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# Reconciliation of sea-level observations in the Western North Atlantic during the last glacial cycle

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**Abstract**

A south to north gradient of increasing marine isotope substage (MIS) 5a ($\sim$80 ka BP) sea level has been recorded across the Caribbean and surrounding region. Relative to present, MIS-5a sea levels range from −19 m to more than +3 m between Barbados, Haiti, the Bahamas, Florida, Bermuda and the US Atlantic Coast. In contrast, no gradient in sea level is observed for the last interglacial period MIS-5e ($\sim$128–118 ka BP) at tectonically stable localities in the same region, with deposits generally lying several metres above present. We demonstrate here that these controversial observations are reconciled by taking into account the isostatic response of the Earth to glacial loading and unloading – a fundamental effect that is commonly overlooked in the interpretation of sea-level observations from different locations to define a 'global sea-level curve'. Furthermore, the observed gradient can be used to place constraints on Earth rheology and is an important indicator of the behaviour of the North American ice sheets during the last glacial cycle.


*Keywords:* sea level; glacio-hydro-isostasy; Caribbean; MIS-5a

## 1. Introduction

Knowledge of the timing and magnitude of variations in global ice volume during the last glacial cycle plays an important role in reaching an understanding of the mechanisms involved in controlling climate change. As a result, sea-level data sets from a range of locations are increasingly being compared and combined in an attempt to define a 'global sea-level curve'. However, these comparisons often reveal apparent discrepancies in the estimates of relative sea level for a given event at different locations. For example, in the Western North Atlantic sea-level estimates for the marine isotope substage (MIS) 5a event vary by over 20 m between the southern Caribbean island of Barbados and the US Atlantic Coast. These differences are often attributed to uncertainties in tectonic setting or stratigraphic context of the samples analysed.

Sea-level history at a given location does not only reflect changes in ice volume. Rather, in

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the absence of tectonics, relative sea-level change reflects both variations in global ice volume and the response of the Earth to changes in surface loading in the form of surface deformation and geoid changes, or glacio-hydro-isostasy [1–3]. In the Western North Atlantic (Fig. 1), for example, an important contribution to relative sea-level change is the glacio-isostatic effect associated with the North American ice sheets (NAIS). Of particular importance to this region is the peripheral bulge surface deformation that occurs during ice-sheet growth as a consequence of the displacement of mantle material from beneath the large ice load to the adjacent unloaded region. As the ice sheet melts, the crust beneath the ice rebounds and the peripheral bulge region subsides. The magnitude of the isostatic response as a function of time and position is dependent on global and local melting history and the rheology of the Earth, which determines the magnitude and rate of response to changes in surface loading [4,5]. Observations of spatial differences in relative sea level, therefore, provide constraints on the ice history as well as on Earth rheology.

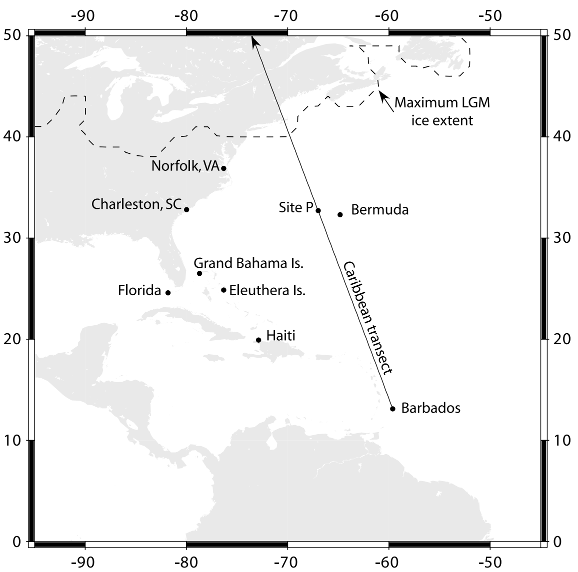


Fig. 1. Map of the Caribbean area. Sites marked are those at which evidence of MIS-5a sea level has been recorded. The marked transect is used for sea-level calculations in Figs. 3 and 4. Site P is used for reference in those figures. The dashed line shows the maximum extent of the Laurentide Ice Sheet during the LGM [32].

Past sea levels are measured relative to present-day sea level. That is to say, relative sea level of past events is a function of the isostatic state of the Earth at that time relative to the present-day isostatic state. It is important to note that the present-day Earth is not in an equilibrium state because of its continuing readjustment following the last major deglaciation. As a consequence, the relative sea level of past events is dependent on surface loading history both before and after the time of interest. In other words, sea-level observations for events prior to the last glacial maximum (LGM) can therefore be used to constrain ice-sheet melting history since the LGM.

