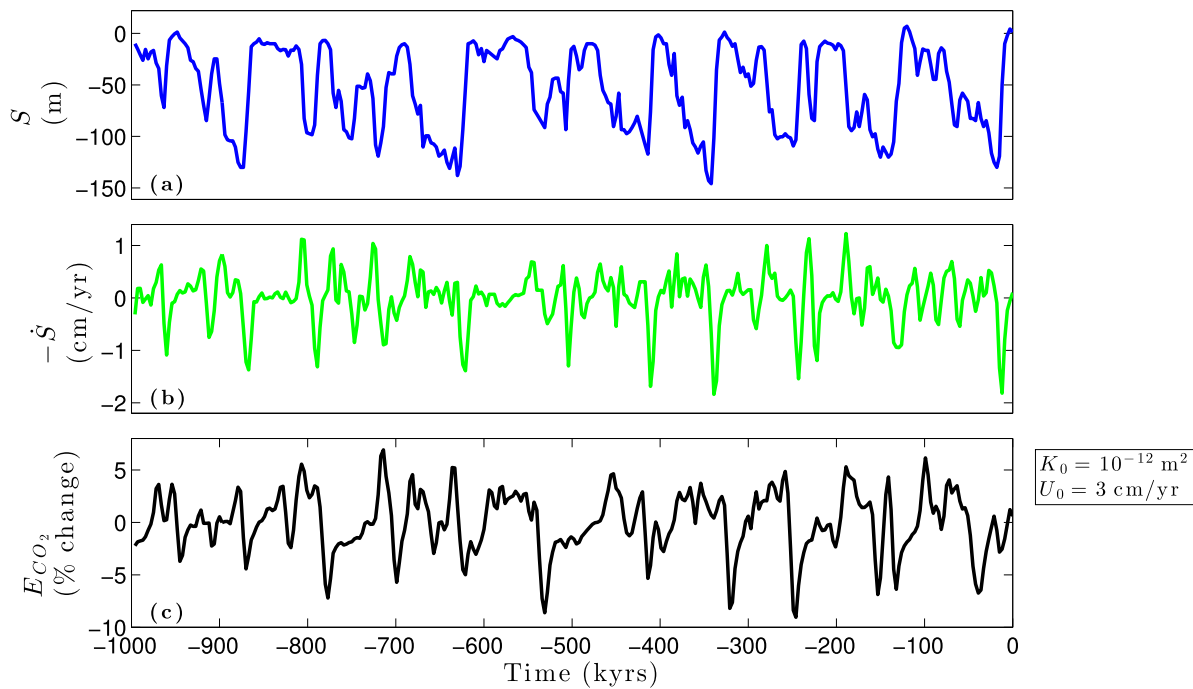
opposing emissions effect relative to the prior negative or positive peak. If there is an unmatched peak affecting the bottom of the melting region, the amplitude of  $E_{CO_2}$  variations is larger and the admittance is higher.

Broadly, the patterns of admittance and lag imply that, in terms of  $CO_2$  emission variation, the dominant sea-level changes will be those with large amplitude and short period changes. The emissions variation associated with such changes will lag the forcing by approximately  $\tau_{min}$ . The modelled magnitude and lag of  $E_{CO_2}$  changes are affected by both  $K_0$  and  $U_0$ .

### 3.4. Reconstructed Pleistocene sea level

The simple scenarios of sea-level variation presented above give insight into the behaviour of the model, but are not representative





**Fig. 8.** Reconstructed sea level. Plots show (a) sea-level change, (b) the negative rate of sea-level change, and (c) CO<sub>2</sub> emissions from a section of mid-ocean ridge. The lag is ~90 kyrs.

of the variations that have occurred naturally, over the past million years. We move, therefore, to a model forced by the time-series of reconstructed global sea level from Siddall et al. (2010), shown in Fig. 8(a). Other reconstructions exist, but the differences between them are small enough that we follow Crowley et al. (2015) and consider only this one. Siddall et al. (2010) record data every 3 kyrs and, based on their reconstruction, the highest rates of sea-level change (Fig. 8(b)) meet the condition  $\max(\dot{z}_m(t)) < W_m$  required for validity of equation (3).

