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ICE-5G and ICE-6G models of postglacial relative sea-level history applied to the Holocene coral reef record of northeastern St Croix, U.S.V.I.: investigating the influence of rotational feedback on GIA processes at tropical latitudes

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ABSTRACT

Fossil coral reefs along the northeastern coast of St Croix in the Caribbean Sea provide an 8000 year record of dated and interpreted Holocene sea-level change. We herein compare this record with the predictions of models of glacio-hydro-isostatic adjustment for St Croix and for additional sites at similar latitudes in the Greater and Lesser Antilles region. RSL predictions are based upon the model ICE-5G (VM2), and with a modified model ICE-6G (VM5A), both including and excluding the influence of rotational feedback. Misfits between the modeled sea levels and the local geologic data are most apparent for models without rotational feedback, particularly in the prediction of a +2 to +4 m unsupported mid-Holocene misfit at ~4 ka, as well as a small-amplitude highstand that extends from 2.5 to 1.5 ka. Incorporation of the influence of rotational feedback provides the best fit to the data, largely eliminating the unsupported mid-Holocene misfit between the data field and the sea-level histories predicted by the models without rotational feedback, and fitting data older than 5 kyr more closely than a previously published latitudinally-averaged sea-level curve for the western Atlantic. The St Croix data therefore demonstrate that rotational influence extends at least 27° further south from its 45° N mid-latitude extremum along the US east coast, and identifies tropical latitudes as influenced by proglacial forebulge collapse. Implications for reef-based sea-level reconstruction include the ability to accurately model sea levels at specific tropical sites with partial Holocene chronologies using the ICE-6G (VM5A) model with rotational feedback. Latitudinally-averaged sea-level curves are therefore of limited use in understanding the relative importance of contributing physical influences on postglacial sea-level history.

1. Introduction

1.1. GIA modeled relative sea-level predictions and the latitudinal extent of rotational feedback

Even the earliest form of the modern theory of postglacial relative sea-level (RSL) (Peltier, 1974, 1976; Farrell and Clark, 1976; Peltier and Andrews, 1976; Clark et al., 1978; Peltier et al., 1978) demonstrated that the history of RSL change at any location on Earth's surface could be accurately predicted by solving an integral equation referred to as the "Sea Level Equation (SLE)". These analyses demonstrated that initially enigmatic observations of mid-Holocene highstands of the sea on islands in the equatorial Pacific Ocean were explained as a consequence of the gravitational interaction that ensues when massive accumulations of land ice collapse, releasing meltwater into the global ocean. The influence of self-gravitation causes the meltwater to be attracted back towards the poles to ensure that the equilibrium surface of the oceans is at all times constrained to lie on a gravitational equipotential. Although fully embodied in these original analyses the effect was termed "ocean siphoning" in a later analysis in Mitrovica and Peltier (1991) which employed a spherical harmonics based methodology to solve the SLE rather than the original grid point method of Peltier et al. (1978) but which delivered essentially identical results.

The formal theory of glacial isostatic adjustment (GIA) was further refined in Peltier (1982) and Wu and Peltier (1984), who developed methods to accurately predict the impact upon Earth's rotational state of the quasi-periodic 100,000 year Late Quaternary ice-age cycle. Peltier (1994) thereafter described an accurate

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method for prediction of the evolution of continental topography and oceanic bathymetry caused by ice-sheet loading and unloading. The complete theory was applied in Peltier (1996) in the context of a formal Bayesian inversion of the available constraints on the GIA process to infer a spherically-symmetric model of the radial visco-elastic structure of the planetary interior called VM2. The validity of this model of the radial visco-elastic structure has been independently verified by Paulson et al. (2007), who augmented the data set employed in Peltier (1996) with gravity field time dependence observations from the Gravity Recovery and Climate Experiment (GRACE). Their analyses have provided an independent test of the validity of the most recent ICE-5G (VM2) model of Peltier (2004).

The methodology that has been developed to describe the GIA process in the Physics Department at Toronto has led to the creation of a new industry in the geophysical sciences that has now entrained a very large number of scientists who have developed their own extensions of the enterprise. Some of these efforts are the product of former students in the Toronto Laboratory (e.g. Wu, 1992; Wolf, 1993; Mitrovica and Milne, 2003; Milne et al., 2001) and others are independent efforts by groups that began their work at Toronto but have developed programs at other institutions (e.g. Sabadini and Gasperini, 1989) or which were entirely independent from the start (e.g. Lambeck, 1993, 1997; Spada, 2003) but whose work is based upon reproductions of the Toronto theoretical structure. This international enterprise continues to deliver new insights into both the physics of the planetary interior and into ice-age climate related processes.

The present paper involves an application of the theoretical structure to the understanding of observational data from an especially important region. As in Horton et al.'s (2009) analyses of data from the east coast of the United States and in the follow-on paper on the same region by Engelhart et al. (2011), we address the importance of the process of "rotational feedback" on sea-level history. By this term is meant the influence on sea-level history of the change in Earth's rotational state that accompanies the isostatic adjustment process. Initial analyses by Milne and Mitrovica (1996) and Peltier (1998), based on Peltier (1982) and Wu and Peltier (1984) for the GIA induced changes in rotation, suggested that this influence was negligible. Peltier's (2002) analysis, using RSL data from the eastern passive continental margin of South America compiled by Rostami et al. (2000), demonstrated that this was not in fact the case. Those data strongly suggested the action of a process causing a mid-Holocene highstand along this coast that increased in elevation relative to present sea level with increasing latitude towards the south. Incorporation of the influence of rotational feedback in the ICE-4G (VM2) model of Peltier (1996) produced the effect on RSL history needed to fit these highstand observations. Further analyses in Peltier (2007) and Peltier and Luthcke (2009) including data from additional regions wherein the effect is expected to be significant, demonstrated that in each case, even where the nature of the impact was opposite to that along the coast of South America, the influence of rotational feedback was found to be critical to the explanation of the data.

There are four regions on Earth's surface where the influence is predicted to be strong, corresponding to the four extrema of a spherical harmonic of degree two and order one. Based on the analysis of Dahlen (1976) this is the expected geometry of the impact on Earth's gravitational potential field of the influence of polar wander. Fig. 1 shows the predicted pattern of the present day rate of relative sea-level rise for the ICE-6G (VM5A) global model of the isostatic adjustment process. The uppermost plate of the figure shows the result including rotational feedback, the middle plate shows the result for the time rate of change of radial displacement and the bottom plate shows the time rate of change of geoid height which is the sum of the fields in the upper and middle plates. Of interest in this paper is the extremum due to the influence of rotational feedback that exists at ~45° north latitude along the US east coast. The magnitude of the impact of this extremum in the predicted present day time dependence of geoid height on RSL history itself is explicitly discussed in Engelhart et al. (2011).

As pointed out in Peltier (2002) and Horton et al. (2009), interpretation of the importance of the rotational feedback component of the predicted sea-level history along this coast is complicated by the dominant influence on sea-level records of proximity to the region once covered by the Laurentide ice sheet. Although some evidence was provided that the feedback effect was also needed in this region, the results were not unequivocal. We attack this issue in the present paper from the perspective of the coral record from the island of St Croix as a means of investigating the southwards extent of rotational influence in the Caribbean Sea which is well beyond the latitude of the extremum of the expected impact. Since all of the GIA models have been primarily constrained, insofar as the total mass of land-ice that must have melted across the glacial–interglacial transition is concerned, by the Barbados data set which is proximate to St Croix (Fig. 2), we will compare the two Caribbean records to differentiate between equally plausible tunings of the GIA models, and to further investigate the importance of rotational feedback to the understanding of records of RSL history. This will turn out to be extremely useful because the 5 m error bar on the *Acropora palmata* species of coral, which provide the best constraints on sea level, allow for a range of equally plausible variations in the mass loss history from the Late Pleistocene ice-sheets.

