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Evaluation of coral reef carbonate production models at a global scale

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Abstract

Calcification by coral reef communities is estimated to account for half of all carbonate produced in shallow water environments and more than 25 % of the total carbonate buried in marine sediments globally. Production of calcium carbonate by coral reefs is therefore an important component of the global carbon cycle. It is also threatened by future global warming and other global change pressures. Numerical models of reefal carbonate production are essential for understanding how carbonate deposition responds to environmental conditions including future atmospheric CO_2 concentrations, but these models must first be evaluated in terms of their skill in recreating present day calcification rates. Here we evaluate four published model descriptions of reef carbonate production in terms of their predictive power, at both local and global scales, by comparing carbonate budget outputs with independent estimates. We also compile available global data on reef calcification to produce an observation-based dataset for the model evaluation. The four calcification models are based on functions sensitive to combinations of light availability, aragonite saturation (Ω_a) and temperature and were implemented within a specifically-developed global framework, the Global Reef Accretion Model (GRAM). None of the four models correlated with independent rate estimates of whole reef calcification. The temperature-only based approach was the only model output to significantly correlate with coral-calcification rate observations. The absence of any predictive power for whole reef systems, even when consistent at the scale of individual corals, points to the overriding importance of coral cover estimates in the calculations. Our work highlights the need for an ecosystem modeling approach, accounting for population dynamics in terms of mortality and recruitment and hence coral cover, in estimating global reef carbonate budgets. In addition, validation of reef carbonate budgets is severely hampered by limited and inconsistent methodology in reef-scale observations.

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1 Introduction

Coral reefs are the product of long-term $CaCO_3$ accretion by calcifying organisms of the reef community (e.g. Hatcher, 1997; Perry et al., 2008), principally scleractinian corals and crustose coralline algae (CCA; e.g. Chave et al., 1972; Barnes and Chalker, 1990; Kleypas and Langdon, 2006; Mallela, 2007; Vroom, 2011). Coral reefs persist where net $CaCO_3$ accretion is achieved, i.e. where calcification by reef organisms exceeds dissolution and bioerosion (reviewed by Kleypas and Langdon, 2006; Fig. 1; Perry, 2011). Globally, coral reef calcification accounts for ~ 50 % of shallow water (neritic) $CaCO_3$ production (Milliman, 1993) with an estimated budget of 0.65–0.83 Pg of $CaCO_3$ each year (Vecsei, 2004). Most of this annual global carbonate production (G_{global}) is preserved and buried, and so coral reefs play an important role in global carbon cycling (Vecsei, 2004) and hence the control of atmospheric CO_2.

Although the precise mechanisms by which calcification occurs in both corals and CCA are still poorly understood (reviewed by Allemand et al., 2011), it is thought that the rate of calcification is environmentally modulated by some combination of seawater aragonite saturation state (Ω_a), temperature and light availability (E; Buddemeier and Kinzie, 1976; Kleypas and Langdon, 2006; Tambutté et al., 2011). As a result, it is anticipated that calcification on coral reefs is sensitive to climate change and ocean acidification (e.g. Kleypas et al., 1999; Erez et al., 2011; Hoegh-Guldberg, 2011). In particular the reduction of Ω_a due to ocean acidification (OA) causing decreased calcification of individual corals (reviewed by Kleypas and Yates, 2009; Andersson and Gledhill, 2013) and CCA (e.g. Anthony et al., 2008; Johnson and Carpenter, 2012; Johnson et al., 2014), and rising sea surface temperatures (SSTs) causing an increase in coral bleaching frequency due to heat stress (e.g. Donner et al., 2005; Baker et al., 2008; Frieler et al., 2013).

The global reef carbonate budget (i.e. G_{global}) is inherently difficult to evaluate because it is impossible to empirically measure this variable; instead it must be extrapolated from reef-scale observations. Vecsei (2004) synthesized census-based methods

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to produce values of reef calcification rates (G_{reef}; Fig. 1) – that varied both regionally and with depth – to estimate G_{global} (0.65–0.83 Pg yr^{-1}). This represents an improvement on previous estimates, for example Milliman (1993) calculated G_{global} (0.9 Pg yr^{-1}) from two modal values for G_{reef} (reefs: 0.4 g cm^{-2} yr^{-1}, lagoons: 0.08 g cm^{-2} yr^{-1}). Census-based methods calculate G_{reef} by summing the calcification by each reef-calcifier, multiplied by its fractional cover of the reef substrate (Chave et al., 1972; Perry et al., 2008). The calcification by individual components of the reef community may be derived from linear extension rates or published values for representative species (Vecsei, 2004). Often it is only calcification by scleractinian corals (G_{coral}) and coralline algae (G_{algae}) that are considered, due to their dominance in $CaCO_3$ production (e.g. Stearn et al., 1977; Eakin, 1996; Harney and Fletcher, 2003). G_{reef} values can also be calculated from the total alkalinity change (ΔTA) of seawater (e.g. Silverman et al., 2007; Shamberger et al., 2011; Albright et al., 2013) because precipitation of $CaCO_3$ decreases the total alkalinity (TA) of seawater whereas dissolution has the opposite effect (sensu Erez et al., 2011). By measuring the change in TA over a discrete time interval (Δt), it is possible to calculate the net ecosystem calcification (NEC) or net G_{reef} (Eq. 1; Albright et al., 2013):

$$G_{reef} = -0.5 \cdot pz \frac{\Delta TA}{\Delta t} \quad (1)$$

where p is seawater density (kg m^{-3}) and z in water depth (m). G_{reef} measured using ΔTA accounts for inorganic precipitation (G_i; Fig. 1) and dissolution; however, unlike census-based methods for calculating G_{reef}, it is not possible to break down the contribution of individual calcifers in the reef community (Perry, 2011). G_{coral} calculated from the width and density of annual bands within the colony skeleton is commonly used in census-based observations of G_{reef} (Fig. 1; Knutson et al., 1972).

Estimates of G_{global} alone tell us little about how reefs will be affected by climate change at a global scale. Instead, if coral calcification (G_{coral}) and reef community calcification rates (G_{reef}) can be numerically modeled as a function of the ambient physio-

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chemical environment (e.g. E, Ω_a and SST), then the results could be scaled up to produce an estimate of G_{global} that could be re-calculated as global environmental conditions change. Examples of this approach (Table 1) include: (1) ReefHab^{Irr}, which is sensitive to E only and was initially developed to predict global reef calcification (G_{global}) and habitat area (Kleypas, 1997) and used to estimate changes in G_{global} since the last glacial maximum (LGM), (2) Kleypas$^{Irr\Omega}$, which simulates G_{reef} as a function of E and Ω_a and was originally developed to simulate carbonate chemistry changes in seawater on a reef transect (Kleypas et al., 2011), (3) Lough^{SST} which simulates G_{coral} as a function of SST and was derived from the strong relationship observed between SST and G_{coral} in massive *Porites* sp. colonies from the Great Barrier Reef (GBR), Arabian Gulf and Papua New Guinea (Lough, 2008); and (4) Silverman$^{SST\Omega}$, which simulates G_{reef} as a function of SST and Ω_a and was used to simulate the effects of projected future SSTs and Ω_a at known reef locations globally (Silverman et al., 2009). Although further models exist describing G_{coral} as a function of carbonate ion concentration ([CO_3^{2-}]; Suzuki et al., 1995; Nakamura and Nakamori, 2007) these are synonymous to the Ω_a function used in Kleypas$^{Irr\Omega}$ and Silverman$^{SST\Omega}$.

To date it remains to be demonstrated that any of the published models are capable of reproducing present day reef calcification rates (i.e. G_{reef}). Despite this, simulations of the effects of future climate scenarios have been attempted using calcification rate models. For example, McNeil et al. (2004) incorporated Lough^{SST} with the linear relationship observed between Ω_a and calcification in the BioSphere-2 project (Langdon et al., 2000), and predicted that G_{reef} will increase in the future. In contrast, a similar study by Silverman et al. (2009; Silverman$^{SST\Omega}$) concluded that coral reefs will start to dissolve. Whilst McNeil's study was criticized for its underlying assumptions (Kleypas et al., 2005), the contradictory predictions from these two models highlights the importance of comparing reef calcification models and evaluating them against present day observations.