Fig. 8(c) shows the result of applying reconstructed sea level to ridge  $E_{CO_2}$ . There is a  $\pm 8\%$  range in  $E_{CO_2}$  for moderate half-spreading rate and permeability. The  $E_{CO_2}$  curve is, qualitatively, an offset version of  $\dot{S}$  with small variations smoothed out – as expected from  $E_{CO_2}$  being approximated by convolving  $\dot{S}$  with the emissions response in Fig. 3(c). Within this framework, we now consider how to apply the model to global MOR emissions.

### 3.5. Global mid-ocean ridges

The global MOR system is composed of ridge segments spreading at different rates, ranging from the ultra-slow Gakkel ridge to the fast East Pacific Rise. The baseline emissions depend on the half-spreading rate, as does the character of the emissions response to sea-level change. The global response to sea-level change should therefore be computed as the segment-scale response, integrated over the global MOR system,

$$\mathcal{G}_{CO_2}(t, K_0) = \int_0^{L_{MOR}} E_{CO_2}(t, K_0, U_0(l)) dl, \quad (9)$$

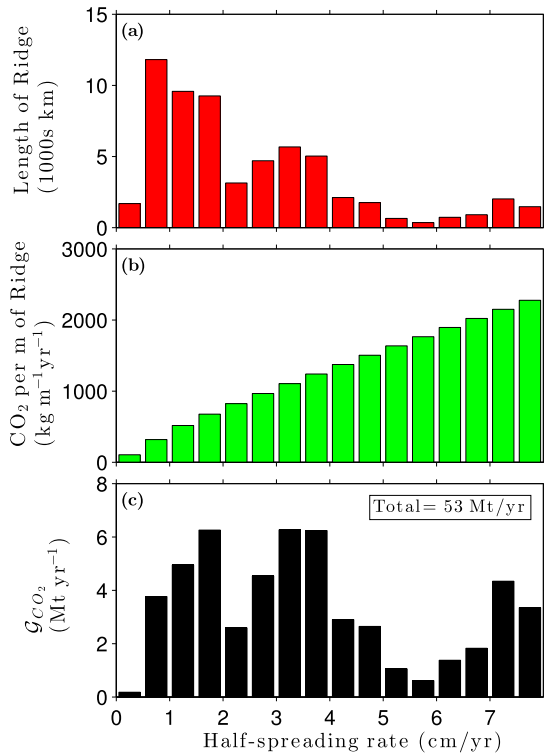
where  $\mathcal{G}_{CO_2}$  is global MOR emissions of CO<sub>2</sub> in kg/yr,  $l$  is arc length along the ridge, and  $L_{MOR}$  is the total length of the MOR system. This integral can be approximated by discretising the half-spreading rate into bins  $U_{0i}$  and summing the local response in each bin. A weighting is applied to each entry in the sum to account for the total length of segments with half-spreading rates in that bin. The sum is written as

$$\mathcal{G}_{CO_2}(t, K_0) = \sum_{i=1}^N E_{CO_2}(t, K_0, U_{0i}) L_i(U_{0i}), \quad (10)$$

where  $N$  is the total number of spreading rate intervals to sum over and  $L_i(U_{0i})$  is the total length of MOR in a particular spreading-rate bin. The local emission rate  $E_{CO_2}$  in each bin is computed by adopting the average half-spreading rate of the bin and assuming that sea-level change is eustatic – the same for all segments globally.

Gale et al. (2013) provide a catalogue of segment lengths and spreading rates for the global MOR system; the total ridge length is 61 000 km with a mean half-spreading rate of 2.5 cm/yr. A histogram of these data is plotted in Fig. 9(a). Fig. 9(b) shows, for each spreading-rate bin, the rate of baseline emissions per metre of ridge. Panel (c) then shows the product of ridge length and emissions rate per metre, giving the total emissions rate associated with each spreading rate bin. These are summed in accordance with eqn. (10) to give the total baseline global response. The global baseline emission rate thus predicted is 53 Mt CO<sub>2</sub> per year assuming a sub-ridge mantle CO<sub>2</sub> concentration of 125 ppmw. This can be compared to other estimates of  $91 \pm 45$  MtCO<sub>2</sub>/yr (Coltice et al., 2004; Cartigny et al., 2008; Marty and Tolstikhin, 1998). If we instead constrain the model to have baseline emissions of 91 Mt CO<sub>2</sub>/yr, it requires a sub-ridge mantle CO<sub>2</sub> concentration of 215 ppmw (0.65 kg per m<sup>3</sup>).