## 2. Observations

Previous observations of MIS-5a sea level define a south to north increasing gradient of more than 20 m from Barbados in the south to the US Atlantic coast in the north (Fig. 2). The types of sea-level indicators include dated coral reef, dated coral rubble in marine facies, amino acid dated deposits (combined with stratigraphic considerations) and dated submerged speleothems.

Recent evidence from Barbados indicates that the MIS-5a interstadial has a total duration of at least 7 kyr and may have consisted of two distinct sea-level highstands [6–9] of approximately −19 m and −18 m (±4 m) at ∼84 ka and ∼77 ka BP. MIS-5c sea level at Barbados reached approximately −15±4 m [8]. At Haiti, observations from uplifted coral reefs indicate that MIS-5a sea level reached −13 m and MIS-5c peaked at approximately −10 m [10].

Further north, at several sites in the Bahamas, such as Eleuthera, aeolianites estimated to be of MIS-5a age indicate that local sea level was between −5 m and 0 m [11]. Dating of a submerged speleothem at Lucayan Caverns near Grand Bahama Island suggests that sea level there remained below −8.5 m (revised from an originally quoted depth of −15 m) during MIS-5a [12,13]. Based on the age of a submerged speleothem from Grand Bahama Island, MIS-5a sea level fell below −18 m by 79.4 ka BP [14]. This age can be corrected for initial thorium contamination to a revised value

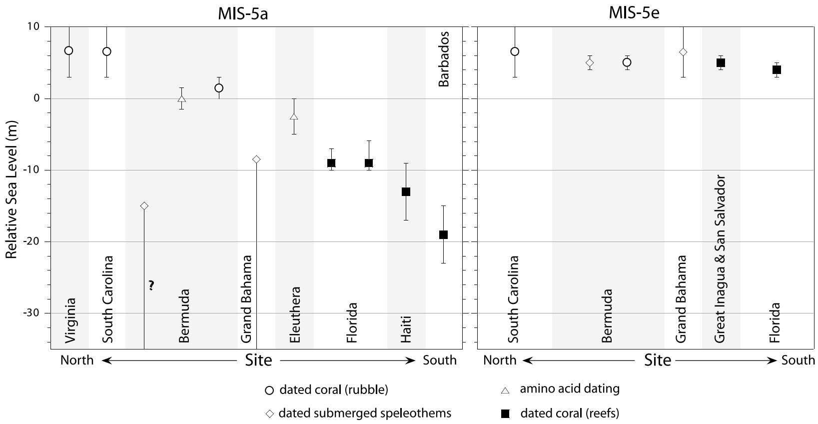


Fig. 2. Summary of observations in the Caribbean and surrounding region for peak sea level during MIS-5a and MIS-5e. See text for discussion and references. Observations include dated coral reef, dated coral rubble in marine facies, amino acid dated deposits (combined with stratigraphic considerations) and dated speleothems (references in text). The sea-level estimates shown here for tectonically active sites (Barbados and Haiti) include uplift corrections and uncertainties.

of ∼73.6 ka ([15] and D. Richards, personal communication).

A submerged coral reef of MIS-5a age (∼83 ka) off the southeast Florida Keys indicates that sea level reached 6–10 m below present [13,16]. At Bermuda, stratigraphic considerations, aminostratigraphy and U–Th dating of samples from coral rubble deposits above present sea level show that sea level was near or above present during MIS-5a [16–18]. However, a submerged speleothem at Bermuda (marked with '?' in Fig. 2) contradicts this with ages suggesting sea level remained below −15 m [19] for the duration of MIS-5a. These speleothem data have not been corrected for initial thorium contamination, which would lower the age estimate, and it is possible that this may bring them into agreement with the other Bermuda observations.

On the US Atlantic coast exposed marine facies deposits, including coral rubble of MIS-5a age, point to sea level having reached an elevation of between 3 and 10 m [20–22]. The ages of these US coastal deposits range between 72 and 84 ka BP, with younger deposits dominating the northernmost site of Norfolk, Virginia [22].

Various reasons have been suggested to explain the apparent discrepancies in these MIS-5a observations, including poor sample quality, uncertainties in tectonic setting and poor stratigraphic context. In contrast to the large gradient in MIS-5a sea levels, evidence of peak MIS-5e sea level remains at a near constant elevation of several metres above present at stable sites across the same region [11,17,19,23,24] (see Fig. 2). This observation has previously been used as an argument against a glacio-hydro-isostatic explanation for the MIS-5a gradient [18].