1.2. Sea-level reconstruction from coral reef data

Reconstructing local RSL histories from deposits of the reef crest coral *Acropora palmata* has yielded insights into sources, rates and significant events defining the last deglaciation (Lighty et al., 1982; Fairbanks, 1989; Guilderson et al., 1994; Toscano and Lundberg, 1998; Peltier and Fairbanks, 2006) and provided essential data for testing and refining GIA model predictions of sea-level history. Until recently, geologic sea-level reconstructions have routinely been attempted using core and outcrop data combined with careful paleoenvironmental interpretations of the relationships of sea-level indicators such as coral and peat. Most such reconstructions were realized without the perspective provided by GIA modeling or the opportunity to combine the two knowledge bases to achieve comprehensively-determined, site-specific sea-level curves.

For example, geologic RSL reconstruction in the Caribbean has been based on cored and dated *A. palmata* with interpreted depth ranges for in situ samples from −2 m MSL (based on the living range of *A. palmata* forming coral framework at the reef crest) to −5 m MSL (based on the living maximum depth range for *A. palmata* growing along the fore-reef slope and reef spurs; Lighty et al., 1982; Fairbanks, 1989; Peltier and Fairbanks, 2006; Macintyre et al., 2008). The sample sites employed for the purpose of the Lighty et al. (1982) compilation spanned, of necessity, a latitudinal range that provided the time and depth coverage needed to fully reconstruct the past 9 kyr of the Holocene epoch. Sites included the western Caribbean (Panama; 9.4°), the Lesser Antilles (Martinique; 14.6°; Antigua; 17.08°), the Greater Antilles (Puerto Rico; 18.2°) and the Florida-Bahamas platforms (24°–27°). A 5 m positive vertical error was assigned to each sample in Lighty et al. (1982) to account for the maximum probable depth range for reef framework growth. This dataset also extended the seminal Barbados deglacial sea-level curve of Fairbanks (1989) from 10 ka to ~300 yr BP. Whereas the Barbados sea-level record is considered to be a good approximation to eustatic sea-level history itself (Peltier, 2002) due to its location well to the south of the region of most intense "forebulge collapse"

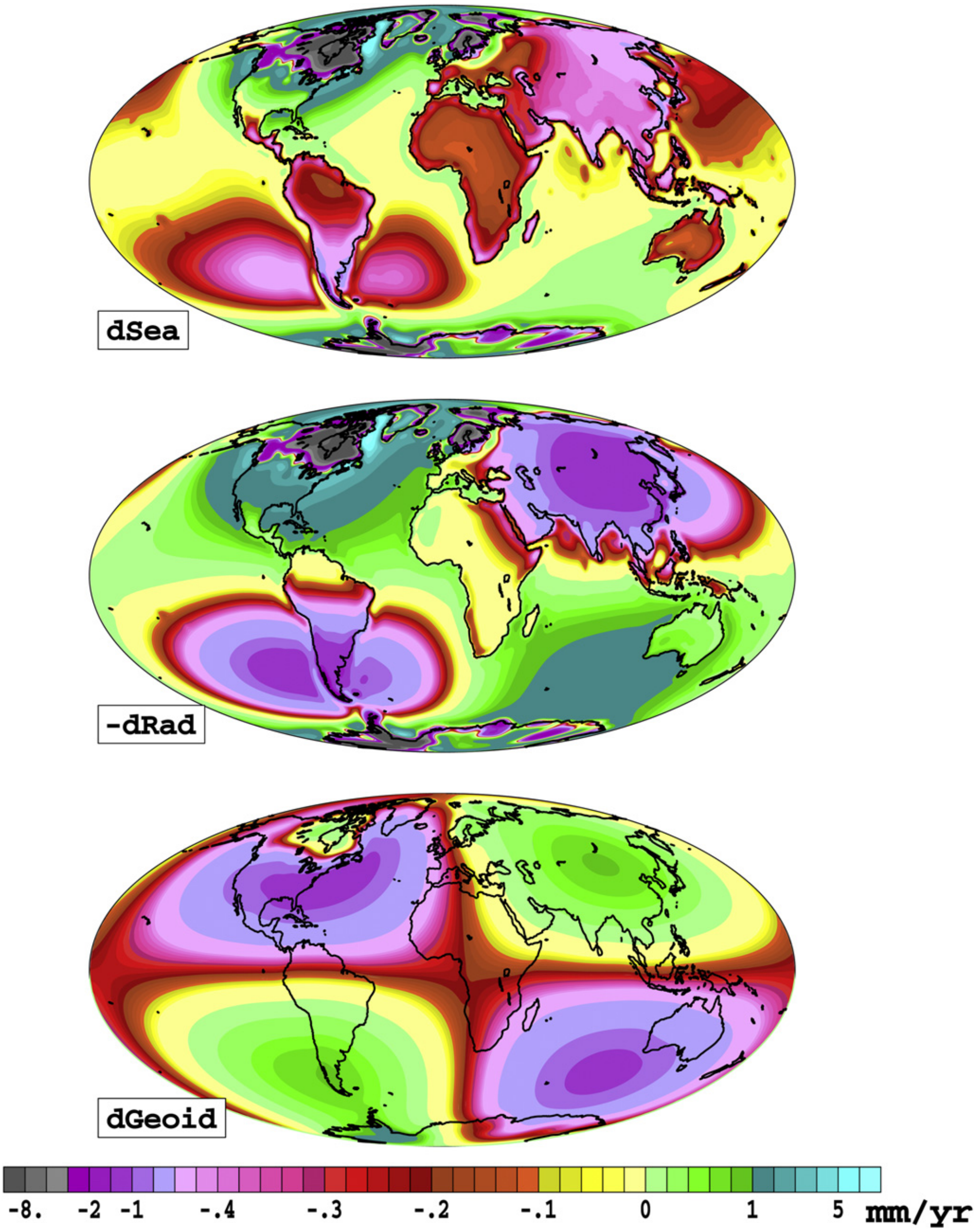

Fig. 1. Predicted patterns of several global fields for the ICE-6G (VM5A) model of the isostatic adjustment process. Top – the result for the time rate of change of relative sea level (dSea), including rotational feedback; Middle – the result for the time rate of change of radial displacement (dRad); Bottom – the time rate of change of geoid height (dGeoid) which is the sum of the fields in the top and middle panels of the figure, for the model ICE-6G (VM5A). Notable is the strong overprint of the degree two and order one pattern on the geoid height field due to the action of the influence of polar wander. The nomenclature dSea, dRad and dGeoid is used to denote the time derivative ("d") of the particular space dependent field (Sea = relative sea level, Rad = radial displacement, geoid = geoid height).

(Peltier and Fairbanks, 2006), the other Caribbean sites are expected to be influenced by latitudinal GIA differences (Lambeck et al., 2002), suggesting that a regional sea-level synthesis is inherently inaccurate for application to each site separately. Toscano and Macintyre (2003) acknowledged this issue but lacked the model predictions and sufficient data for each site that would be required to address GIA differences between them. They nevertheless expanded and calibrated Lighty et al.'s (1982) coral database, adding a regional compilation of dated intertidal mangrove peat which may form close to sea level within a small elevation range (15–20 cm MSL; Woodroffe, 1995) and the microtidal range (20–60 cm) typical at these localities (McKee et al., 2007). The mangrove peat data were intended to provide an upper constraint to the sea-level estimate that could be invoked to decrease the 5 m coral depth uncertainty in the original Lighty et al. (1982) curve. Toscano and Macintyre (2003) also noted that the peat database was inconsistent and variable, requiring further sampling with greater elevation control, dating precision and paleoenvironmental interpretation to decrease the spread of the data field. The latitudinally-averaged western Atlantic sea-level (WASL) curve was accordingly based upon the shallowest coral data that were interpreted to represent the most reliable sea-level indicators.