Before applying the reconstructed sea-level forcing to the weighted global emissions sum in eqn. (10), we consider the simple sea level forcing that was used to probe the behaviour of  $E_{CO_2}$  in Fig. 3. This linear ramp in sea level is applied to compute the global emissions response in Fig. 10(a) for a range of mantle permeabilities. Global emissions in Fig. 10(a) are, unsurprisingly, more complex than the  $E_{CO_2}$  equivalent, as they consist of a summation of  $N$   $E_{CO_2}$  peaks from Fig. 3, weighted according to the ridge length in each bin and offset due to the variation in  $\tau$  with  $U_{0i}$ . Compared with Fig. 3,  $\mathcal{G}_{CO_2}$  has a smaller percentage difference in the rate of CO<sub>2</sub> emissions and is spread out over a longer time-period.



**Fig. 9.** Quantities associated with discrete bins of half-spreading rate. (a) The total length of MOR (Gale et al., 2013). (b) Baseline emissions per metre of MOR from our model. (c) Baseline global CO<sub>2</sub> emissions as the product of quantities in panels (a) and (b). Calculated for 0.38 kg CO<sub>2</sub> per m<sup>3</sup> of upwelling mantle (125 ppmw). Baseline emissions are independent of  $K_0$ .

Finally, we apply the reconstructed sea-level time series to the global model. Fig. 10 shows  $\mathcal{G}_{\text{CO}_2}$  for reconstructed sea level, calculated and plotted for a set of three values of permeability constant  $K_0$  in panels (d-i), (d-ii), and (d-iii). These curves demonstrate a reduction in  $\mathcal{G}_{\text{CO}_2}$  range from 6.6 MtCO<sub>2</sub>/yr for  $K_0 = 10^{-11} \text{ m}^2$  to 1.2 MtCO<sub>2</sub>/yr for  $K_0 = 10^{-13} \text{ m}^2$ . The reduction in  $\mathcal{G}_{\text{CO}_2}$  range occurs because  $K_0$  affects the range of  $\tau_{\text{min}}$  that is implicit in the global sum in eqn. (10). A large value of  $K_0$  gives higher overall permeability, shorter melt-transport times, and a global range in  $\tau_{\text{min}}$  that is smaller. Therefore the emissions response to a box-pulse in  $\dot{S}$  (Fig. 10(a)) is temporally concentrated and attains a higher peak value. Hence, larger  $K_0$  causes greater amplitude of variation in  $\mathcal{G}_{\text{CO}_2}$  for reconstructed sea level.

#### 4. Discussion

The model prediction for global MOR CO<sub>2</sub> emissions at constant sea level using a mantle CO<sub>2</sub> concentration of 125 ppmw is 53 Mt CO<sub>2</sub> per year (14 Mt carbon per year), a value that is within error of estimates from analyses of mid-ocean ridge basalts of  $91 \pm 45 \text{ MtCO}_2/\text{yr}$  (Coltice et al., 2004; Cartigny et al., 2008; Marty and Tolstikhin, 1998). However, note that our prediction is not independent of MORB studies because our choice of  $C_{\text{CO}_2}$  is based on observed MORB chemistry. If we instead choose to constrain the model to fit published CO<sub>2</sub> emissions, we require a source mantle CO<sub>2</sub> concentration of  $\sim 215 \text{ ppmw}$ .