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Here we describe a novel model framework, the global reef accretion model (GRAM), and compare the four calcification models ($\text{ReefHab}^{\text{Irr}}$, $\text{Kleypas}^{\text{Irr}\Omega}$, $\text{Lough}^{\text{SST}}$ and $\text{Silverman}^{\text{SST}\Omega}$) in term of their skill in predicting G_{coral} and G_{reef}. The evaluation dataset comprises observations of G_{reef} from census-based methods and ΔTA experiments as well as G_{coral} measured from coral cores. The individual model estimates of G_{global} are discussed in comparison with previous empirical estimates. We highlight where model development is required in order to accurately simulate the effects of future climate on calcification rates in coral reefs.

2 Methods

2.1 Model description

Four calcification models were selected for evaluation in global scale simulations: (1) $\text{ReefHab}^{\text{Irr}}$ (Kleypas, 1997), (2) $\text{Kleypas}^{\text{Irr}\Omega}$ (Kleypas et al., 2011), (3) $\text{Lough}^{\text{SST}}$ (Lough, 2008) and (4) $\text{Silverman}^{\text{SST}\Omega}$ (Silverman et al., 2009; Table 2). Previous applications for these models cover a hierarchy of spatial scales (colony, $\text{Lough}^{\text{SST}}$; reef, $\text{Kleypas}^{\text{Irr}\Omega}$ and global, $\text{ReefHab}^{\text{Irr}}$ and $\text{Silverman}^{\text{SST}\Omega}$) as well as representing different approaches for measuring G_{coral} (Fig. 1; $\text{Lough}^{\text{SST}}$) and G_{reef} (Fig. 1; $\text{ReefHab}^{\text{Irr}}$, $\text{Kleypas}^{\text{Irr}\Omega}$ and $\text{Silverman}^{\text{SST}\Omega}$).

2.1.1 $\text{ReefHab}^{\text{Irr}}$

Kleypas (1997) developed ReefHab to predict changes in the global extent of reef habitat since the last Glacial Maximum (Kleypas, 1997). Like photosynthesis, calcification is light saturated (Allemand et al., 2011); as the rate of calcification increases toward a maximum value, it becomes light saturated after irradiance increases beyond a critical value. This curvilinear relationship can be described with various functions, however, hyperbolic-tangent and exponential functions have been found to best describe the re-

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lationship (Chalker, 1981). The ReefHab model calculates vertical accretion (G_{reef}) as a function of light penetration (E_z) and maximum growth rate ($G_{max} = 1\,\mathrm{cm\,yr^{-1}}$). The hyperbolic-tangent function uses a fixed light saturation constant ($E_k = 250\,\mu\mathrm{E\,m^{-2}\,s^{-1}}$) to generate a scaling factor for G_{max} (Eq. 2):

$$G_{reef} = G_{max} \cdot \tanh\left(\frac{E_z}{E_k}\right) \cdot \mathrm{TF} \quad E_z > E_c \tag{2}$$

where E_z is derived from the surface irradiance (E_{surf}) and the inverse exponent of the product of K_{490} and depth (z; Eq. 3). If E_z is less than the critical irradiance ($E_c = 250\,\mu\mathrm{E\,m^{-2}\,s^{-1}}$) $G_{reef} = 0$. TF is the topography factor (Eq. 4), which reduces G_{reef} in areas of low topographic relief.

$$E_z = E_{surf} \cdot e^{-K_{490} z} \tag{3}$$

$$\mathrm{TF} = \frac{\ln(\alpha \cdot 100)}{5} \tag{4}$$

where α is calculated form a nine cell neighborhood (center index 2,2) by summing the inverse tangent of the difference between cell depths ($z_{i,j} - z_{2,2}$) divided by the distance between cell centers ($D_{i,j-2,2}$).

$$\alpha = \sum_{i=1}^{3} \sum_{j=1}^{3} \frac{\tan^{-1} z_{i,j} - z_{2,2}}{D_{i,j-2,2}} \tag{5}$$

Vertical accretion is converted to $CaCO_3$ mass by multiplying average carbonate density ($2.89\,\mathrm{g\,cm^{-3}}$) and porosity (50 %) as defined by Kleypas (1997).

2.1.2 Kleypas$^{Irr\Omega}$

Anthony et al. (2011) performed laboratory flume incubations on *Acropora aspera* to parameterize the relationship between (day and night) calcification rates and Ω_a, determining the reaction order (n) and maximum calcification rates (k_{day} and k_{night}). The

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resultant model was then implemented by Kleypas et al. (2011), with the addition of an exponential light sensitive function that accounted for light enhanced calcification, to simulate seawater chemistry changes along a reef transect at Moorea, French Polynesia. The transect did not exceed 2 m in depth; therefore, it was appropriate to use the surface irradiance (E_{surf}) for the calculation of G_{reef}. In this study G_{reef} is calculated (Eq. 6) using E_z (Eq. 3) rather than E_{surf} because the maximum depth in the model domain is 100 m, greatly exceeding the depth of the original application.

$$G_{reef} = \left(G_{max}(1 - e^{-E_z/E_k})^n + G_{dark}\right) \cdot A_c \tag{6}$$

where A_c is the fractional cover of live coral (i.e. LCC 100 %, $A_c = 1$). G_{reef} is calculated here in mmol m^{-2} d^{-1} and is divided into day and night rates (G_{max} and G_{dark}) both are calculated as a function of Ω_a. For this study it was necessary to introduce day length (L_{day}; h) to Eqs. (7) and (8) because of the daily time step as opposed to the hourly timestep of the original model.

$$G_{max} = k_{day}(\Omega_a - 1)^n L_{day} \tag{7}$$

$$G_{dark} = k_{dark}(\Omega_a - 1)^n (24 - L_{day}) \tag{8}$$

L_{day} was calculated using the method described by Haxeltine and Prentice (1996), which uses Julian day (J_d) and latitude (lat) as follows:

$$L_{day} = 0 \qquad u \leq v \tag{9}$$

$$L_{day} = 24 \cdot \frac{\cos^{-1} \cdot (-u/v)}{2\pi} \qquad u > -v,\ u < v \tag{10}$$

$$L_{day} = 24 \qquad u \geq v \tag{11}$$

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where the variables u and v are calculated from lat and aa (a function of J_d; Eq. 14).

$$u = \sin(\text{lat}) \cdot (aa) \quad (12)$$

$$v = \cos(\text{lat}) \cdot \cos(aa) \quad (13)$$

$$aa = -23.4^o \cdot \cos\left(\frac{360(J_d + 10)}{365}\right) \quad (14)$$

$CaCO_3$ production in mmol was converted to mass, in grams, using the relative molecular weight of $CaCO_3$ (MR = 100).

2.1.3 Lough^{SST}

ReefHab^{Irr} and Kleypas$^{Irr\Omega}$ were both derived from theoretical understanding of the process of calcification and parameterized by values observed in the literature or in situ. In contrast, Lough^{SST} was derived from the observed relationship between annual calcification rates of massive *Porites* sp. colonies and local SST (Lough, 2008). A linear relationship (Eq. 15) was fitted to data from 49 reef sites from the Great Barrier Reef (GBR; Lough and Barnes, 2000), Arabian Gulf and Papua New Guinea (Lough, 2008), and accounted for 85 % of the variance ($p < 0.001$).

$$G_{coral} = \frac{0.327 \cdot \text{SST} - 6.98}{365} \quad (15)$$

2.1.4 Silverman$^{SST\Omega}$

Using ΔTA methods, Silverman et al. (2007) found a correlation between rates of inorganic precipitation (G_i) and net G_{reef}. Silverman et al. (2009) fitted observations to Eq. (16) to calculate G_i as a function of Ω_a and SST (Eq. 17):

$$G_i = k_{SST}(\Omega_a - 1)^{n_{SST}} \quad (16)$$

$$G_i = \frac{24}{1000}(-0.0177 \cdot \text{SST}^2 + 1.4697 \cdot \text{SST} + 14.893)(\Omega_a - 1)^{(0.0628 \cdot \text{SST} + 0.0985)} \quad (17)$$

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Incorporating Eq. (17) with SST and Ω_a sensitivity of coral calcification gives G_{reef} (Eq. 18):

$$G_{reef} = k_r' \cdot G_i \cdot e^{-\left(k_p'(SST - T_{opt})/\Omega_a^2\right)^2} \cdot A_c \qquad (18)$$

where k_r' ($38\,m^2\,m^{-2}$) and k_p' ($1\,^\circ C^{-1}$) are coefficients controlling the amplitude and width of the calcification curve. T_{opt} is the optimal temperature of calcification and is derived from the WOA 2009 monthly average SST (Locarnini et al., 2010) for June (in the Northern Hemisphere) and December (in the Southern Hemisphere).