## 3. Modelling

### 3.1. Model parameters

The rise in sea level associated with the melting of a volume of ice is not uniform across the oceans. Instead, local sea-level change reflects the superposition of changes in ocean volume and the effects of glacio-hydro-isostasy. The latter component takes the form of deformation of the Earth's surface and the perturbation of the geoid in response to changing ice and water surface loads. The form of this response to surface loading is dependent on a number of factors including the size, distribution and melting history of the ice and water loads as well as the Earth's rheology. In the following sections, the Earth is modelled as a spherically symmetric Maxwell body with a linear viscoelastic rheology [1,25].

Here we define the term ice-equivalent sea-level change as the ocean-averaged change in relative sea level. The ice-equivalent sea-level curve used for the following simulations is drawn from a number of sources. Sea-level change since the LGM has been recorded by coral growth at a number of locations such as Barbados, Tahiti and Papua New Guinea [26–28]. Micropalaeontological studies of sediment cores from the Northwestern Australian shelf have also been used to constrain sea level during the LGM [29]. With preliminary adjustments for isostatic effects, these records can be combined to define an ice-equivalent sea-level curve since the LGM [30].

Evidence of sea-level change prior to the LGM is often overprinted or destroyed during subsequent sea-level oscillations. At rapidly uplifting sites however, these deposits can be preserved and exposed above sea level. In particular, the high rate of tectonic uplift at Huon Peninsula, Papua New Guinea, provides access to reef growth features that are not exposed at other locations. The ice-equivalent sea-level curve for the period between the last interglacial and the LGM is based on the Huon Peninsula terrace record [4]. The morphology of the reefs and published U-series ages are used to estimate the magnitude of each associated sea-level highstands. The sea-level minima in this model are based on the position of stream deltas overlapping the terrace deposits [4,31]. The sea-level history for the last interglacial period and earlier is simplified because sea level during MIS-5a, which is the focus of this study, is not sensitive to the ice melting history during or beyond the last interglacial. For simplicity, the ice-equivalent sea level during the penultimate deglaciation (MIS-6 to 5e) is modelled as a monotonic rise of 140 m followed by a sea-level plateau during the last interglacial period. The sea-level history during MIS-6 and 7 is also simplified. Because of the uncertainties involved, this sea-level curve is open to revision, however it provides a reasonable first estimate of ice-equivalent sea level that can then be refined by comparing other observations with isostatic model predictions.

A preliminary estimate of the ice distribution of individual ice sheets must be made in order to model the glacio-isostatic components of sea-level change. For the period since the LGM, ice distribution for most major ice sheets is constrained by geological observations of ice extent. Constraints on the volume of individual ice sheets during this period are dependent on dynamical models of ice behaviour and are subject to uncertainties. In the initial ice-sheet construction in this study, individual ice-sheet models were scaled to match the total ice volume defined by the preliminary ice-equivalent sea-level curve at each time step during the deglaciation. Indicators of ice-sheet distribution prior to the LGM have often been destroyed or hidden by subsequent ice advances. In these cases, the preliminary ice distribution models are inferred from the behaviour of the ice sheet during the last deglaciation, i.e. the relationship between ice volume and ice distribution. For further details on the construction of this model, see reference [8]. The NAIS provide the most important contribution to the isostatic component of sea-level change in the Northwest Atlantic and ice distribution for this region was based on the detailed ice-sheet reconstruction (since the LGM) of Licciardi et al. [32] and compilation of geological observations for the earlier period [33]. Modifications to the preliminary model ice distribution are then made based on comparisons of observations and model predictions.

### *3.2. Sea-level predictions*

Based on the above-described ice melting history and Earth-response function, Fig. 3 illustrates the glacio-isostatic components (due to surface ice loading) that are important in defining relative sea level along the transect shown in Fig. 1 at the time of the peak of MIS-5a. The effects of surface deformation dominate the effects shown in the curves plotted in Fig. 3 but they also include a contribution from the perturbation of the geoid due to internal and surface mass redistribution. For ease of discussion, in the following sections we refer to isostatic deformation, but this also implicitly includes the geoid component. The glacio-isostatic component of sea-level change (or isostatic deformation) at the peak of MIS-5a measured relative to an equilibrium state (curve ii, Fig. 3) does not have a significant gradient across the region of interest. In contrast, the present-day glacio-isostatic component associated with the