The ranges in global CO<sub>2</sub> emissions under reconstructed variation of past sea level (Fig. 10 for 125 ppmw CO<sub>2</sub>) are 1 MtCO<sub>2</sub>/yr, 3 MtCO<sub>2</sub>/yr, and 7 MtCO<sub>2</sub>/yr for mantle permeabilities at 1% porosity of  $10^{-13} \text{ m}^2$ ,  $10^{-12} \text{ m}^2$ , and  $10^{-11} \text{ m}^2$  respectively. These idealised predictions assume that 100% of CO<sub>2</sub> transported to the ridge axis is degassed into the oceans, rather than retained in the crust or mantle. This may, in fact, be rather accurate; Cartigny

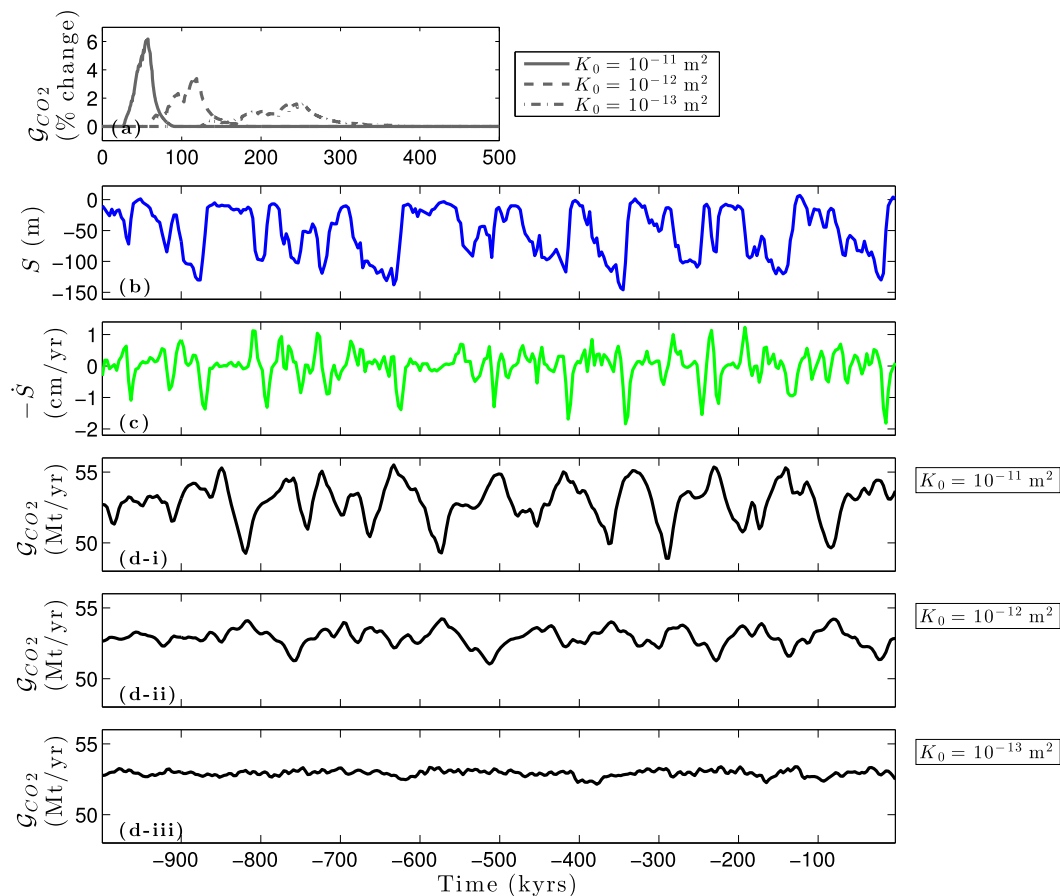
et al. (2008) estimated that over 80% of CO<sub>2</sub> in primitive MORB is degassed near the ridge axis. Furthermore, 100% degassing is assumed in the papers that calculate the source mantle CO<sub>2</sub> concentration we use. It has previously been speculated that variations in ridge CO<sub>2</sub> emissions would have an effect on global climate (Huybers and Langmuir, 2009; Lund and Asimow, 2011); it is beyond the scope of the present manuscript to investigate this question, though it is a target for future work.