Coral data from several St. Croix reef sites combine to provide comprehensive temporal (~8 kyr) and spatial (~15 m elevation) coverage of Holocene reef development that will allow meaningful comparison of geologic sea-level reconstructions to GIA model curves. There is no peat database for St. Croix. Numerous dated coral samples from northern St Croix (Burke et al., 1989; Macintyre

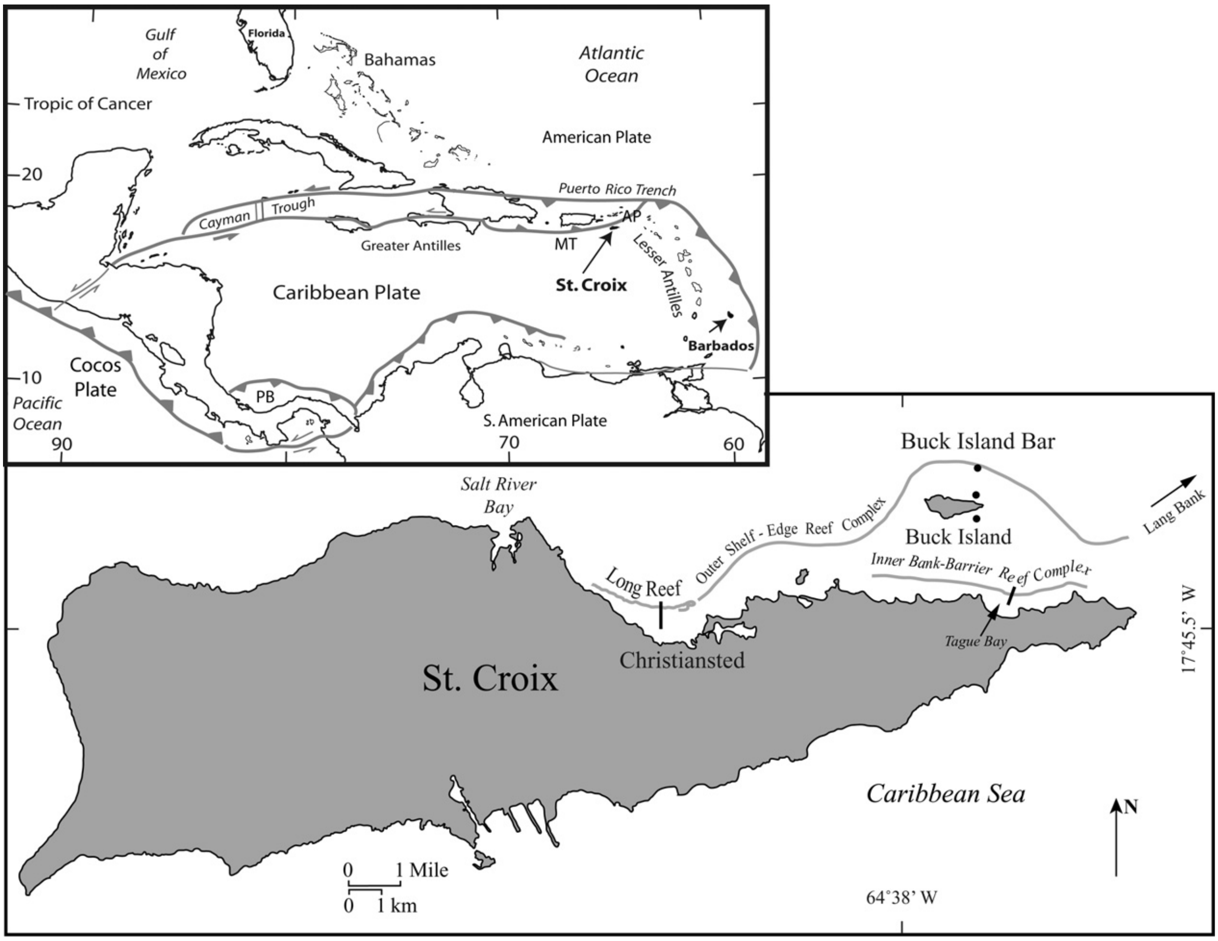

Fig. 2. Caribbean tectonic regional map (top) indicating boundaries of the Caribbean, North American, South American, and Cocos Plates, the Muertos Trough (MT), Cayman Trough, Puerto Rico Trench and the Anegada Passage (AP) (after Masson and Scanlon, 1991; Speed, 1989; Dolan et al., 1998; van Gestel et al., 1998; Jansma et al., 2000; Mann et al., 2002). The location of Barbados (on the accretionary wedge eastward of the lesser Antilles subduction zone) is shown relative to St Croix (a stable platform on the interior of the Caribbean plate) for spatial reference to the comparison between the St Croix model results and those for Barbados. The lower St. Croix map indicates sampled areas including the *Outer Shelf-Edge Reef Complex*, including the western end of Lang Bank, Buck Island/Buck Island Bar and its western terminus at Long Reef. The *Inner Bank-Barrier Reef* includes Tague Reef in Tague Bay as well as reefs to the west and to the east in Boiler Bay. Core transects are indicated by shore-perpendicular lines and single core locations by circles. After Macintyre et al. (2008).

and Adey, 1990; Hubbard et al., 2005; Macintyre et al., 2008; Fig. 3A–D), while in apparent agreement with the WASL curve (Toscano and McIntyre, 2003) provide a site-specific basis for testing GIA model curves with and without rotational feedback. These models additionally incorporate other geophysical factors which may also influence RSL history at this locality such as that associated with the complexity of the land-sea distribution.

1.3. Reconciliation of geologic data and modeled sea-level reconstructions

Coral-based reconstructions for St. Croix will be compared in this paper to predicted RSL histories from the ICE-5G (VM2) model (Peltier, 2004) and the modification of this model which we refer to here as ICE-6G (VM5A). The most significant difference between the ICE-6G (VM5A) model and its precursor ICE-5G (VM2) is that the loading history over North America has been adjusted to eliminate misfits to space geodetic data that have recently been identified in Argus and Peltier (2010). The VM5A radial visco-elastic structure also differs from VM2 in that it is a 5-layer approximation to the highly variable VM2 structure in which the lithospheric layer consists of a 60 km thick elastic component underlain by a 40 km thick layer with a viscosity of 10^{22} Pa s rather than the 90 km thick elastic layer that describes the lithosphere in VM2. The case study at St. Croix suggests that differential development of Holocene reefs in response to post-glacial sea-level rise was dependent on variations in geologic and oceanographic factors (sea-level rise, antecedent topography, and response of individual species to environmental conditions) along the northeast coast (Hubbard et al., 2005; Macintyre et al., 2008). The Caribbean Holocene sea-level reconstruction (WASL curve; Toscano and Macintyre, 2003) provided the initial context for the study of environmental changes and the relationship of sea level and antecedent topography to Holocene reef development in St. Croix (Macintyre et al., 2008). This comprehensive synthesis of multiple reef histories is compared to both the ICE-5G (VM2) and ICE-6G (VM5A) models, with and without rotational feedback, to determine the most accurate Holocene sea-level curve for northeastern St. Croix. As we will show, the differences between the latitudinally-averaged western Atlantic sea-level curve and the records at both St Croix and Barbados are highly significant.