2.1.5 Global Reef Accretion Model (GRAM) framework

The calcification production models above were implemented within our global reef accretion model (GRAM) framework. In this study, GRAM was implemented on a 0.25° × 0.25° global grid. Vertically, the model domain was resolved with 10 depth levels at equal 10 m intervals with the fraction, by area, of a model cell (quasi-seabed) within each 10 m layer recorded for calculating total carbonate production (Fig. 2). An environmental mask was imposed to limit $CaCO_3$ production to shallow-water tropical and sub-tropical areas. This mask was defined following Kleypas (1997; Kleypas et al., 1999b): SST (> 18 °C), salinity (23.3–41.8 ‰) and depth (≤ 100 m). Calcification was calculated on a daily basis over the course of one full calendar year and according to the environmental conditions at each grid cell (described below).

2.2 Input data description

Table 1 lists the data used to force GRAM. Ocean bathymetry was calculated from GEBCO One Minute dataset (http://www.gebco.net/) and mapped to the model grid. Monthly values for SST (Locarnini et al., 2010) and salinity (Antonov et al., 2010) were obtained from the World Ocean Atlas (WOA) 2009. These climatologies are reanalysis products of observations collected 1955–2009. The WOA data have a scaled vertical resolution with 24 layers, with a maximum depth of 1400 m; however, only surface values were used in this study. Daily photosynthetically available radiation (PAR), for the period 1991–1993, were obtained from the Bishop's High-resolution (DX) surface solar irradiance data (Lamont-Doherty Earth Observatory, 2000) derived from the International Satellite Cloud Climatology Project (ISCCP) data (Bishop and Rossow, 1991; Bishop et al., 1997). Monthly diffuse light attenuation coefficient of 490 nm light (K_{490}) was obtained from the Level-3 binned MODIS-Aqua products in the OceanColor database (available at http://oceancolor.gsfc.nasa.gov). Surface Ω_a was derived from the University of Victoria's Earth System Climate Model (Schmittner et al., 2009; Turley et al., 2010) for the decade 1990–2000. All input data were converted, without interpolating, to the same resolution as the model by recording the closest data point to the coordinates of the model grid cell's center. Missing values were extrapolated as an unweighted mean from the nearest values in the dataset found in the model cell's neighborhood (including diagonals) in an area up to 1° from the missing data point.

2.3 Evaluation dataset and methodology

To evaluate model performance, an independent dataset of in situ measured calcification rates (G_{reef} and G_{coral}) was collated from the literature. In total, data from 11 coral core studies (Table 3; *Montastrea* and *Porites* sp.), 8 census-based and 12 ΔTA studies (Table 4) were assembled. This dataset is not comprehensive of all studies that have measured G_{reef} and G_{coral}; many older studies were excluded, for example, Sadd (1984) due to errors in their calculation of G_{reef} that were resolved by Hubbard et al. (1990). The studies sampled cover a representative range of SST and Ω_a conditions in which present day reefs are found (Fig. 3). The positions of the in situ measurements were used to extract the equivalent data points from the gridded model output. Where location coordinates were not reported, Google Earth (available at http://earth.google.com) was used to establish the longitude and latitude, accurate to the model resolution of 0.25°. For uniformity, reported units of measurement were converted to g ($CaCO_3$)

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cm^{-2} yr^{-1}. The values of live coral cover (LCC) reported in the census-based and ΔTA studies were used to convert model G_{coral} to G_{reef}.

Model skill in reproducing the observed data was assessed using simple linear regression analysis preformed on observed calcification rates paired with their equivalent model value. When testing Lough^{SST} against coral core data, values that were used in the original formulation of the model (Lough, 2008) were excluded so as to preserve the independence of the data. Similarly, when correlating Silverman$^{SST\Omega}$ with ΔTA data, the Silverman et al. (2007) datum was excluded. A global average LCC of 30 % (Hodgson and Liebeler, 2002) was applied to model $CaCO_3$ production in model comparisons with census-based and ΔTA G_{reef} at a global scale. Global mean G_{reef} and G_{global} were calculated by applying a further 10 % reefal area to model $CaCO_3$ production; this follows the assumption in Kleypas (1997) that 90 % of the seabed is composed of unsuitable substrate for reef colonization and growth. Global and regional values are compared to the most recent estimates by Vecsei (2004), although other global estimates are also considered.

3 Results

3.1 Model carbonate production rates

Globally averaged values of G_{reef} (summarized in Table 5) vary little between ReefHab^{Irr} (0.65 ± 0.35 g cm^{-2} yr^{-1}), Kleypas$^{Irr\Omega}$ (0.51 ± 0.21 g cm^{-2} yr^{-1}) and Lough^{SST} (0.72 ± 0.35 g cm^{-2} yr^{-1}), with Silverman$^{SST\Omega}$ producing a somewhat smaller value (0.21 ± 0.11 g cm^{-2} yr^{-1}). A consistent feature across all models is the high carbonate production in the southern Red Sea along the coast of Saudi Arabia and Yemen and, in Kleypas$^{Irr\Omega}$ and Lough^{SST}, the East African coast (Fig. 4). In all models, there was very low carbonate prouction in the northern Red Sea compared to the south. There is higher carbonate production in the western Pacific than in the east, and along the Central American and northern South American coastline, and this is more pronounced in Kleypas$^{Irr\Omega}$ and Lough^{SST} than ReefHab^{Irr}. In scaling up to the global scale, estimates of G_{global} based on the models ReefHab^{Irr} (1.40 Pg yr^{-1}) and Silverman$^{SST\Omega}$ (1.1 Pg yr^{-1}) were substantially smaller than for the other model setups (3.06 Pg yr^{-1} for Kleypas$^{Irr\Omega}$ and 4.32 Pg yr^{-1} for Lough^{SST}).

3.2 Observed carbonate production rates

Figure 5 shows the location and magnitude of the calcification observations. Coral core (G_{coral}) values are higher (0.5–2.8 g cm^{-2} yr^{-1}; full dataset in online Supplement) than G_{reef} measurements from either census-based (0.1–0.9 g cm^{-2} yr^{-1}) or ΔTA (0.003–0.7 g cm^{-2} yr^{-1}; Table 4) methods. In general, coral core data show decreasing G_{coral} with increasing latitude that is most pronounced in Hawaii and along both east and west Australian coastlines (Fig. 5). However, G_{coral} is not always smaller at higher latitudes, particularly in the Arabian Gulf (1.44 ± 0.57 g cm^{-2} yr^{-1}; full dataset in online Supplement) where it is toward the upper end of the observed range in G_{coral}. Despite its equitable latitude G_{coral} in the Gulf of Aqaba is two fold smaller (0.78 ± 0.28 g cm^{-1} yr^{-1}). This result can not be corroborated by ΔTA or census data as there is no observation for the Arabian Gulf, however, there is agreement that calcification in the Gulf of Aqaba is toward to lower end of the observed range for ΔTA measured G_{reef} (0.18 ± 0.09 g cm^{-2} yr^{-1}) and G_{coral} measured from coral cores. In contrast, the census-based and ΔTA measurements show no latitudinal trends.