Uncertainty in mantle permeability translates to uncertainty in both the amplitude of variations and the lag of global CO<sub>2</sub> emissions from MORs. There are various experimental constraints on mantle permeability (e.g. Miller et al., 2014; Connolly et al., 2009); these tend to agree on the scaling with porosity, but disagree on the magnitude of  $K_0$ . Furthermore, permeability is sensitive to grain size, a parameter that is poorly known for the mantle beneath MORs (although see Turner et al., 2015). Our chosen range of  $K_0$  is intended to accommodate these uncertainties, as well as represent an effective permeability for melt transport that may be channelised into high-porosity, high-permeability dunite channels (e.g. Jull et al., 2002; Kelemen et al., 1995). Our  $K_0$  range of  $10^{-13}$ – $10^{-11} \text{ m}^2$  encompasses a change in the amplitude of  $\mathcal{G}_{\text{CO}_2}$  variation by a factor of 5, a difference in lag of 200 kyrs, and qualitative difference in the time-series of  $\mathcal{G}_{\text{CO}_2}$  (Fig. 10). Therefore  $K_0$  represents a leading source of uncertainty in the model. Uranium series disequilibria may provide an independent constraint on magma travel time from the base of the melting region (e.g., Jull et al., 2002), although interpreting the various species in the decay chain is fraught with complexity. Preservation of <sup>230</sup>Th disequilibrium (half-life of 75 kyrs) suggests a permeability of  $K_0 \geq 10^{-12} \text{ m}^2$ , and community consensus similarly favours  $K_0$  at the higher end of our considered range.

Our model is based on the assumption that melt travels vertically from the depth of first melting to the top of the melting region and is then focused along a sloping, high porosity decompaction channel to the ridge axis (Sparks and Parmentier, 1991). The travel time of the vertical flow is modelled by a 1D compaction column; we assume that transport in the decompaction channel is instantaneous. The systematic error introduced by the latter assumption is zero on the ridge axis ( $x=0$ ), and increases with distance  $x$  from the ridge axis. This means  $\tau$  plotted in Fig. 4(b) is more accurate at small  $x$ , but increasingly underestimates  $\tau$  for larger  $x$ . Therefore, assuming  $\tau_{\text{min}}$  is accurately modelled,  $\tau_{\text{max}}$  is probably too small, such that  $E_{\text{CO}_2}$  in Fig. 3 should have a longer tail on the right of the graph. However, long tails have little effect on the resultant  $E_{\text{CO}_2}$  pattern for complex sea-level changes or on the  $\mathcal{G}_{\text{CO}_2}$  pattern for reconstructed sea level. Therefore the overall effect of including a finite travel time along the high porosity channel would be to make a small adjustment to the  $E_{\text{CO}_2}$  response. This suggests that assuming instantaneous travel time along the channel has little effect on the results of the model.

Another assumption made is that travel time is constant with respect to time, despite changes in melting rate (and thus, porosity) caused by changing sea-level. This follows the approach in the reduced model of Crowley et al. (2015), where the perturbations in porosity were taken as negligible disturbances to the travel time in a steady-state compaction column solution from Hewitt (2010).

A more significant assumption underpinning the model is that carbon dioxide behaves as a perfectly incompatible tracer — meaning that carbon concentration does not affect the mantle's physical or thermodynamic properties. However, carbon is not a trace element. In contrast, experiments by Kono et al. (2014) document the very low viscosity of incipient, carbon-rich melts present at small melt fraction below the base of the silicate melting region. The experiments also show that viscosity rises sharply as the carbon is diluted by silicate melting. It would be challenging to capture this



**Fig. 10.** Global MOR emissions. Panel (a) shows CO<sub>2</sub> emissions from the global MOR system for a step change in sea-level identical to that of Fig. 3(a). Subsequent panels consider reconstructed sea level and its effect. (b) Reconstructed sea level; (c) the negative rate of sea-level change; and (d-i–iii) CO<sub>2</sub> emissions from the global MOR system. The sea level time-series has been applied further back in time than shown, such that the left-most point in  $\mathcal{G}_{CO_2}$  is affected by more than  $\tau_{\max}$  kyrs of prior sea-level change. For (d-i, ii, iii) the lags in  $\mathcal{G}_{CO_2}$  are, respectively,  $\sim 60$  kyrs,  $\sim 120$  kyrs, and  $\sim 250$  kyrs.

variability in models, especially since the wetting properties (and hence the mobility) of carbon-rich melts are poorly constrained.