2. Regional setting

2.1. Regional geology of St Croix

The extensional Virgin Islands Basin and adjacent basins form a structurally complex region southeast of Puerto Rico, extending northeast through the Anegada Passage to intersect with the Lesser

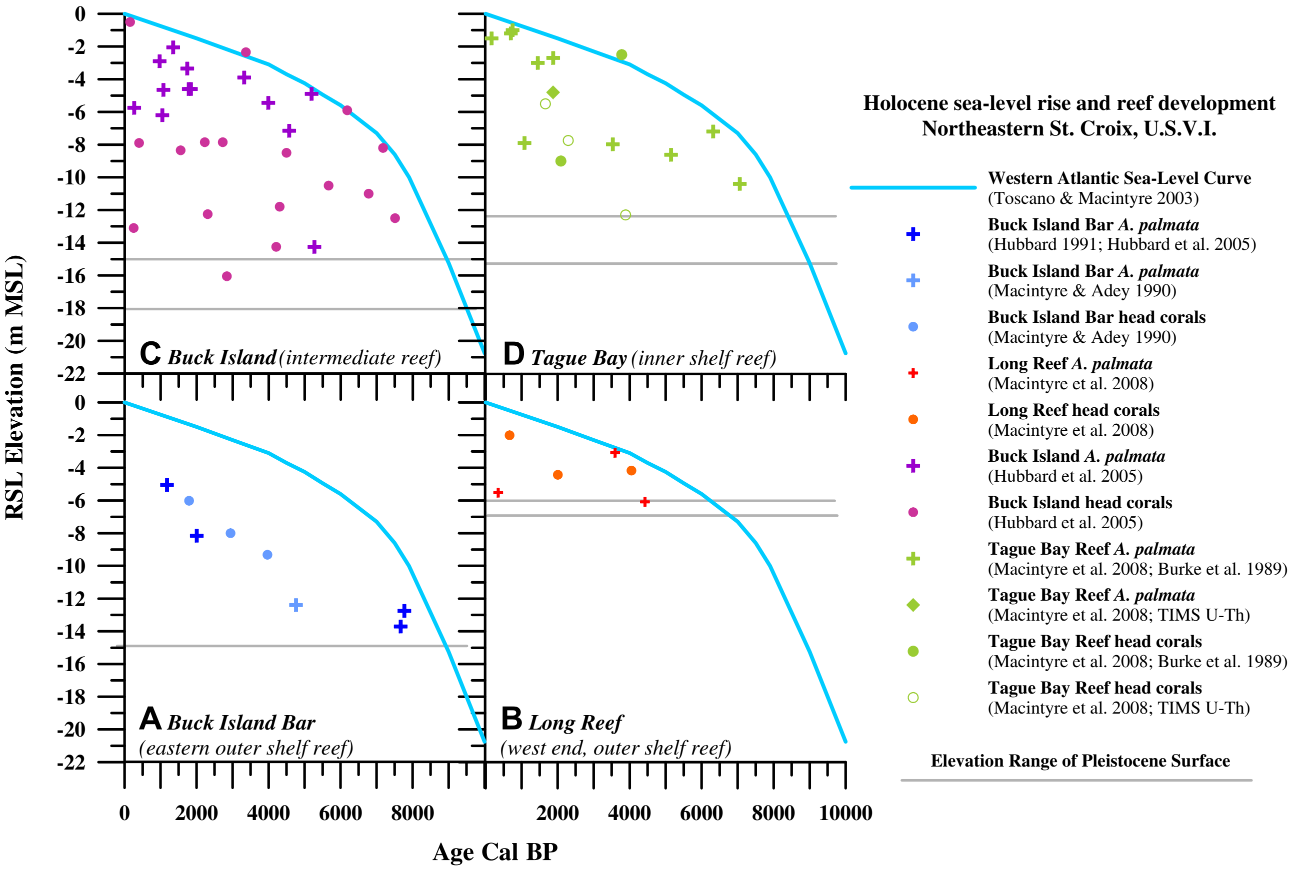

Fig. 3. Geologically-based sea-level reconstruction for northeastern St Croix from radiocarbon- and TIMS- dated coral samples (*A. palmata* and head corals) plotted relative to the WASL curve (Macintyre et al., 2008), documenting east-west shallowing of the antecedent surface underlying the outer shelf complex and the offshore-onshore shallowing of this surface from Buck Island to Tague Reef. Coral data are plotted at sampled depths. Available coral data record the stages of development of each site and the accretion style of these reefs in response to sea-level rise. A. Buck Island Bar (easternmost *Outer Shelf-Edge Reef Complex*); dated samples indicate this reef never attained typical shallow reef crest depths, remaining 4–5 m below MSL for 7700 yr (Macintyre and Adey, 1990; Macintyre et al., 2008). B. Long Reef (western terminus of *Outer Shelf-Edge Reef Complex*); maximum 4.5 m accumulation (since ~4500 cal BP) of Holocene reef above the highest point of the Pleistocene surface at −6 m MSL. C. Buck Island (intermediate between outer and inner reef trends); initiated ~ 7500 cal BP on a −15 to −18 m Pleistocene surface dominated by a head coral facies contemporaneous with shallower reef crest *A. palmata* until ~5000 cal BP. D. Tague Reef (*Inner Bank-Barrier Reef*); optimum development of 10 m of Holocene reef framework on the eastward dipping, deeper Pleistocene limestone substrate (−12 m MSL vs −6 m MSL at Long Reef) began ~7030 cal BP, after Buck Island Bar (at −15 to −16 m MSL). Data suggest a hiatus in *A. palmata* framework from ~6500 cal BP to ~2000 cal BP at Tague Reef (Macintyre et al., 2008).

Antilles compressional zone (Anegada Fault; Jolly et al., 2008). A complex zone of NW-SE trending faults occurs northeast of St. Croix (Masson and Scanlon, 1991). North-easterly trending extensional faults occur on the Virgin Islands Shelf (Donnelly, 1966) and in St. Croix (post-Oligocene; Whetten, 1966).

In numerous papers on the tectonic history and fragmentation of the Greater/Lesser Antilles region, little has been stated about St. Croix, which lies 56 km to the south of the other (US and British) Virgin Islands. St Croix is predominantly composed of meta-sedimentary and volcaniclastic rocks, and is geologically more similar to Puerto Rico, Cuba, and Hispaniola than to the volcanic Lesser Antillean islands along the collision zone between the North American and Caribbean plates (Holmes and Kindinger, 1985). Barbados, which lies outside the volcanic island arc on the active accretionary prism over the subduction zone (Westbrook et al., 1988; Fig. 2), has a coral cap which has been uplifted at a rate of ~34 mm/yr (Fairbanks, 1989; Peltier and Fairbanks, 2006). Case et al. (1984) categorized St. Croix and its platform as one of several moderately to strongly deformed basins of the Anegada Province. The island has a complex structural and tectonic geologic history, with units segmented by major fault zones as part of a deformed collisional plate boundary with "initial compression followed by transcurrent tectonics and extension" (Whetten, 1966, 1974; Ratte, 1974; Holmes and Kindinger, 1985; Stanley, 1987a,b, 1988, 1989; Nagle and Hubbard, 1989; Speed, 1989; Dolan et al., 1998). The St Croix platform, as part of the rigid interior of the Caribbean Plate, is moving east-northeast at 19–20 mm/year relative to the North American Plate (via GPS measurements; Jansma et al., 2000; Mann et al., 2002). Jansma et al. (2000) indicated that there has been little displacement and hence little lateral velocity difference (<2 mm/yr) across and along the Anegada passage between Virgin Gorda to the north and St Croix to the south. Independent geophysical evidence of Holocene vertical displacement (either gradual or sudden) has not yet been determined for St Croix (van Gestel et al., 1998); hence St. Croix sample elevations are not tectonically corrected. Even if the vertical motion of St. Croix were as strong as that at Barbados of ~0.34 mm yr^{-1}, the maximum displacement during the Holocene would be less than 0.34 m. The misfit between models that do not contain rotational feedback and the coral data at 4 ka is almost an order of magnitude greater than this. This misfit is eliminated by the incorporation of rotational feedback.

2.2. Holocene reef histories, northeastern St. Croix

Two separate linear reef trends document reef development around the northeastern end of St Croix (Adey et al., 1977; Burke et al., 1989; Macintyre and Adey, 1990; Hubbard, 1991; Hubbard

Table 1
Twenty-seven ^{14}C and one TIMS U-Th dated *A. palmata* samples from Holocene sections of the reefs of northeastern St Croix (Macintyre et al., 2008; 1-Macintyre et al., 2008; 2-Burke et al., 1989; 3-Hubbard et al., 2005). Localities (Fig. 2) include those of the *Outer Shelf-Edge Reef complex* - Buck Island Bar, Long Reef, Buck Island; and those of the *Inner Bank-Barrier Reef complex* – (Tague Bay, Tague Reef, Sand Cay Reef, and Sand Cay Candlelight Reef). ^{14}C dates (provided as reported in the source references) from all locations except Buck Island were originally reported as standard radiocarbon ages which required conversion to conventional ages (see text). Dates from Buck Island were originally reported as conventional radiocarbon ages (Hubbard et al., 2005). Calibrated age ranges were calculated from the conventional ages using Calib 5.1 (see text) and are the age ranges plotted on Figs. 4–6. A 5 m maximum positive depth error has been applied to all samples (as a vertical bar) on Figs. 4–6.