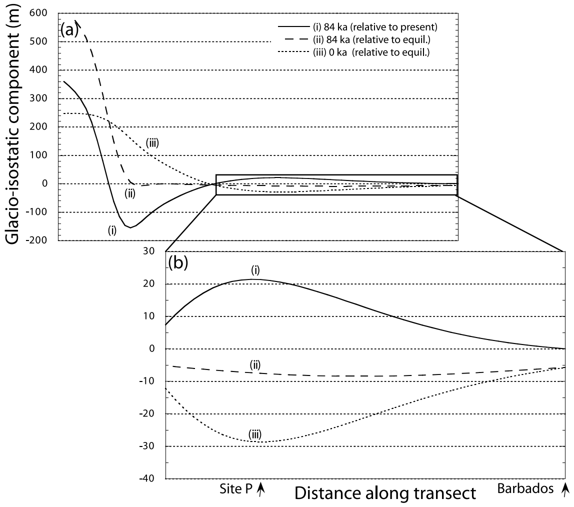


Fig. 3. Glacio-isostatic component of sea-level change for the transect marked in Fig. 1 at (i) MIS-5a relative to equilibrium; (ii) the present day relative to equilibrium; and (iii) MIS-5a relative to the present day. The glacio-isostatic contribution to sea-level change shown here is mainly a measure of surface deformation (but of opposite sign) due to the global and North American ice loads but also includes contributions due to perturbations in the geoid. Part b focuses on the Caribbean region where the change in relative sea level at MIS-5a relative to present is dominated by the present-day residual LGM peripheral bulge.

collapsing LGM peripheral bulge has a gradient of more than 20 m along the transect (curve iii, Fig. 3). It is the difference between these two components that defines the isostatic deformation of the Earth's surface at the peak of MIS-5a relative to the present day (curve i, Fig. 3). Because the isostatic deformation of the Earth at MIS-5a relative to the present day changes along this section, there will be a gradient of increasing MIS-5a relative sea level from the southern to the northern Caribbean, followed by a fall at sites closer to the ice-sheet margin (curve i, Fig. 3). In the future, as the present-day residual glacial bulge collapses further the apparent gradient in MIS-5a relative sea level will decrease and approach the form defined by the MIS-5a component relative to equilibrium (curve ii, Fig. 3).

The situation for MIS-5e peak sea level is not shown explicitly in Fig. 3 but can be explained as follows. If the melting history of the NAIS is broadly similar for both the penultimate and the last deglaciations, then the glacio-isostatic state of the Earth at a time during the last interglacial period, relative to an equilibrium state, will be similar to that for the present day (curve iii, Fig. 3). Therefore the glacio-isostatic deformation during the last interglacial relative to the present day will not display a significant gradient across this region.

### 3.3. Sensitivity analysis

The magnitude of glacio-isostatic deformation and the resulting gradient in MIS-5a sea level is determined by both the Earth response ($E$) and the ice load history ($I$). Fig. 4a,b illustrate the dependence of relative sea level for the Caribbean transect on ice and Earth model parameters for a three-layer mantle model with an elastic lithosphere of 65 km thickness, an upper mantle, of viscosity $\eta_{\mathrm{um}}$, extending to 670 km depth and a lower mantle of viscosity $\eta_{\mathrm{lm}}$ [3,34]. These calculations include both glacio- (ice loading) and hydro-isostatic (water loading) effects.

In the case of the $E$ dependence (Fig. 4a) the viscosities of the upper and lower mantle control the rate of the response and hence the magnitude and location of the peripheral bulge. In the region of interest, the present-day glacio-isostatic deformation of the Earth (curve iii, Fig. 3) is the component that is most sensitive to changes in mantle viscosity. Because the shape of the peripheral bulge evolves as it collapses, the position as well as the magnitude of the present-day bulge relative to the ice-sheet margin is highly sensitive to upper-mantle viscosity. For an increase in upper-mantle viscosity, the Earth's response to the last deglaciation is slower and the present-day peripheral bulge is larger and closer to the ice-sheet margin. This translates into the higher gradient in MIS-5a sea level in the southern Caribbean (compare E5 and E0, Fig. 4a).