3.3 Model evaluation

Figure 6 shows the correlation of corresponding model and observed calcification rates. With a slope of 0.97, the only significant correlation was that between Lough^{SST} and independent coral core data ($R^2 = 0.66$, $p < 0.0001$). The G_{reef} measured by Perry et al. (2013) in the Caribbean also fell close to a 1 : 1 line with Lough^{SST}, but the posi-

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tive trend was not significant, either when considering just this data sub-set ($R^2 = 0.74$, $p = 0.14$, $n = 4$), or all ΔTA measured G_{reef} ($R^2 = 0.57$, $p = 0.14$, $n = 11$). The average regional G_{reef} estimated by all models showed little geographic difference (Fig. 7), which conflicts with the conclusions of Vecsei (2004) who found the Atlantic, including Caribbean reefs, had the highest G_{reef} of all regions, followed by the Pacific and GBR (Table 5).

The Silverman$^{SST\Omega}$ model produced a global average G_{reef} (0.21 g cm^{-2} yr^{-1}) that falls within Vecsei's (2004) estimated range (0.09–0.27 g cm^{-2} yr^{-1}) but all other models were in excess of this (Table 5). Similarly, all model estimates of G_{global} (1.10–4.32 Pg yr^{-1}; Table 5) exceed estimates by Vecsei (2004; 0.65–0.83 Pg yr^{-1}). This difference was greatest for Kleypas$^{Irr\Omega}$ and Lough^{SST} (3.06 and 4.32 Pg yr^{-1} respectively). Global reef area (the area sum of all model cells where $G_{coral} > 0$ g cm^{-2} yr^{-1} and with the 10 % reefal area applied) varies significantly between models (Table 5). ReefHab^{Irr} designates 195 × 10^3 km^2 as global reef area, which is less than that reported by Vecsei (2004; 304–345 × 10^3 km^2), however, the other model setups estimate almost double this (500–592 × 10^3 km^2).

4 Discussion

Four coral reef carbonate production models, contrasting in terms of dependent environmental controls, were evaluated at local, regional and global scales. The results show that SST (Lough^{SST}) can be used to predict G_{coral}, and to a degree G_{reef} (Fig. 6). However, there is a large disparity between empirical and all four model estimates of G_{global} (Table 5), with the Lough^{SST} G_{global} estimate approximately a factor of five greater than previous estimates by Milliman (1993) and Vecsei (2004). Because empirical estimates of G_{global} cannot themselves be evaluated, it is necessary to examine the factors involved in the estimation of G_{global}. For example, the global reef area used in extrapolating G_{reef} to empirically estimate G_{global} may have a significant effect.

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The Lough^{SST} model achieves a global reef area of 567×10^3 km^2, comparable to that used by Milliman (1993) of 617×10^3 km^2 (Smith, 1978). Whereas Vecsei (2004) used a revised reef area of 304–345 $\times 10^3$ km^2 (Spalding and Grenfell, 1997) almost half the size. Despite this difference in global reef area used, Milliman (1993) and Vecsei (2004) estimate comparable values of G_{global}, further confounding evaluation of modeled G_{global}. The question of where to draw the line in terms of establishing reef boundaries is highly pertinent to modeling G_{global} as it dictates the area considered to be "coral reef". In this analysis, all grid cells with positive $CaCO_3$ production (i.e. $G > 0$ g cm^{-2} yr^{-1}) are considered to contain coral reef, even those that may be close to 0 g cm^{-2} yr^{-1}. Recently formed (immature) reefs with coral communities that have positive G_{reef} but where little or no $CaCO_3$ framework is present do exist (Spalding et al., 2001) and are accounted for by all four models. However, these coral communities are not included in reef area reported by Spalding and Grenfell (1997) and further information about their production rates and global abundance is needed to accurately quantify their significance in estimating G_{global} empirically. The presence of these coral communities has been correlated with marginal environmental conditions where low (highly variable) temperatures and high nutrient concentrations are seen (Couce et al., 2012). It logically follows that excluding these marginal reefs by tightening the physiochemical mask for SST to > 20 °C, as derived by Couce et al. (2012), would reduce global reef area and may help in the estimation of G_{global}. Further to this is the assumption within GRAM that the area between reef patches in a "reef" cell (i.e. a cell with $G > 0$ g cm^{-2} yr^{-1}) accounts for 90 % of the cell's area, with only 10 % assumed to be composed of suitable substrate for reef formation and coral recruitment. The availability of suitable substrate has the greatest impact on the biogeography of coral reefs (Montaggioni, 2005) and so clearly needs to be evaluated to improve G_{global} estimates.

Reef area does not account for all of the disparity between estimates of G_{global}; attenuation of G_{reef} with depth may also be a causal factor. In both Atlantic and Indo-Pacific reefs, there was an exponential trend, decreasing with depth (≤ 60 m), in G_{reef} data synthesized by Vecsei (2001). The empirical data used by Vecsei shows that any mod-

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eled G_{reef} estimates should also decrease with depth exponentially. Lough^{SST} does not include environmental variables that vary as a function of depth and so it produces the same value for G_{reef} throughout the water column. We can account for this model limitation by imposing a light-sensitive correction in the form of an exponential function to the output from Lough^{SST} so that G_{reef} is a function of surface G_{reef} (G_{surf}) and depth (z; Eq. 19):

$$G_{reef} = G_{surf} \cdot e^{-k_g z} \quad (19)$$

where k_g is a constant controlling the degree of attenuation with depth, in this estimate K_{490} was used. Equation (19) has the same form as that for calculating light availability (Eq. 3) used in both ReefHab^{Irr} and Kleypas$^{Irr\Omega}$. Lough^{SST} G_{global} is reduced to 2.56 Pg yr^{-1} as a result, which is closer to empirical estimates. Because light availability alone does not show significant skill in predicting G_{coral} or G_{reef} (ReefHab^{Irr} and Kleypas$^{Irr\Omega}$ in Fig. 6) it must be implemented within Lough^{SST} and not alone, as in ReefHab^{Irr}.

A further factor that strongly affects G_{reef} and G_{global} estimates is the percentage of the reef covered by calcifying organisms (reduced as the term "live coral cover" although implicitly including other calcifiers). Applying the global average LCC of 30 % clearly does not account for the large spatial and temporal variation in LCC (< 1–43 % in the dataset collated here; Table 4). Indeed, LCC on few (4/46) Pacific islands collated by Vroom (2011) were found to be ≥ 30 % between 2000 and 2009. The global average of 30 % was calculated from surveys of 1107 reefs between 1997 and 2001 (Hodgson and Liebeler, 2002) and represents total hard coral cover (LCC plus recently killed coral), so is an overestimate of LCC. Lough^{SST} has significant skill in replicating observed G_{coral} and has some skill in predicting G_{reef} values observed by a standardized census method (ReefBudget; Perry et al., 2012), but only when the local observed LCC is applied. However, if the global average LCC is applied the correlation with G_{reef} is lost. In addition, the global average LCC may also account for the uniformity of regional G_{reef} values (Fig. 7), in contrast to the significant differences between regions

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identified by Vecsei (2004). For example, the Atlantic reefs (including the Caribbean) having the greatest G_{reef} (0.8 g cm^{-2} yr^{-1}) and reefs in the Indian Ocean the smallest G_{reef} (0.36 g cm^{-2} yr^{-1}; Vecsei, 2004; Table 5). The pattern is reversed for coral cover with Indo-Pacific reefs having ~ 35 % hard coral cover compared to ~ 23 % on Atlantic reefs (Hodgson and Liebeler, 2002). Further studies have shown that Caribbean reefs have greater G_{reef} and vertical accumulation rates than Indo-Pacific reefs, which is thought to be due to less competition for space (Perry et al., 2008). These issues highlight the need for LCC to vary dynamically within models, allowing LLC to vary spatially and temporally according to coral population demographics (mortality, growth and recruitment).