Sample ID	Site Name (reference)	Sampled Depth (m MSL)	Maximum Depth Error (m)	^{14}C Date	Error	Conventional Age (yr BP)	Age Error	cal BP 2σ range or TIMS U-Th ◇
BB1-23	Buck Island Bar[3]	−12.75	5	6950	80	7360	80	7649–7973
BB1-26	Buck Island Bar[3]	−13.7	5	6860	90	7270	90	7568–7917
LR H4 C1	Long Reef[2]	−5.52	5	270	50	677	50	226–456
LR H4 C2	Long Reef[2]	−6.08	5	3890	70	4297	70	4181–4623
LR H2 C2	Long Reef[2]	−3.08	5	3250	120	3657	120	3285–3878
BI4-14	Buck Island[3]	−4.9	5	–	–	4860	70	4897–5324
BI1-24	Buck Island[3]	−7.15	5	–	–	4440	100	4340–4846
BI1-13	Buck Island[3]	−5.45	5	–	–	4010	80	3798–4274
BI1-02	Buck Island[3]	−3.90	5	–	–	3440	70	3104–3482
BI2-05	Buck Island[3]	−4.6	5	–	–	2250	80	1634–2059
BI2-05 (dup)	Buck Island[3]	−4.6	5	–	–	2310	70	1737–2108
BI2-01	Buck Island[3]	−3.35	5	–	–	2175	70	1569–1933
BI2-16	Buck Island[3]	−2.05	5	–	–	1830	60	1261–1514
BI5-22	Buck Island[3]	−4.65	5	–	–	1540	60	948–1234
BI5-24	Buck Island[3]	−6.2	5	–	–	1510	70	914–1224
BI5-12	Buck Island[3]	−2.9	5	–	–	1450	70	829–1168
BI7-2	Buck Island[3]	−5.75	5	–	–	620	60	76–417
SCR-3D C17	Tague Bay Romney Pt[1]	−10.4	5	6135	80	6542	80	6846–7240
SCR-2 C17	Tague Bay Romney Pt[1]	−7.2	5	5490	85	5897	94	6096–6540
TB H8 C2b	Tague Bay[1]	−8.62	5	4525	80	4932	80	4989–5461
TB H8 C2	Tague Bay[1]	−7.98	5	3220	75	3627	75	3339–3718
TB Core 13	North Shore Reef[1]	−2.7	5	1850	65	2257	65	1688–2033
TR H8 C1-5	Tague Reef[2]	−4.8	5	–	5	–	–	◇ 1873
TB Core 11	Sand Cay/Candlelight Reef[2]	−3.0	5	1495	60	1902	60	1300–1588
TB H9 C2	Tague Bay[1]	−7.9	5	1115	65	1522	65	926–1223
TB Core 17	Tague Bay Romney Pt[2]	−1.0	5	803	50	1210	50	657–878
SCC-3 C19	Tague Bay Romney Pt[2]	−1.2	5	720	80	1127	90	529–871
TB Core 16	Tague Bay[2]	−1.5	5	120	80	527	80	1–291

et al., 2005). The outer shelf-edge reef complex trends westward from northeastern Lang Bank, through Buck Island Bar, ending at Long Reef (Fig. 2). The inner shelf complex includes Tague Reef and its extensions (Fig. 2). Macintyre et al. (2008) presented comprehensive stratigraphic and age data for these reef trends, and interpreted variations in Holocene reef development in response to local conditions, regional sea-level rise (SLR; based on the WASL curve), and the rising slope of the antecedent surface from east to west (Fig. 3A–D).

Northeastern Lang Bank began building *Acropora palmata* framework at ~7700 cal BP (Hubbard et al., 2005). The Pleistocene surface is estimated to be below −15 m MSL. To the west, Buck Island Bar (Fig. 2; Fig. 3A) has >10 m accumulation of mainly *A. palmata* and sand near the shelf edge (Macintyre and Adey, 1990; Hubbard, 1991; Hubbard et al., 2005). The reef forming Buck Island Bar established on a Pleistocene ridge at ~−15 m MSL prior to 7700 years ago, but ceased active framework construction at ~1200 cal BP, as indicated by *A. palmata* dated at 1180 cal BP at ~−5 m MSL (Hubbard et al., 2005). In addition, the surface of this reef has remained below −4.5 m MSL, never building to sea level for the last 4000 years, a situation interpreted to be due to the limitation or interruption of *A. palmata* accumulations by high-energy conditions (or storm damage; Macintyre and Adey, 1990). The resulting hiatus in *A. palmata* growth was followed by water deepening to beyond the functional depth (~5 m) of reef framework accumulation, thus not allowing this reef to catch up to sea-level rise. The *A. palmata* samples from Buck Island Bar which did not keep pace with sea-level rise, remaining at or below −5 m MSL (Macintyre and Adey, 1990), have been excluded from this analysis since they cannot be considered true shallow-water indicators. Long Reef, the westernmost extension of the outer shelf-edge reef, rests on the landward edge of the pre-Holocene surface and is the northwestern limit of the shelf-edge reef system (Fig. 2 and 3B). Macintyre et al.'s (2008) 5-core transect of Long Reef documented up to 5 m of Holocene reef deposits on a −5 to −7 m MSL Pleistocene surface.

The thick sections of Buck Island (intermediate reefs) and the Tague Bay reef system (inner bank-barrier reef complex; Fig. 2 and 3C, D) are related to the lower elevations of the Pleistocene substrate there (~−9 m to −16 m MSL; Burke et al., 1989; Hubbard et al., 2005). One outlier, a deep-plotting *A. palmata* sample (Fig. 3C) interpreted as core cave-in material (Macintyre et al., 2008), was also excluded from this analysis. The eastward-dipping surface allowed early initiation of reef construction at Tague Bay by 7030 cal BP, following the reefs at Buck Island Bar. These interpreted data determine the new GIA model sea-level synthesis below.

3. Materials and methods

3.1. Coral core data

Core drilling is described in Macintyre et al. (2008). Nine cores from Tague Bay bank-barrier reef, five cores from Long Reef and two cores drilled at Buck Island Bar (Macintyre and Adey, 1990; Hubbard, 1991; Hubbard et al., 2005) are included in this analysis. Elevation errors for dated samples include the time of coring during the tidal cycle (not precisely recorded), the tidal range (~0.25 m MSL), and the depth error measurements by diver-drillers (less than 0.5 m). All Holocene corals from St Croix were cored from identifiable reef framework, with topographic as well as ecological depth ranges of −2 to −5 m MSL. Therefore the comprehensive potential elevation error for all plotted data is estimated at a maximum of 1 m for *A. palmata*, which overlaps the maximum 5 m depth error applied to the core data in Table 1 and plotted as vertical bars in Figs. 4–6.