The magnitude of the present-day peripheral bulge, and hence the trend in relative sea level at the peak of MIS-5a, is also dependent on the lower-mantle viscosity. An increase in lower-mantle viscosity (compare E3 and E0, Fig. 4a) leads to a larger present-day bulge because the redistribution of lower-mantle material does not respond as

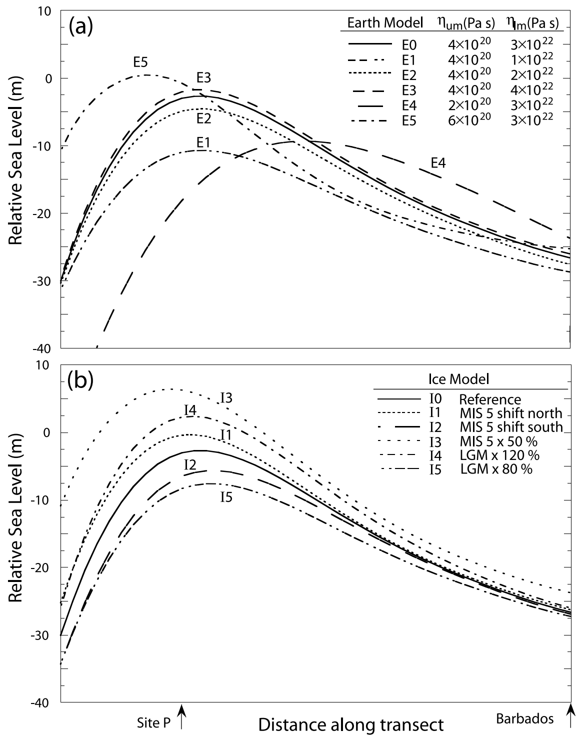


Fig. 4. The dependence of relative sea-level change on Earth and ice model parameters at the peak of MIS-5a relative to present day across the transect marked in Fig. 1. These calculations are for total relative sea-level change and include both glacio-isostatic (ice loading) and hydro-isostatic (water loading) components. (a) Relative sea-level change dependence on upper- (E4–E5) and lower-mantle (E1–E3) viscosities. The viscosities models (E2–E3) represent the range judged as representative for the lower mantle based on previous studies [5,37,44,45]. The comparison of these models with an even lower viscosity for the lower mantle (E1) is shown to demonstrate the sensitivity of this parameter over a larger range. (b) Relative sea-level change dependence on melting history of the NAIS during the period prior to MIS-5a (I1–I3) and during the last deglaciation (I4–I5). Models I1 and I2 represent 2.5° latitude shift of the Laurentide Ice Sheet, north and south respectively, during the period of ice build-up following MIS-5e. I3 represents a scaling of the volume of the Laurentide Ice Sheet during that period relative to the reference model. I4 and I5 represent scaling of the volume of the Laurentide Ice Sheet during the entire deglacial period since the LGM.

rapidly to unloading at the surface. The location of the peak of the collapsing bulge is not particularly sensitive to lower-mantle viscosity. The lower-mantle model alternative with a lower viscosity (E1) demonstrates the sensitivity for this parameter over a larger viscosity range.

In the case of the *I* dependence (Fig. 4b), a change in the volume or distribution of ice within the NAIS during the last glacial cycle is an important factor in determining the Earth's isostatic response. A decrease in the volume of NAIS during the early stadials of the MIS-5 period leading up to MIS-5a results in a smaller surface deformation at MIS-5a relative to equilibrium and hence to a larger gradient in MIS-5a sea level relative to the present (compare I3 and I0, Fig. 4b). The isostatic response is also sensitive to the location of the ice. A northward shift of ice during the MIS-5 stadials, relative to the reference model, also leads to a reduction of the surface deformation in the southern Caribbean and therefore increases the gradient of MIS-5a relative sea level in that region (compare I1 and I0, Fig. 4b).

The ice melting history of the NAIS during the last deglaciation controls the present-day deformation of the Earth and hence the apparent relative sea level of past events. Because a reduction of LGM ice volume leads to a decrease in the present-day surface deformation, the resulting gradient in MIS-5a sea level across the southern Caribbean is also reduced (compare I5 and I0, Fig. 4b). This contrasts with the effect of reducing the MIS-5 stadial volume discussed above.

### 3.4. Constraining model parameters

Fig. 5 shows a comparison of peak MIS-5a sea-level observations with a band of model predictions (including both glacio- and hydro-isostatic components) for a preferred NAIS ice melting history for MIS-5 and since the LGM (described below) and range Earth models judged as appropriate for this region. The aim of this comparison is to demonstrate that for realistic ice and Earth models the observed gradient of MIS-5a sea-level observations in the Western North Atlantic can be easily reproduced. Due to the complexity of the dependence of MIS-5a sea level on these parameters the model predictions presented here are not unique, however the very high gradient observed allows a number of broad constraints to be made.