A specific example of unrealistic G_{reef} is seen for the Gulf of Carpentaria, where there are no known currently-accreting reefs (Harris et al., 2004) but carbonate production is particularly extreme in the Lough^{SST} model (Fig. 4). At least seven submerged reefs have been discovered in the Gulf of Carpentaria and a further 50 may exist, but these reefs ceased growth ~ 7 kyr BP when they were unable to keep-up with sea level rise (Harris et al., 2008). Failure to repopulate may be due to a combination of factors including very low larval connectivity in the Gulf of Carpentaria (Wood et al., 2014) and high turbidity, due to re-suspension of bottom sediments and particulate input from rivers (Harris et al., 2008). ReefHab^{Irr} is the only model to predict an absence of reef accretion in the majority of the Gulf (Fig. 4) indicating model sensitivity to light attenuation is essential. This example also raises two further points: firstly, that there are certainly undiscovered reefs that are not accounted for in empirical estimates of G_{global} and, secondly, that larval connectivity should be considered in simulations of G_{reef} because of its role in regulating LCC after disturbance (Almany et al., 2009; Jones et al., 2009).

In addition to static LCC, growth parameters (G_{max}, Eq. 2; E_k, Eqs. 2 and 6; k_{day}, Eq. 7; k_{dark}, Eq. 8; k'_r and k'_p, Eq. 18) did not vary geographically, having the same value in all model grid cells. This may have affected the skill of Kleypas$^{Irr\Omega}$ in reproducing G_{coral} and G_{reef} since in the original application of the model (Kleypas et al., 2011) parameters (k_{day}, k_{dark} and E_k) were determined from observations at the location of the reef transect that was simulated. However, when looking at the correlation of model to data it is important to acknowledge the observational variability and error. The standard deviation, where reported, for census-based and ΔTA measured G_{reef} is ≤ 100 % of the mean (Table 4). In addition to this variability, observational error is greater in census-based measurements of G_{reef} than ΔTA measurements (Vecsei, 2004). In a review of reef metabolism, G_{reef} was shown to vary considerably (0.05–1.26 g cm^{-2} yr^{-1}) depending on the LCC and CCA abundance (Gattuso et al., 1998). G_{reef} (measured by ΔTA) appears to vary little across Pacific coral reefs (Smith and Kinsey, 1976) but Gattuso et al. (1998) attribute this to the similarity of these reefs in terms of community structure and composition, as well as LCC. The apparent agreement between Lough^{SST} and Caribbean G_{reef} reported by Perry et al. (2013) indicates that a standardized experimental methodology for measuring G_{reef} is needed and implementing this would also provide a consistent dataset for model evaluation. Unexpectedly, this result also suggests that Lough^{SST} may have skill in predicting G_{reef} in the Atlantic Ocean despite the absence of massive *Porites* sp. on which the Lough^{SST} model is built. *Porites* is a particularly resilient genera (e.g. Barnes et al., 1970; Coles and Jokiel, 1992; Loya et al., 2001; Hendy et al., 2003; Fabricius et al., 2011) and so applicability to other reef settings, coral genera and calcifiers as a whole is surprising. G_{coral} of a single species has been used in some census-based studies to calculate the G_{coral} of all scleractinian corals present (Bates et al., 2010) and the Lough^{SST} results suggest this generalization may be appropriate.

Unlike census-based and ΔTA methodologies, G_{coral} measured from coral cores span multiple centuries (Lough and Barnes, 2000) and so smooth the stochastic nature of coral growth and variations in reef accretion. G_{coral} and G_{reef} do vary a great deal temporally. For example, diurnal fluctuations may be up to five fold and result in net dissolution at night (e.g. Barnes, 1970; Chalker, 1976; Barnes and Crossland, 1980; Gladfelter, 1984; Constantz, 1986; McMahon et al., 2013). At intermediate time scales (weekly–monthly) G_{coral} may vary by a factor of three, with a degree of sea-

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sonal chronology (Crossland, 1984; Dar and Mohammed, 2009; Albright et al., 2013). Over longer time scales (≥ 1 yr), G_{coral} is less variable (Buddemeier and Kinzie, 1976) and both Hatcher (1997) and Perry et al. (2008) describe reef processes hierarchically according to temporal and spatial scales, finding that time spans of a year or more are required to study processes of reef accretion. The numerous observations of G_{coral} measured from coral cores is a further advantage over the sparse census and ΔTA determinations of G_{reef} which are generally more costly and labor-intensive. More observations of G_{reef} are, however, essential to improve statistical power and evaluation of model outputs. G_{reef} is also invaluable from a monitoring perspective (reviewed by Baker et al., 2008; e.g. Ateweberhan and McClanahan, 2010) by providing an effective measure of reef health that encompasses the whole reef community and accounting for different relative compositions of corals and algae (Vroom, 2011; Bruno et al., 2014). These benefits provide impetus for future measurements of G_{reef} and our results demonstrate that a standardization of the methodology (as demonstrated in Perry et al., 2013) must be applied.

This study has shown that it is possible to predict global variations in coral carbonate production rates (G_{coral}) with significant skill simply as a function SST ($Lough^{SST}$). However, we find that no model has no significant skill in capturing global patterns of G_{reef}. Successful up-scaling of carbonate production to the reef (G_{reef}) and global domain (G_{global}) will require accounting for both depth attenuation (e.g. light sensitivity) and inclusion of population demographics affecting live coral cover (LCC). An ecosystem modeling approach that captures demographic processes such as morality and recruitment, together with growth, would result in a dynamically and spatially varying estimate of LCC. It is also clear that a standardized methodology for census-based measurements is required, as evident from the improved model–data fit in a subset of data collected using the ReefBudget methodology. Coral calcification rates have slowed by an estimated 30 % in the last three decades (e.g. Bruno and Selig, 2007; Cantin et al., 2010; De’ath et al., 2013; Tanzil et al., 2013) reinforcing the pessimistic prognosis for reefs into the future under climate change (e.g. Hoegh-Guldberg et al.,

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2007; Couce et al., 2013; Frieler et al., 2013); numerical modeling is an essential tool for validating and quantifying the severity of these trends.

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Table 1. Summary of calcification models implemented in the global reef accretion model (GRAM) framework.

	$\text{ReefHab}^{\text{Irr}}$	$\text{Kleypas}^{\text{Irr}\Omega}$	$\text{Lough}^{\text{SST}}$	$\text{Silverman}^{\text{SST}\Omega}$
Source	Kleypas (1997)	Kleypas et al. (2011)	Lough (2008)	Silverman et al. (2009)
Application or Formulation	Predicting changes to reef habitat extent, globally, since last glacial maximum.	Seawater carbonate chemistry changes on a transect in Moorea, French Polynesia[a].	Derived from coral core (*Porites* sp.) measurements and temperature form the HadISST dataset (Rayner et al., 2003).	Future climate simulations at reef locations provided by ReefBase[b].
Scale applied	Global	Reef	Colony	Reef/Global
E_{surf}	✓	✓	–	–
Ω_a	–	✓	–	✓
SST	–	–	✓	✓
Units	$\text{mm m}^{-2}\,\text{yr}^{-1}$	$\text{mmol m}^{-2}\,\text{h}^{-1}$	$\text{g cm}^{-2}\,\text{yr}^{-1}$	$\text{mmol m}^{-2}\,\text{yr}^{-1}$

[a] Model output was compared to alkalinity changes measured in situ at Moorea by Gattuso et al. (1993, 1996, 1997); Boucher et al. (1998).

[b] ReefBase: A Global Information System for Coral Reefs (http://www.reefbase.org).

Table 2. Environmental data description (variable name, units, temporal and spatial resolution), and their sources, used to produce the physio-chemical domain mask (ranges shown) and force the calcification models (ReefHab^{Irr}, Kleypas$^{Irr\Omega}$, Lough^{SST} and Silverman$^{SST\Omega}$) in the global reef accretion model (GRAM) framework.