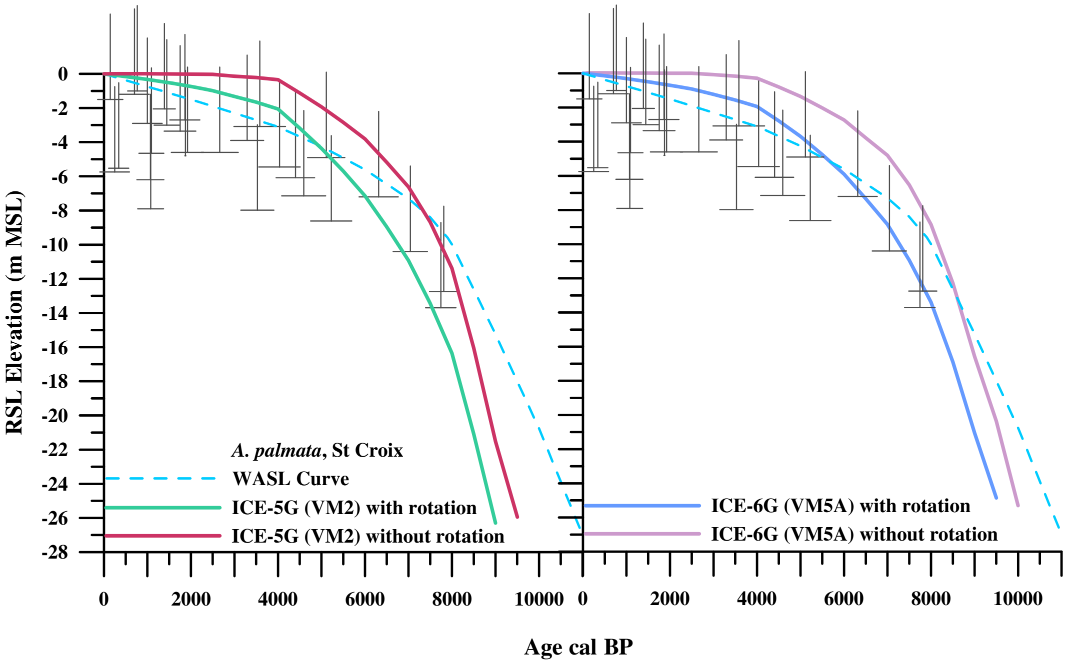

Fig. 4. Side-by-side comparison of ICE-5G (VM2) and ICE-6G (VM5A) models (with and without rotation), in situ *A. palmata* data and the geologically-derived WASL curve. For both models, rotational feedback is crucial to predicting a sea-level curve consistent with the reef data while minimizing the indication of large mid-Holocene misfits and later highstands that are not consistent with the reef data. The revised model ICE-6G (VM5A) with rotation corrects the long timescale error (producing misfits from 5 kyr to 11 kyr) that would otherwise exist in the model predictions for the St Croix site and provides a better fit to the data greater than 5 kyr old than does the WASL curve.

3.2. Radiometric dating

A total of 63 radiometric dates on *Acropora palmata* and head corals (*Montastraea* sp., *Diploria* sp., *Porites astreoides*, and *Siderastrea siderea*) constituted the complete geologic database for the local sea-level reconstruction as reported in Macintyre et al. (2008; their Table 1; Fig. 3A–D). *Acropora palmata* is used exclusively as a sea-level indicator in this and other studies. Twenty-eight *A. palmata* samples are used in this analysis, including previously published radiocarbon dates (Burke et al., 1989; Hubbard et al., 2005) and one TIMS U-Th date (Macintyre et al., 2008) (Table 1). Radiocarbon dates from the Tague Bay and Long Reef transects were analyzed by the Smithsonian Radiocarbon Lab and Beta Analytic Inc., respectively. These dates were not originally corrected for $\delta^{13}C_{PDB}$ and did not incorporate an oceanic reservoir correction, hence were published as basic ^{14}C dates based on the Libby half life (5568 years). Standard radiocarbon ages require correction for isotope fractionation by normalizing $\delta^{13}C$ to $0‰_{PDB}$ for corals. For these samples we have calculated $\delta^{13}C_{PDB}$ values using the Calib spread sheet d13ccorr.xls (http://calib.qub.ac.uk/calib), assuming the original measurement was a $^{14}C/^{12}C$ ratio. The $\delta^{13}C$ correction spreadsheet also calculates the corresponding conventional radiocarbon date for each sample, which can then be calibrated to calendar ages. Buck Island dates were reported as conventional radiocarbon ages (Hubbard et al., 2005; Table 1). All conventional radiocarbon dates were calibrated using the Calib 5.1.0 program (Stuiver and Reimer, 1993; http://calib.qub.ac.uk/calib; on-line version Stuiver et al., 2005), the marine calibration dataset (Marine04) and a time-dependent global ocean reservoir correction of ~400 years (applicable to the age range of data presented; CALIB Manual version 4.1; Stuiver and Reimer, 1993). The difference in age between the local ocean reservoir and modeled values (ΔR) was set at -5 ± 20 (Beta Analytic; Stuiver and Braziunas, 1993).

Thermal Ionization Mass Spectrometric (TIMS) U-Th dating reported in Macintyre et al. (2008) was done in the Isotope Geochemistry and Geochronology Research Facility, Carleton University, Ottawa, Ontario, following standard techniques (e.g., Ivanovich et al., 1992). The sample included in this study was ultrasonically cleaned, ignited for 5 h at 875 °C to remove organics, dissolved in HNO_3 and spiked with ^{233}U-^{236}U-^{229}Th tracer. U and Th were co-precipitated with iron hydroxide, and purified twice on anion exchange columns (Dowex AG1-X 200-400 mesh). Measurement of U and Th isotopic ratios was done on the Triton TIMS, in peak jumping mode using secondary electron multiplier with retarding quadrupole filter. The age was calculated using half lives from Cheng et al. (2000).

3.3. Geophysical sea-level modeling

The ICE-5G (VM2) GIA model is based upon the assumption of a spherically-symmetric, self-gravitating and elastically compressible Maxwell visco-elastic Earth model with a (perfectly elastic) lithospheric thickness of 90 km (Peltier, 2004) and may either include or exclude the influence of rotational feedback on the postglacial sea-level response to the GIA process. The ICE-6G (VM5A) model differs slightly from this as described above. The impact of the change in the Earth's rotational state upon sea-level history is a consequence of the dominant role of the true polar wander component of the rotational response (e.g., Peltier, 1998; Peltier, 2004; Peltier and Luthcke, 2009). The impact upon sea-level history of the induced changes in the length of day, on the other hand, is extremely small. In mid-latitude areas like the mid-Atlantic coast of the USA, which are in the near field of the vast Laurentide ice sheet, rotational feedback in the model is not unequivocally required to achieve an acceptable fit to RSL observations (e.g. Horton et al., 2009). The difficulty has to do with the interplay between this physical process and the depth dependent visco-elastic structure that exists because sea-level histories along this coast are sensitive to the influence of both properties of the model. Further discussion of this interplay will be found in Engelhart et al. (2011).

Table 2
ICE-5G (VM2) and ICE-6G (VM5A) model curve RSL points (with and without rotation) for the geographic area of St Croix, USVI (17.8°N). RSL values for the ICE-6G (VM5A) model for the south side of Barbados (Cobbler's Reef; 13.05°N) and areas at similar latitudes in the Lesser Antilles are included for comparison.