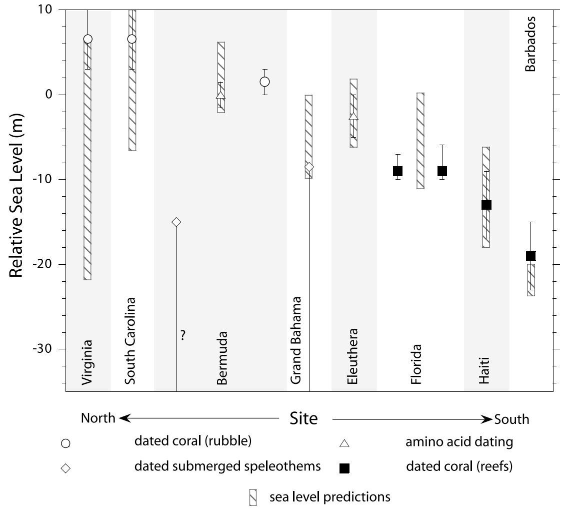


Fig. 5. Comparison of MIS-5a observed and predicted sea levels. These calculations include both the glacio- and hydro-isostatic components. The bars represent the predicted sea levels, for the preferred ice model using a range of Earth model alternatives judged as appropriate for this region. There is excellent agreement between the observations and model predictions. To reproduce the large MIS-5a sea-level gradient required: (i) a small, northerly located NAIS during the early phase of MIS-5 ice-sheet development, (ii) a large LGM ice volume and (iii) a high lower-mantle viscosity. A single best-fit model is not given here because of the large effects of the laterally variable upper-mantle viscosity. The best fit for the northernmost sites is achieved with a high upper-mantle viscosity.

The best agreement of observed and predicted relative sea levels for these sites (Fig. 5) is achieved with a small, northerly situated MIS-5 NAIS. As shown in Fig. 4b, both a reduction in the ice volume and a shift of the ice northwards act to increase the gradient of MIS-5a sea level in the southern Caribbean region relative to the reference model. Furthermore, these ice-model changes also shift the location of peak sea level (defined by site P in the reference model in Fig. 4) further north, which is required by the high sea levels observed at the US Atlantic Coast sites. This MIS-5 ice-sheet scenario is consistent with the independent, but limited geological observations and dynamical models that indicate that the NAIS was initiated in the north, over Keewatin, Quebec and Baffin Island [33] and did not advance southwards across the St Lawrence Lowlands and into the Great Lakes region until during and after the MIS-5/4 transition [33]. Furthermore, this result confirms the suggestion of dynamical ice models that during the entire MIS-5d–5a period the contribution of the Laurentide Ice Sheet to global ice volume never exceeded 15 m of sea level [35].

Changing only the MIS-5a ice-sheet history cannot easily reproduce the very high gradient in MIS-5a sea level. An increase in the volume of the NAIS during the last deglaciation also leads to an increase in the predicted gradient in sea level across the region of interest (demonstrated in Fig. 4). The comparison of observations with model predictions points towards a larger LGM volume of the Laurentide Ice Sheet than suggested by recent dynamical ice models [32]. In the model used for the calculations shown in Figs. 5–7, the ice volume for the NAIS at the

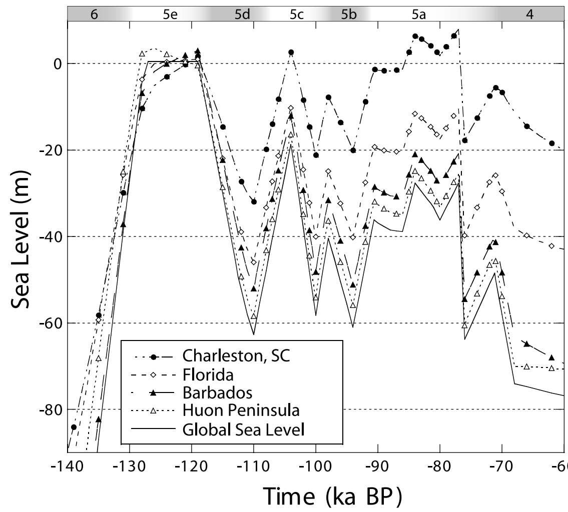


Fig. 6. MIS-5 ice-equivalent sea-level model and Caribbean relative sea-level predictions. These calculations are for a preferred ice history (discussed in text) and reference Earth model, E0 (from Fig. 4a), and include both the glacio- and hydro-isostatic components. The preferred global sea-level curve has been modified from reference [4] based on comparison of model predictions and global observations. Note that there is a greater variation of predicted relative sea levels across the region for the MIS-5a highstand than for MIS-5c, with 5a levels higher than 5c at Charleston, and the reverse at Barbados, consistent with the observational evidence. Note also that the predicted relative sea levels for the younger MIS-5a event are slightly higher than the earlier MIS-5a event at the northern sites [21], consistent with the suggestion of a complex MIS-5a highstand [8].