Variable	Unit	Temporal	Spatial	Mask Range	ReefHab^{Irr}	Kleypas$^{Irr\Omega}$	Lough^{SST}	Silverman$^{SST\Omega}$	Source
SST	°C	Monthly	1°	18.0–34.4	–	–	✓	✓	WOA 2009 (Locarnini et al., 2010) http://www.nodc.noaa.gov/OC5/WOA09/netcdf_data.html
Salinity	‰	Annual	1°	23.3–41.8	–	–	–	–	WOA 2009 (Antonov et al., 2010) http://www.nodc.noaa.gov/OC5/WOA09/netcdf_data.html
Bathymetry	m	–	1/60°	≤ 100	✓	✓	–	–	GEBCO One Minute Grid https://www.bodc.ac.uk/data/online_delivery/gebco/
PAR	dW m^{-2}	Daily	0.5°	–	✓	✓	–	–	Bishop's High-Resolution (DX) Surface Solar irradiance (Lamont-Doherty Earth Observatory, 2000) http://rda.ucar.edu/datasets/ds741.1/
k_{490}	m^{-1}	Annual	1/12°	–	✓	✓	–	–	OceanColor (2013) http://oceancolor.gsfc.nasa.gov/
Ω_a	–	Decadal	3.6° × 1.8°	–	–	✓	–	✓	University of Victoria's Earth System mate Model (Weaver et al., 2001; Schmittner et al., 2009; Turley et al., 2010)

SST – sea surface temperature; WOA – World Ocean Atlas; GEBCO – general bathymetric chart of the Oceans; BODC – British Oceanographic Data Centre; PAR – surface photosynthetically available radiation; k_{490} – 490 nm light attenuation coefficient; Ω_a – aragonite saturation.

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Table 3. Details of studies used for evaluating model calcification rates; observed coral calcification rates (G_{coral}) derived from annual density banding in coral cores; " – " indicates fields that were not reported. Full data, including values of G_{coral}, are supplied in online Supplement. Studies are listed alphabetically by their ID.

ID	Source	Sea/Region	Genus	No. Sites	Period Observed	Latitude °N	Longitude °E
Ca	Carricart-Ganivet and Merino (2001)	Gulf of Mexico	Montastrea	6	1968–1991	19.08 to 22.53	264.15 to 270.35
Ch	Chen et al. (2011)	South China Sea	Porites	1	–	22.45	114.69
Co	Cooper et al. (2012)	Western Australia	Porites	6	1900–2010	−28.47 to −17.27	113.77 to 119.37
De	De'ath et al. (2009)	GBR	Porites	69	1900–2005	−23.55 to −9.58	142.17 to 152.75
Ed	Edinger et al. (2000)	Java Sea	Porites	5	1986–1996	−6.58 to −5.82	110.38 to 110.71
Fa	Fabricius et al. (2011)	Papua New Guinea	Porites	3	–	−9.83 to −9.74	150.82 to 150.88
Gr	Grigg (1982)	Hawaii	Porites	14	–	19.50 to 28.39	181.70 to 204.05
He	Heiss (1995)	Gulf of Aqaba	Porites	1	–	29.26	34.94
Po	Poulsen et al. (2006)	Arabian Gulf	Porites	4	1968–2002	27.20 to 28.35	48.90 to 49.96
Sc	Scoffin et al. (1992)	Thailand	Porites	11	1984–1986	7.61 to 8.67	97.65 to 98.78
Sh	Shi et al. (2012)	South China Sea	Porites	1	1710–2012	9.90	115.54

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Table 4. Details of studies used for evaluating model calcification rates; observed calcification rates are for the reef community (G_{reef}) and are derived from census-based methods or alkalinity reduction experiments (ΔTA); " – " indicates fields that were not reported. Studies are listed alphabetically by their ID.

	ID	Source	Region	Genus or Groups	G_{reef} ± SD ($g\,cm^{-2}\,yr^{-1}$)	Cover ± SD (%) Coral	CCA	No. Sites	Period Observed	Latitude °N	Longitude °E
CENSUS-BASED	Ea	Eakin (1996)	Panama	Pocillopora and CCA	0.37 ±0.08	30 ±30	63 ±32[a]	–	1986–1995	7.82	278.24
	Gl	Glynn et al. (1979)	Galapagos	Pocillopora and CCA[b]	0.58	26–43		2	1975–1976	−1.22	269.56
	Hy	Harney and Fletcher (2003)	Hawaii	Porites, Montipora and CCA	0.12 ±0.04 ±27	32	44 ±29	60	–	21.41	202.27
	Ht	Hart and Kench (2007)	Torres Strait	Corals, CCA, Halimeda, foraminifera, molluscs	0.17 ±0.18	43	47	–	–	−10.21	142.82
	Hu	Hubbard et al. (1990)	St Croix	Montastrea, Agaricia, Porites and CCA[b]	0.12	16	59	4	–	17.78	295.19
	La	Land (1979)	Jamaica	Acropora, Montastrea, Agaricia and red/green algae[b]	0.52	30 ±16	–	–	–	18.55	282.60
	P1	Perry et al. (2013)	Bonaire	Montastrea, Agaricia, Diploria, Millepora and CCA	0.54 ±0.54	19 ±12	–	30	2010–2012	12.09	291.79
	P2		Belize		0.30 ±0.21	16 ±7	–	36		16.66	272.00
	P3		Grand Cayman		0.30 ±0.20	12 ±6	–	26		19.30	278.92
	P4		Bahamas		0.16 ±0.05	7 ±3	–	9		25.41	283.28
	St	Stearn et al. (1977)	Barbados	7 coral genera and CCA	0.90	37 ±22	41 ±14	6	1969–1974	13.20	300.36
ΔTA	Al	Albright et al. (2013)	GBR	NEC	0.48 ±0.48	9 ±2	8.5 ±3.5	1	Aug and Dec 2012	−18.33	147.65

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Table 4. Continued.

	ID	Source	Region	Genus or Groups	G_{reef} ± SD ($g\,cm^{-2}\,yr^{-1}$)	Cover ± SD (%) Coral	CCA	No. Sites	Period Observed	Latitude °N	Longitude °E
ΔTA	G1	Gattuso et al. (1993)	French Polynesia	NEC	0.09	16[c] (1–31)	–	2	Nov and Dec 1991	−17.48	210.00
	G2	Gattuso et al. (1996)	French Polynesia	NEC	0.68	16[d]	4–21	2	Jul and Aug 1992	−17.48	210.00
			GBR	NEC	0.92	30	–	2	Dec 1993	−14.58	145.62
	G3	Gattuso et al. (1997)	French Polynesia	NEC	0.003 ± 0.002	∼ 1	∼ 3	1	Jul 1992	−17.48	210.00
	Ka	Kayanne et al. (1995)	Japan	NEC	0.37	19[e]	< 1[e]	1	Mar 1993 and 1994	24.37	124.25
	La	Lantz et al. (2014)	Hawaii	NEC	0.60 ± 0.15	14	5	2	Apr 2010–May 2011	21.38	202.26
	Na	Nakamura and Nakamori (2009)	Japan	NEC	0.16 ± 0.27	20 ± 19	–	10	Aug 2004, Jun–Aug 2006 and Jul/Aug 2007	24.37	124.25
	Oh	Ohde and van Woesik (1999)	Japan	NEC	0.79	22	2	2	Oct 1993–Oct 1995	26.17	127.50
	Sh	Shamberger et al. (2011)	Hawaii	NEC	0.72 ± 0.36	30	–	2	Jun 2008, Aug 2009 and Jan/Feb 2010	21.47	202.19
	Si	Silverman et al. (2007)	Gulf of Aqaba	NEC	0.18 ± 0.09	35[c] (30–40)	–	4	2000–2002	29.51	34.92
	Sm	Smith and Harrison (1977)	Marshall Islands	Acropora, Montipora and CCA	0.44 ± 0.66	14 ± 10	58 ± 30	–	–	11.45	162.37
	SP	Smith and Pesret (1974)	Line Islands	NEC	0.1	30	–	100	Jul/Aug 1972	4.00	201.00

CCA – crustose coralline algae; NEC – net ecosystem calcification.
[a] The value for CCA cover is the average of the % framework reported by Eakin (1996) that is defined as the area of dead coral upon which CCA grows.
[b] Authors note that the underlying assumptions for calculating calcification by algae may be unrealistic but make best use of the available data at the time of the study.
[c] Median LCC values of the reported ranges were applied to model ouput for the regression analysis.
[d] The LCC range reported by Gattuso et al. (1993) was assumed to be the same as in the subsequent study at Moorea (Gattuso et al., 1996).
[e] Values reported in Suzuki et al. (1995) for study conducted in 1991 (Nakamori et al., 1992) at the same location.