Yrs BP	ICE-5G (VM2) *without rotation* SL prediction m MSL ~17.8° N NE St Croix, USVI	ICE-5G (VM2) *with rotation* SL prediction m MSL ~17.8° N NE St Croix, USVI	ICE-6G (VM5A) *without rotation* SL prediction m MSL ~17.8° N NE St Croix, USVI	ICE-6G (VM5A) *with rotation* SL prediction m MSL ~17.8° N NE St Croix, USVI	ICE-6G (VM5A) *with rotation* SL prediction m MSL ~13.05° N South Barbados
0	0	0	0	0.00	0.00
500	0.01	−0.16	0.03	−0.15	−0.14
1000	0.01	−0.33	0.02	−0.31	−0.3
1500	0	−0.52	0.02	−0.49	−0.46
2000	−0.02	−0.74	0.01	−0.70	−0.64
2500	−0.03	−0.99	0.01	−0.92	−0.82
3000	−0.14	−1.32	−0.08	−1.23	−1.08
3500	−0.22	−1.66	−0.16	−1.56	−1.35
4000	−0.34	−2.06	−0.29	−1.94	−1.65
4500	−1.12	−3.18	−0.8	−2.78	−2.38
5000	−1.93	−4.36	−1.35	−3.69	−3.15
5500	−2.84	−5.69	−2.02	−4.75	−4.05
6000	−3.81	−7.15	−2.73	−5.90	−5.01
6500	−5.18	−8.96	−3.78	−7.34	−6.27
7000	−6.62	−10.93	−4.8	−8.84	−7.55
7500	−8.68	−13.44	−6.53	−10.94	−9.46
8000	−11.39	−16.36	−8.85	−13.40	−11.82
8500	−16.06	−21.09	−12.28	−16.89	−15.32
9000	−21.52	−26.3	−16.57	−21.05	−19.45
9500	−25.95	−30.66	−20.36	−24.86	−23.16
10,000	−30.76	−35.32	−25.3	−29.54	−27.9
10,500	−35.37	−39.99	−30.7	−34.70	−33.13
11,000	−40.48	−45.06	−36.39	−40.06	−38.65
11,500	−52.07	−54.6	−49.45	−53.53	−52.02
12,000	−55.67	−58.27	−54.47	−57.90	−56.68
12,500	−60.55	−63.11	−58.8	−62.18	−60.96
13,000	−67.61	−69.19	−64.52	−67.25	−66.35
13,500	−72.46	−73.92	−68.94	−71.61	−70.77
14,000	−79.16	−79.82	−75.08	−77.15	−76.75
14,500	−95.45	−91.52	−94.53	−92.80	−94.81
15,000	−98.69	−94.29	−98.05	−95.78	−98.13
15,500	−103.01	−98.26	−101.08	−98.60	−101.07
16,000	−108.29	−102.79	−104.7	−101.56	−104.44
16,500	−110.3	−104.57	−106.99	−103.66	−106.73
17,000	−111.45	−105.79	−108.26	−104.99	−108.04
17,500	−113.3	−107.44	−109.6	−106.27	−109.36
18,000	−115.1	−109.01	−111.09	−107.64	−110.8
18,500	−116.29	−110.03	−112.37	−108.77	−111.99
19,000	−117.47	−111.02	−113.44	−109.67	−113.0
19,500	−118.71	−112.09	−114.08	−110.16	−113.56
20,000	−119.93	−113.12	−114.98	−110.91	−114.38
20,500	−120.81	−113.84	−115.76	−111.50	−115.04
21,000	−121.69	−114.52	−116.59	−112.19	−115.8

Although St Croix is latitudinally well to the south of the region most strongly influenced by the process of proglacial forebulge collapse, it is not so far south as to be entirely unaffected by this process. In fact data from Barbados have previously been interpreted (Peltier and Fairbanks, 2006) to imply that this site was inboard of the trailing edge of the forebulge since there was no evidence of the existence of a mid-Holocene highstand of the sea at this site. The availability of the proximate data from St Croix provides us with the opportunity to further test this interpretation of the effective latitudinal width of the forebulge region.

4. Results

4.1. Sea-level analysis and data-model reconciliation

Coral (*A. palmata*) data for northeastern St Croix are plotted in Fig. 4 together with the geologically-derived and latitudinally-averaged WASL curve (used by Macintyre et al., 2008) and with the predictions of the ICE-5G (VM2) and ICE-6G (VM5A) models (with and without rotational feedback). The latitudinally-averaged WASL curve fits the *A. palmata* samples younger than 5 kyr, but suggests higher sea levels in relation to the *A. palmata* samples at ages greater than 5 kyr, in part due to the influence of data from higher latitudes, particularly Florida (Toscano and Macintyre, 2003). Both the ICE-5G (VM2) and ICE-6G (VM5A) models *without rotation* predict mid-Holocene sea levels that lie ~2–4 m higher than supported by the coral field at 4 ka, and very small-amplitude (effectively undetectable) highstands (above present sea level) that onset at ~2.5–1.5 ka (ICE-5G), and reach a maximum amplitude of ~3 cm (Table 2). In contrast, the ICE-5G (VM2) and ICE-6G (VM5A) models *with rotation* provide better fits to the data from 0 to 5 kyr, much reduced mid-Holocene sea levels (~1.5 m above the data field) at 4 ka, and eliminate the small-amplitude highstands entirely (Fig. 4; Table 2).

4.2. Model-data comparison: discussion

Coral data specifically from St Croix (Table 1) span a large depth range as a function of environmental factors and local geology discussed above (Fig. 3A–D) and plotted on Figs. 4 and 5. Assuming the

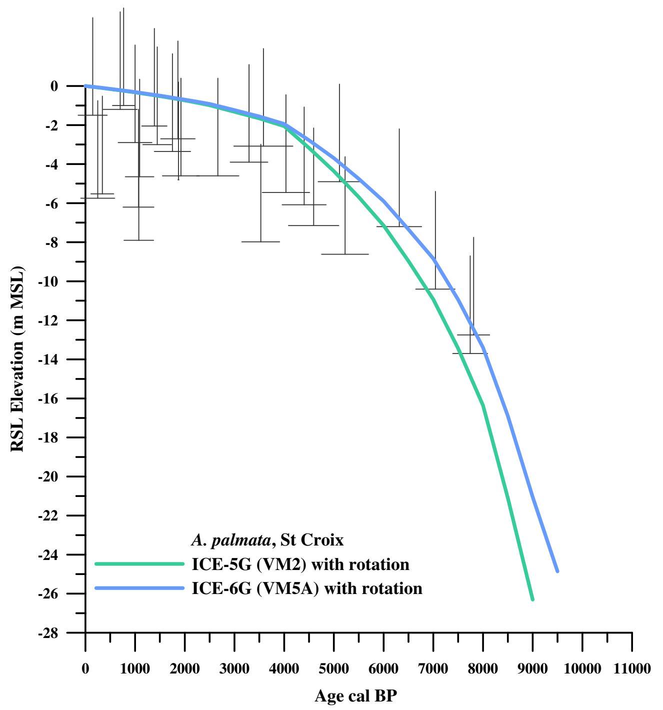

Fig. 5. ICE-5G (VM2) and ICE-6G (VM5A) models with rotation, with *A. palmata* from northeastern St. Croix. The St Croix (17.8°N, −64.6°W) data clearly show preference for the tuning employed for the ICE-6G (VM5A) model, which clearly provides the best fit to the in situ geologic sea-level data from the region and confirms the impact of rotational feedback on postglacial sea-level at sub-tropical latitudes.

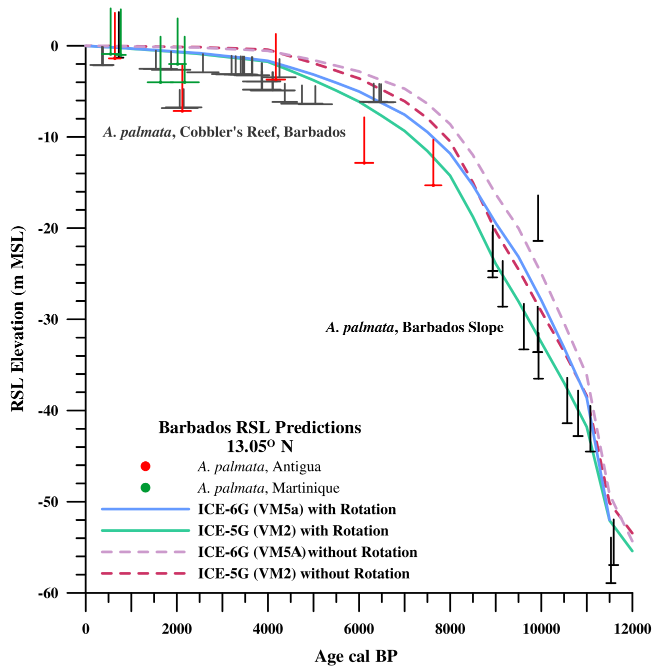

Fig. 6. Explanation of the difference between the ICE-5G and ICE-6G models (for Barbados) in terms of the characteristics of their fit to the Barbados record. ICE-5G fits the Barbados record roughly through the middle of the *A. palmata* samples whereas ICE-6G fits Barbados through the shallowest tips of the error bars on these samples. Samples from Antigua (17.08°N,−61.7°W) and Martinique (14.6°N, −60.8°W) show good agreement with the Barbados model, indicating that rotational feedback is operating across latitudinal and longitudinal ranges within the region. Barbados slope samples are from Peltier and Fairbanks (2006). Cobblers Reef, Barbados samples are from Macintyre et al. (2007). Both datasets are corrected for the 0.34 mm yr^{-1} uplift along the south coast of Barbados.

highest-plotting coral samples at any time represent those that grew closest to sea level at the reef crest, and using those samples as representative of sea level, a distinct difference is observed between models *with rotation* in relation to the St Croix *A. palmata* data older than 5 ka (Fig. 4). The ICE-5G (VM2) model for St. Croix, with rotation, while closely approaching the four oldest *A. palmata* samples, lies just under them, indicating several misfits (of +0.5 m to +2 m) from 5 ka to 9 ka. While these misfits arguably fall into the elevation error range of *A. palmata* sampled from reef framework, the model results suggest under-prediction of sea level in this age range. In contrast, the ICE-6G (VM5A) curve with rotation for St Croix predicts a shallow positive sea-level elevation in relation to these older samples that is consistent with the up to 2 m living range of reef crest *A. palmata* (in contrast to the comprehensive 5 m depth error) and is preferred over ICE-5G (VM2). Fig. 5 includes only the ICE-5G (VM2) and ICE-6G (VM5A) models specifically for St Croix, *with rotation*.