A more significant concern, however, is that treating volatiles as trace elements neglects their thermodynamic effect on melting. Small mantle concentrations of carbon affect the depth at which melting begins, though the melt fractions produced by this incipient melting are probably less than a few tenths of a percent (Dasgupta et al., 2013). Our model assumes that these melts do not segregate until the onset of silicate melting. At such small porosity, it is unclear whether these carbonated melts can percolate. However, water-induced melting at the wet peridotite solidus of  $\sim 90$ – $120$  km (Asimow and Langmuir, 2003; Dasgupta et al., 2013) increases the melt fraction. Again, the threshold of interconnectivity for such melts is not known, so it is possible that such deep, hydrous melts do not segregate, or do so very slowly. If the <sup>230</sup>Th disequilibrium observed in young MOR lavas originates with melt segregation in the presence of garnet (Stracke et al., 2006), it would support the hypothesis of efficient segregation of hydrous melts (although other hypotheses also fit the observations). Overall, our model depends only on the presence of a pressure-dependent boundary that separates non-segregating melts, below, from segregating melts, above. The sharpness that is required of this boundary is unclear.

Finally, our model assumes a chemically and thermally homogeneous mantle, which is certainly not true of the natural system (e.g., Dalton et al., 2014). No data exists that would allow us to accurately incorporate small-scale ( $\lesssim 100$  km) heterogeneity in model. If such heterogeneity is pervasive and at scales of  $\sim 10$  km or smaller, it would affect the style of melt transport (Katz

and Weatherley, 2012), with fertile regions creating pathways for rapid melt transport through the melting region. It may be the case that this is captured by a high effective permeability, though this is probably not a testable hypothesis. Large-scale heterogeneity would leave the mantle homogeneous over the scale at which we calculate  $E_{CO_2}$ , so the underlying melt transport model would be unaffected, though parameters would need to be adjusted according to the oceanic region. It seems likely that such variations would cancel in the integral for global CO<sub>2</sub> emissions rate.

Previous authors have suggested that changing sea level might affect MOR CO<sub>2</sub> emissions almost instantaneously (Huybers and Langmuir, 2009; Lund and Asimow, 2011; Tolstoy, 2015). Their assumption is that pressure changes instantaneously affect melting rates, MOR volcanic productivity and therefore, assuming constant CO<sub>2</sub> concentration in the erupted melt, MOR CO<sub>2</sub> emissions. We disagree with the assumption that CO<sub>2</sub> concentrations would be constant. CO<sub>2</sub> is highly incompatible and therefore additional melting acts to dilute the constant mass of CO<sub>2</sub> in the melt. However, after including these effects, our model can calculate whether changing sea level affects MOR CO<sub>2</sub> emissions (see Appendix A.4). To leading order there is no effect; the reduced (or increased) concentration of CO<sub>2</sub> in the melt counteracts the increased (or reduced) rate of melt delivery to the ridge axis.

We would like to be able to compare the model to data, but there is no dataset of global MOR CO<sub>2</sub> flux over time. Atmospheric CO<sub>2</sub> concentration from Antarctic ice cores (Bereiter et al., 2015) is an existing dataset that might record some influence of  $\mathcal{G}_{CO_2}$ . However, there are many strong, nonlinear controls on atmospheric CO<sub>2</sub> and the relationship between  $\mathcal{G}_{CO_2}$  and atmospheric CO<sub>2</sub> will not

necessarily be constant over time. Nonetheless, comparing atmospheric CO<sub>2</sub> to  $\mathcal{G}_{\text{CO}_2}$  does offer at least one useful insight: if there is no correlation between these quantities within the model's reasonable parameter space, it would be an indication that MOR CO<sub>2</sub> emissions have no effect on atmospheric CO<sub>2</sub>. We find a correlation in Appendix A.5. The best correlation, without considering the very significant complicating factors associated with climatic feedbacks, occurs at  $K_0 = 10^{-11.37}$  with a lag of 73 kyrs. This correlation does not prove any causative link between  $\mathcal{G}_{\text{CO}_2}$  and atmospheric CO<sub>2</sub>.