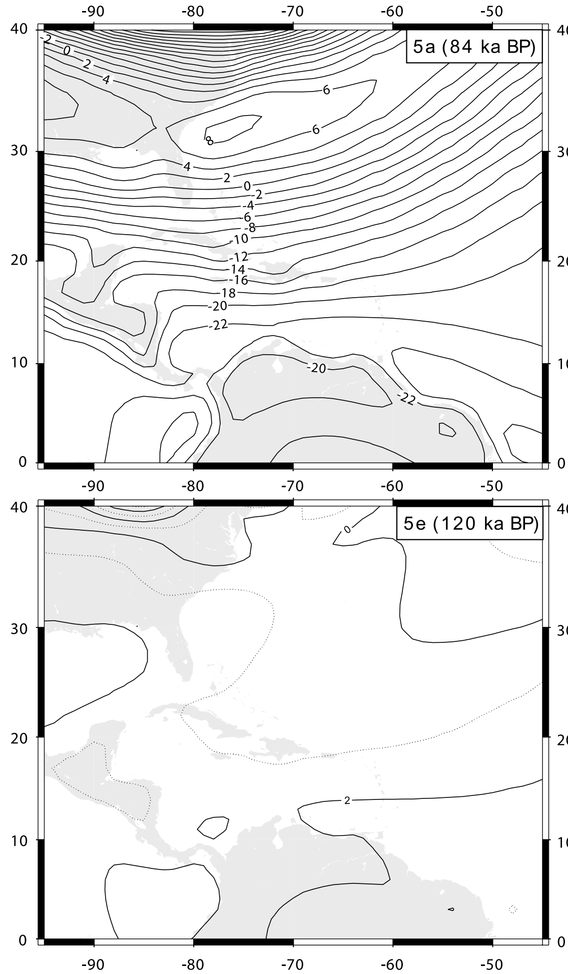


Fig. 7. Spatial variability of MIS-5a and 5e relative sea levels across the Caribbean and West Atlantic region for the preferred ice/Earth model including both the glacio- and hydro-isostatic components. There is a significant gradient in MIS-5a relative sea level across the region of interest that results from the differences in the glacio-isostatic state of the Earth at that time relative to the present day (Fig. 3). In the case of the MIS-5e sea level, the melting history leading up to that time is broadly similar to that of the last deglaciation, producing a glacio-isostatic state of the Earth that was similar to that of the present day and hence very little gradient in the MIS-5e relative sea level.

LGM is scaled by a factor of $\sim$1.3 (compared to [32]) however, this value remains well within previous estimates for a hard-bedded ice sheet [36].

The preferred Earth rheological model arising from the comparison is one with a high lower-mantle viscosity ($\sim 2$–$4\times10^{22}$ Pa s), which produces a larger gradient in sea level across the Caribbean region (Fig. 4a). This is consistent with the constraints placed on lower-mantle viscosity during previous studies of post-glacial sea-level rise [5,37,38]. The preferred value for upper-mantle viscosity is spatially variable with observations closest to the ice-sheet margin requiring a high upper-mantle viscosity ($\sim 6\times10^{20}$ Pa s) while observations at southern Caribbean sites may be more consistent with a lower upper-mantle viscosity ($\sim 2\times10^{20}$ Pa s). This agrees with independent isostatic studies of post-LGM sea-level analyses [5] and is consistent with observations of laterally variable seismic velocity across the North American–Caribbean region that imply a similar behaviour in the viscosity of the upper mantle [39]. The glacial rebound models are not yet at a stage of development where realistic lateral variability can be introduced and hence the analyses are restricted at this time to subsets of the data beneath which the upper-mantle properties can be considered to be laterally constant.