We also test the difference between the ICE-5G and ICE-6G models for Barbados, which is proximal to St. Croix (see Fig. 2), using model output and uplift-corrected coral reef data from Barbados (Peltier and Fairbanks, 2006; Macintyre et al., 2007; Fig. 6). The ICE-5G (VM2) model with rotation fits Barbados coral data roughly through the middle of the assigned 5 m depth error of the *A. palmata* samples (with no highstand predicted), whereas ICE-6G (VM5A) with rotation fits through the shallowest tips of the error bars on these samples (with no highstand). For the Holocene, both the uplift-corrected Cobbler's Reef (south Barbados; Macintyre et al., 2007; Fig. 6) and uncorrected St Croix data (Fig. 5) clearly show preference for the tuning employed for the ICE-6G model for these sites. The revised tuning obtained for the ICE-6G (VM5A) model was solely a consequence of the modification of the ice-loading history over North America that was required to eliminate the misfits to the GPS derived vertical motion observations identified in Argus and Peltier (2010).

At St. Croix, Holocene tectonic stability is assumed, and for the past 8000 years there are no vertical offsets or sudden vertical discontinuities in the data field to indicate rapid rates of sea-level rise or tectonic movements that would have shifted the level of reef growth at any time (Macintyre et al., 2008). One gap in the *A. palmata* record (from ∼2500 to ∼3200 cal BP) does not create a vertical offset in the reef record and is likely an artifact of core coverage or sample selection for dating. As noted above the tectonic setting of St Croix is such that vertical motion of the kind that is active at Barbados is not expected.

Misfits to the data of greatest magnitude (>2 m) occur when rotational feedback is excluded from the models, resulting in the prediction of significantly higher mid-Holocene sea-level elevations at 4 ka, followed by small sea-level highstands (above present MSL) from 2.5 to 1.5 ka, in an area where such features are not geologically documented. The large (up to +4 m) misfits between the modeled sea-level curves *without rotational feedback* and the geologic data from St Croix (Figs. 4 and 5) are greatly reduced, specifically in the ∼4–2 ka age range, where the models *with rotation* predict lower-amplitude mid-Holocene sea levels on the order of 1 m, and eliminate the highstands from 2.5 to 1.5 ka. The ICE-5G (VM2) model *with rotational feedback* also under-estimates sea level in relation to coral elevations in the 5–9 ka age range (Fig. 4). Otherwise, the models with rotational feedback predict sea-level curves more closely consistent with *A. palmata* elevations (Fig. 5). In particular the ICE-6G (VM5A) model with rotation closely predicts a shallow sea-level elevation covering the oldest *A. palmata* samples and providing the best fits of all models analyzed.

The models with rotational feedback are preferred at both the Barbados and St Croix locations because this influence effectively extends the width of the proglacial forebulge further to the south and thereby eliminates or significantly reduces the amplitude of the mid-Holocene (4 ka) misfit that would otherwise be predicted to exist at these locations. The comparison between the fits of the models at these two locations actually allows us to further discriminate between ICE-5G (VM2) and ICE-6G (VM5A) as we will now go on to show.

Fig. 6 is a further crucial contribution of this paper since it fully explains the difference between the ICE-5G and ICE-6G models in terms of the characteristics of their fit to the Barbados record, which is proximal to St. Croix (see Fig. 2). ICE-5G (VM2 with rotation; for Barbados) fits the Barbados record roughly through the middle of the 5m depth errors of the uplift-corrected *A. palmata* samples (with no highstand predicted), whereas ICE-6G (VM5A with rotation; for Barbados) fits Barbados through the shallowest tips of the error bars on these samples (with no highstand). Both the Cobbler's Reef (Barbados) Holocene data of Macintyre et al. (2007) and the St Croix Holocene data (Fig. 5) clearly show preference for the tuning employed for the ICE-6G (VM5A) model for these sites. This is an excellent example of the way in which even closely spaced data sets based upon similar indicators may be employed to eliminate ambiguities in the inference of model parameters that would otherwise remain unresolved. Table 2 lists the ICE-6G (VM5A) model predicted RSL histories (with rotation) for St Croix (17.8°N, −64.6°W) and for Barbados (13.1°N, −59.5°W).

In order to determine the longitudinal range over which this prediction would continue to apply will require explicit comparisons with additional relative sea-level data from this region. Nevertheless, Fig. 6 also includes 5 samples from Antigua (17.08°N, −61.7°W) and 5 from Martinique (14.6°N, −60.8°W) near the edge of the Caribbean plate (Lighty et al., 1982; Toscano and Macintyre, 2003) as a preliminary test of this model at nearby sites, with good agreement for both localities. It will be interesting in further work that is being pursued at present to investigate this issue with data from other sites along the Greater and Lesser Antilles and Central America.

5. Conclusions

Coral reef data from northeastern St Croix indicate a spatially and temporally evolving history of reef development and sea-level rise that is compared to GIA modeled sea levels from the ICE-5G (VM2) and ICE-6G (VM5A) models of Peltier (2004; GJI, in preparation), with and without rotational feedback. Misfits between the modeled sea levels and the geologic data are most apparent in both models without rotational feedback, particularly in the prediction of a large (2–4 m) unsupported mid-Holocene misfit at ~4 ka, as well as highstands from 2.5 to 1.5 ka. These features and other misfits are substantially reduced in the model versions with rotation.

The ICE-6G (VM5A) model with rotation most accurately accounts for the uppermost samples that are most closely linked to sea level in the *A. palmata* data field. It is clear that the addition of rotational feedback to the model of the GIA process identifies tropical latitudes as influenced by proglacial forebulge collapse, effectively increasing the area over which this process dominates in the geographical region to the south of the Laurentide ice sheet. If this process is eliminated from the model the data at St Croix are no longer explained. This further reinforces the importance of this subtle interaction as discussed in the recent papers of Peltier (2002, 2007), Peltier and Luthcke (2009), Horton et al. (2009) and Engelhart et al. (2011).

The Sea Level Equation-based theory predicts sea-level histories that are strongly site dependent. In the Caribbean Sea, across which significant gradients in relative sea-level history exist, greater insight into the processes involved is possible with a geologically-constrained, site-specific prediction. Implications for reef-based sea-level reconstruction include the ability to accurately model sea levels at specific tropical sites with partial Holocene chronologies using the ICE-6G (VM5A) model with rotational feedback. The ICE-5G (VM2) and ICE-6G (VM5A) models result in further refinements to the sea-level history of northeastern St. Croix. Differences between the composite WASL curve and predictions of the ICE-6G (VM5A) model clarify the sea-level curve specific to northeastern St Croix, thereby eliminating misfits and curve inaccuracies, particularly in the older portion of the record. Latitudinally-averaged sea-level curves such as WASL are of limited use in understanding the relative importance of contributing physical influences on post-glacial sea-level history.

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