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Table 5. Average regional and global reef calcification rates (G_{reef}) and global $CaCO_3$ budgets (G_{global}) and reef areas derived from the four model setups (≤ 40 m) and Vecsei (2004). Model G_{reef} is calculated as the total $CaCO_3$ production multiplied by global average live coral cover (LCC) of 30 % (Hodgson and Liebeler, 2002) and 10 % seabed reefal area with the exception of $ReefHab^{Irr}$, which uses a function of seabed topographic relief to modify total $CaCO_3$ production to give G_{reef}. Global reef area is 10 % of the total area accounting for inter-reefal area.

Ocean Region	G_{reef} ± SD (≤ 40 m; $g\,cm^{-2}\,yr^{-1}$)								
	$ReefHab^{Irr}$		$Kleypas^{Ir\Omega}$		$Lough^{SST}$		$Silverman^{SS\Omega}$		Vecsei (2004)
Caribbean Sea	0.86	±0.32	0.61	±0.07	0.82	±0.09	0.23	±0.05	0.80 and
North Atlantic Ocean	0.74	±0.40	0.44	±0.22	0.59	±0.21	0.17	±0.10	0.01[a]
South Atlantic Ocean	0.51	±0.35	0.40	±0.27	0.57	±0.25	0.16	±0.10	
Indian Ocean	0.65	±0.36	0.54	±0.17	0.82	±0.17	0.22	±0.08	0.36
North Pacific Ocean	0.67	±0.35	0.49	±0.22	0.70	±0.22	0.20	±0.11	0.65
South Pacific Ocean	0.67	±0.30	0.61	±0.20	0.93	±0.21	0.29	±0.12	
GBR	0.66	±0.31	0.67	±0.05	0.76	±0.04	0.25	±0.04	0.45
Global Metrics (≤ 40 m)									
G_{global} ($Pg\,yr^{-1}$)	1.40		3.06		4.32		1.10		0.65–0.83
Reef area ($\times 10^3\,km^2$)	195		592		567		500		303–345
G_{reef} ± SD ($g\,cm^{-2}\,yr^{-1}$)	0.65 ± 0.35		0.51 ± 0.21		0.72 ± 0.35		0.21 ± 0.11		0.09–0.27

[a] Values of G_{reef} for Atlantic/Caribbean framework and biodetrital reef respectively.

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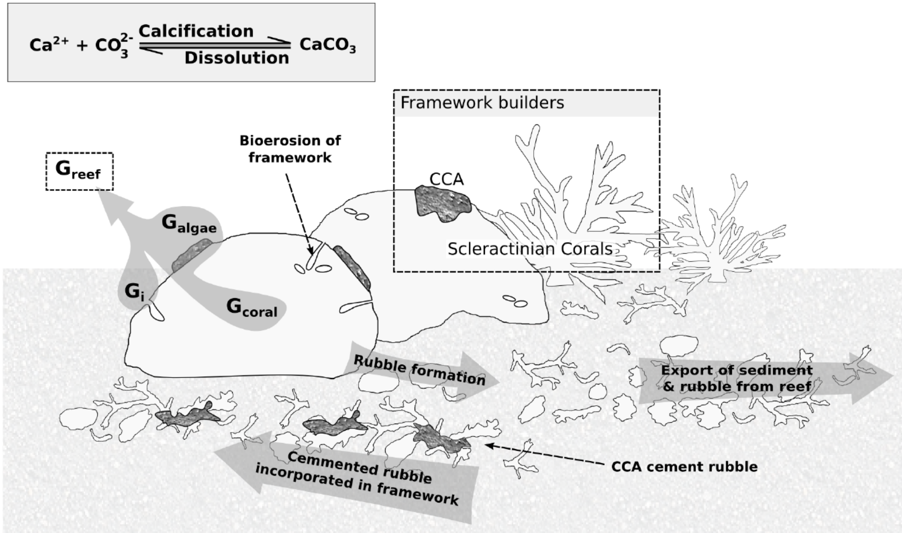

Figure 1. Schematic illustrating the coral reef carbonate budget and the modeled parameters (G_{reef} and G_{coral}) used to quantify carbonate production. Carbonate framework is principally produced by scleractinian corals (G_{coral}) and crustose coralline algae (CCA; G_{algae}); the abiotic (inorganic) precipitation of carbonate cements (G_i) also occurs. Bioeroders breakdown the reef framework internally (e.g. worms, sponges) and externally (e.g. parrot fish, crown-of-thorns starfish). The rubble produced is incorporated back in to the framework, by cementation or burial, or exported from the reef. The observational data available to test models of carbonate budget include G_{coral} measured from coral cores, and G_{reef} calculated from a reef community census or the total alkalinity of surrounding seawater.

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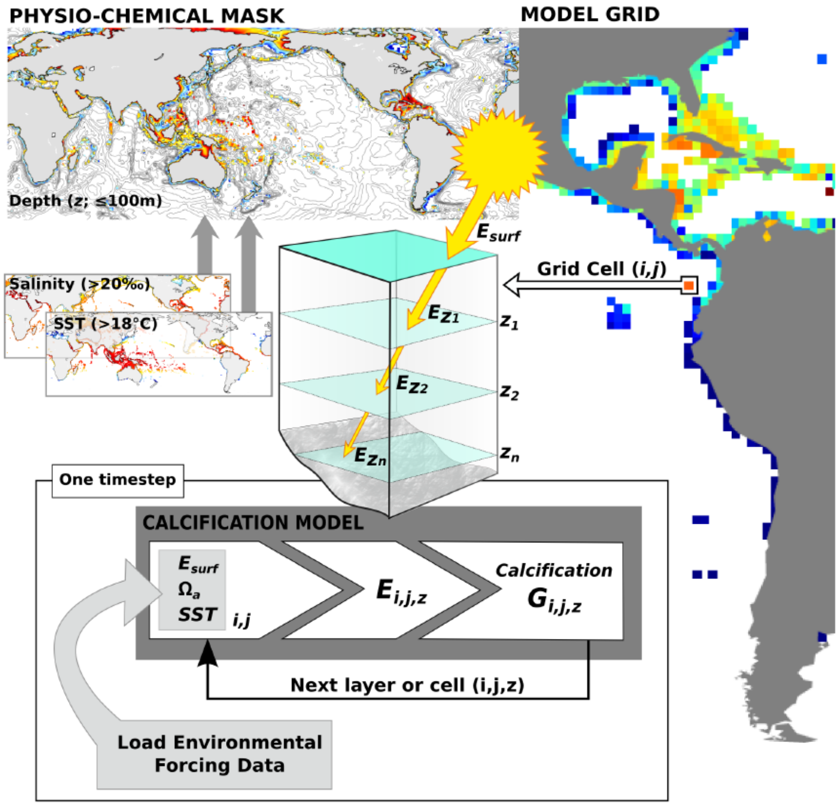

Figure 2. Schematic of logical steps at each timestep within GRAM. GRAM's domain is defined by a bathymetric and physiochemical mask within which calcification is calculated, at each timestep and in every domain grid cell, according to the calcification model used. Where calcification is modeled as a function of light, the availability of light at depth (E_z) is calculated for each model layer (z_i).