Coral ages from the MIS-5a deposits at the most northerly situated US Atlantic Coast site [20–22] are several thousand years younger than the classic MIS-5a event ($\sim$84 ka BP) and appear to correspond better to the younger MIS-5a feature identified at Barbados ($\sim$77 ka BP) with a similar sea level as the principal event [8]. This implies that at these northern sites the sea-level excursion for the younger MIS-5a feature may have reached a higher level and therefore overprinted the earlier event. Indeed, the models predict a small late highstand for an extended MIS-5a event at the northernmost sites (Fig. 6) and the younger ages in the north are consistent with a more complex structure of sea-level change during MIS-5a than a single short-lived peak [8,9].

At Barbados MIS-5c sea level (c. $-15$ m) was somewhat higher than during MIS-5a (c. $-18$ m) [8], but evidence of MIS-5c shorelines is absent at other sites in the northern Caribbean suggesting that the MIS-5a sea level overprinted MIS-5c at those tectonically stable locations. To produce a smaller gradient in MIS-5c sea level (relative to present day) than for MIS-5a requires a larger gradient in isostatic deformation for the MIS-5c event (relative to equilibrium). This can be achieved with a more rapid deglaciation during the MIS-5d to 5c transition than during the MIS-5b to 5a transition [4,13] leading to a less complete relaxation of the Earth during MIS-5c (Fig. 6).

The evidence of MIS-5e shorelines from tectonically stable sites across the region of interest does not exhibit any gradient in peak sea levels (Fig. 2) [11,17,19,23,24]. This indicates that the isostatic state of the Earth at that time, relative to an equilibrium state, was similar to that of the present day and hence that the melting history of the NAIS during the penultimate glacial maximum and subsequent deglaciation was broadly similar to that since the LGM. Calculations of relative sea level in this region for the end of the last interglacial period (MIS-5e) and MIS-5a are shown in a contour plot in Fig. 7 and they clearly illustrate the difference in the gradients for the two epochs, consistent with the observational evidence. In this model, the penultimate glacial maximum has a similar ice distribution to the LGM. The details of the last interglacial sea-level highstand are highly dependent on the melting history during the penultimate deglaciation and a more thorough comparison of MIS-5e sea-level observations and model predictions is beyond the scope of this study.

Sea-level observations from other time periods such as MIS-3 [40,41] and beyond the last interglacial period [42] show similar discrepancies to that observed for the MIS-5a highstand. For example, evidence of MIS-3 sea level at locations far from the ice-sheet margin, such as Huon Peninsula, indicates sea level reached a maximum of −60 m [43]. In contrast, stratigraphic studies of submerged deposits on the US Atlantic Coast and the Texas inner continental shelf imply that MIS-3 sea level reached as high as 20 m at these locations [40,41]. Such observations have the potential to place further constraints on the distribution of ice during the last interglacial–glacial cycle.

## 4. Summary

Glacio-hydro-isostasy has previously been dismissed as a possible reason for the gradient in MIS-5a sea level based on the argument that the same gradient is not observed for MIS-5e deposits [18]. However, as we have shown here, the trend in MIS-5a Caribbean sea levels is explained by the effects of glacio-hydro-isostasy and is also consistent with observed absence of a MIS-5e shoreline gradient. This behaviour is due to the fact that sea level is measured relative to present day and the present-day Earth is not in an equilibrium isostatic state. In fact, a major component of the MIS-5a sea-level gradient is due to the present-day collapsing glacial bulge produced by the LGM ice sheet. Because of the importance of the present-day isostatic deformation of the Earth, the sea-level observations of past events can be used to place constraints on recent ice melting history, i.e. since the LGM. This study highlights the importance of including isostatic effects in the interpretation of relative sea-level observations and when comparing sea-level data from different locations. With a spatially and temporally well-distributed data set both the total ice volume and its distribution through time can be constrained.

Only with the combination of a number of ice and Earth model parameter changes can the high gradient in MIS-5a sea level across the Western North Atlantic be reproduced. While the model predictions presented here are not unique, the observed differences in sea level across the Caribbean region provide important constraints on the behaviour of the North American ice sheets during the last glacial cycle. Firstly, the observations are consistent with a complex MIS-5a highstand during which ice-equivalent sea level reached ∼28 m below present. Secondly, MIS-5c and 5a had a similar global ice volume but the transition to the MIS-5c interstadial occurred more rapidly. Thirdly, following the last interglacial period the initiation of ice growth in the NAIS occurred in the north. Finally, the observations imply both an LGM ice volume that was larger than that indicated by recent dynamical ice models and also that North American ice volume and distribution were similar during both the last and penultimate glacial maxima.

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