Variable MOR CO<sub>2</sub> emissions' effect on atmospheric CO<sub>2</sub> will vary over time, as the fraction of MOR CO<sub>2</sub> emissions into the intermediate ocean that reach the atmosphere is not constant. This fraction depends upon an array of factors that affect ocean alkalinity, ocean upwelling patterns and CO<sub>2</sub> concentration in the atmosphere, and these factors vary on sub-glacial/glacial timescales (as do numerous processes interacting with them, e.g., the biosphere) (Broecker, 1982; Walker, 1986; Brovkin et al., 2012; Yu et al., 2014). This would have to be taken into account if inferring any climate implications from our model.

The MOR carbon flux may vary over time in other ways that we have not considered here. For instance, it is plausible that the intensity of hydrothermal circulation varies with sea level, driven by variations in melt supply (Lund and Asimow, 2011; Crowley et al., 2015). If this is the case, hydrothermal variations would have a different lag than that of CO<sub>2</sub> emissions. Hydrothermal systems have been proposed as both a CO<sub>2</sub> sink, with hot seawater transforming basalts to clay (Gysi and Stefansson, 2012), and a CO<sub>2</sub> source, with hydrothermal fluids transporting CO<sub>2</sub> from magma to the ocean (Sakai et al., 1990). The rate of both these processes might scale with hydrothermal circulation, although it is not clear whether the net effect would be to increase or decrease MOR CO<sub>2</sub> emissions.

## 5. Summary

The model presented above builds on the reduced model of Crowley et al. (2015) to calculate the efflux of a highly incompatible chemical component from a mid-ocean ridge, and how that efflux would vary with changes in sea level. It is based on a description of melt transport through a homogeneous mantle and assumes perfect incompatibility of the component. This leads to a simple but physically consistent model of chemical transport through the melting region beneath a ridge. The model calculates total melt supply rate and global background emissions of CO<sub>2</sub> that are consistent with data and prior estimates.

In the model, changing sea level affects the depth of first silicate melting; this alters the rate at which CO<sub>2</sub> enters the melting region, segregates from its mantle source, and (some time later) arrives at the ridge axis and is degassed into the ocean.

The MOR emission rate of CO<sub>2</sub> is predicted to vary by up to 12.5% when the model is forced with reconstructed Pleistocene sea level variation (7 MtCO<sub>2</sub>/yr for 125 ppmw  $C_{\text{CO}_2}$ ; 11 MtCO<sub>2</sub>/yr for 215 ppmw  $C_{\text{CO}_2}$ ). There is uncertainty in the predicted magnitude and timing (relative to sea-level forcing) of this effect, as two parameters of the model –  $C_{\text{CO}_2}$  and  $K_0$  – are weakly constrained by existing data. However, within reasonable ranges of the model parameters, the amplitude of global MOR CO<sub>2</sub> emission-rate variation will remain on the order of several MtCO<sub>2</sub>/yr. The total difference in the mass of CO<sub>2</sub> emitted from MORs during sea-level driven deviations from global baseline CO<sub>2</sub> is up to ~80 Gt CO<sub>2</sub> for high permeability and 125 ppmw  $C_{\text{CO}_2}$  (see Fig. 10(d-i)). This is 4% of the pre-industrial CO<sub>2</sub> mass in the atmosphere of 2190 Gt, or 0.06% of pre-industrial CO<sub>2</sub> in the oceans (IPCC: Solomon et al., 2007, Fig. 7.3).

Our results indicate that the CO<sub>2</sub> emissions from mid-ocean ridges are temporally variable in response to sea-level change.

These results align with the hypothesis of Huybers and Langmuir (2009); however, whereas they assumed an immediate emissions response, we show that the mid-ocean ridge CO<sub>2</sub> emissions response lags the sea-level forcing by approximately the minimum travel time of CO<sub>2</sub> through the melting region – at least 60 kyrs. Therefore MOR CO<sub>2</sub> emissions cannot feed back into the sea-level change that caused them; instead these CO<sub>2</sub> emissions will enter the climate system during the next glacial cycle. Further work is needed to assess the climatic impact of the variable CO<sub>2</sub> emissions predicted for mid-ocean ridges in this paper and for subaerial volcanoes by Huybers and Langmuir (2009).

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## Appendix A. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.epsl.2015.06.031>.

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