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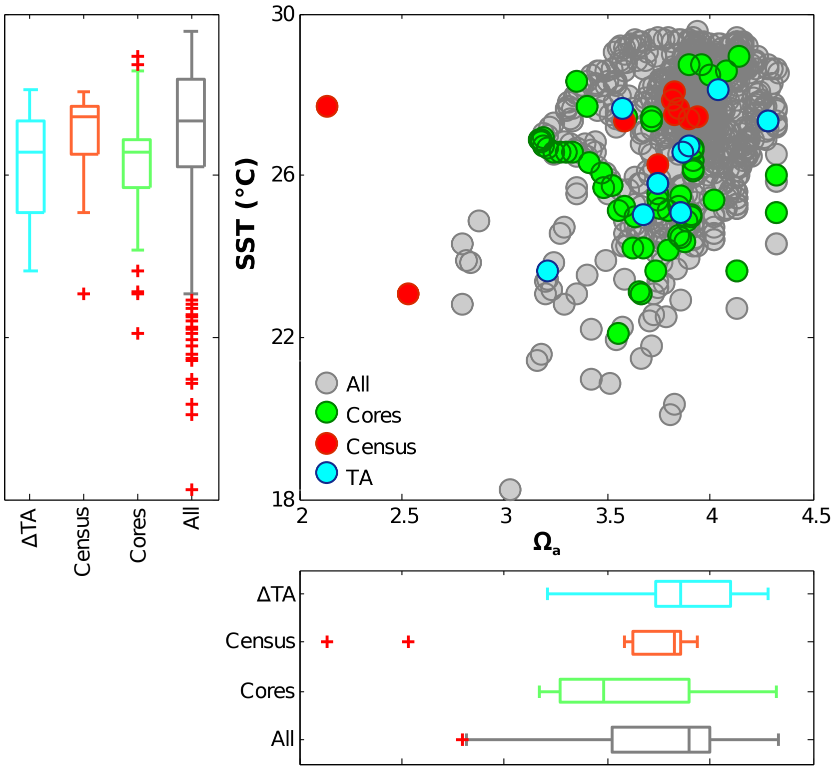

Figure 3. Distribution of sea surface temperatures (SST) and aragonite saturation (Ω_a) at: (All) reef locations (ReefBase: A Global Information System for Coral Reefs. April 2014. http://www.reefbase.org); (Cores) coral core data locations; (Census) census-based study and (ΔTA) ΔTA study locations. SST values are taken from WOA 2009 annual average values (Locarnini et al., 2010) and Ω_a values are derived from UVic model (Weaver et al., 2001; Schmittner et al., 2009; Turley et al., 2010) output. The range, 25th and 75th percentiles, median lines and outliers of SST and Ω_a are displayed in the box and whisker plots.

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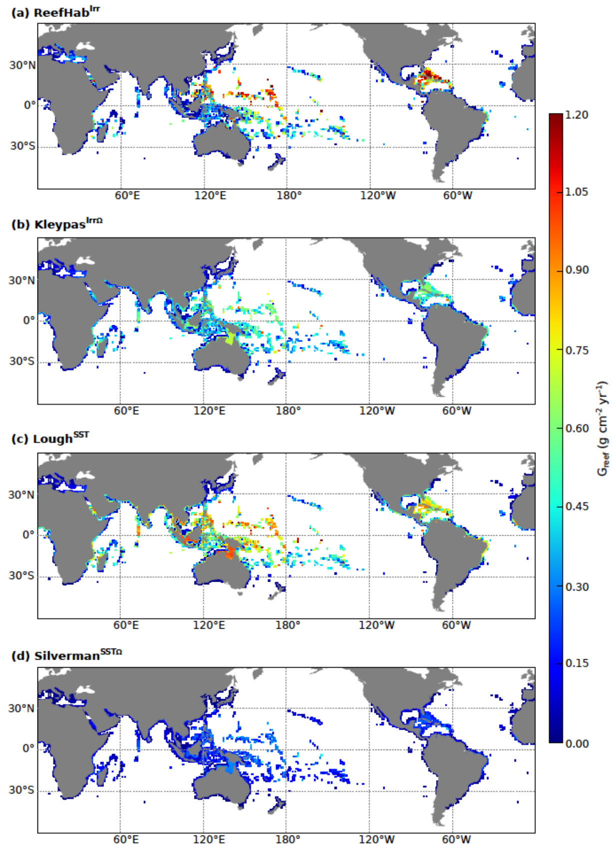

Figure 4. Model outputs of reef carbonate production. Depth integrated (≤ 40 m) $CaCO_3$ production, with 30 % live coral cover (LCC) and 10 % seabed reefal area (G_{reef}) for: **(a)** ReefHab^{Irr}, **(b)** Kleypas^{IrrΩ}, **(c)** Lough^{SST} and **(d)** Silverman^{SSTΩ}. G_{reef} values displayed are aggregated from the model resolution (0.25°) to a 1° grid to facilitate visualization.

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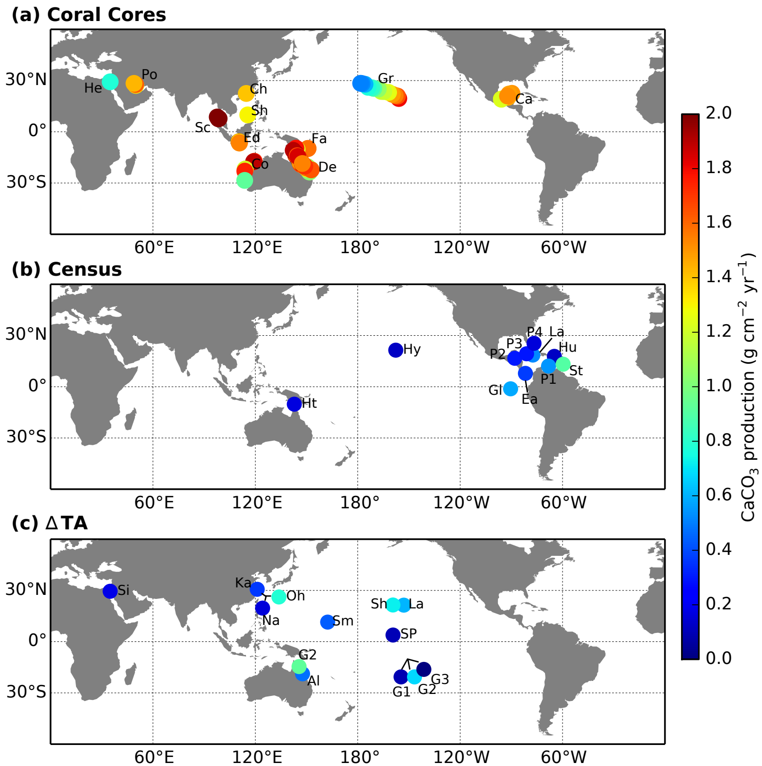

Figure 5. Compilation of published reef carbonate production measurements. Location and magnitude of: **(a)** coral calcification (G_{coral}) observed in coral cores and, reef community calcification (G_{reef}) measured in **(b)** census-based and **(c)** ΔTA studies (see Tables 4 and 5 for study ID keys).

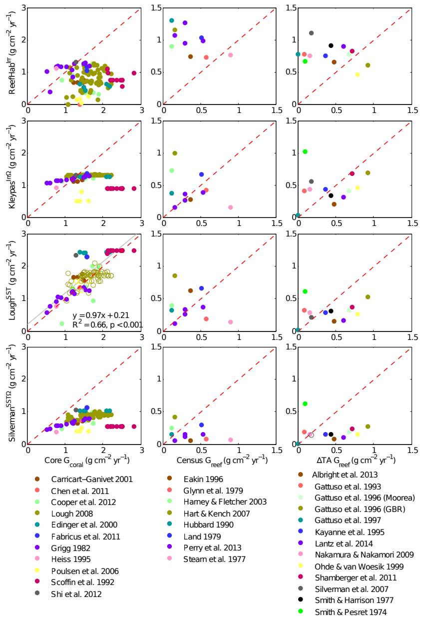

Figure 6. Correlation of observed coral calcification (G_{coral}) and reef community calcification (G_{reef}) to model predictions (1 : 1 relationship shown as red dashed line). All model estimates are multiplied by the live coral cover (LCC) reported in the observation studies to give G_{reef}, except ReefHab^{Irr} in which G_{reef} is calculated using a function of topographic relief (TF). The use of TF follows the method of Kleypas (1997); it was derived from empirical observation of reef growth and was a means to scale potential calcification (G_{coral}) to produce G_{reef} in the absence of global data for LCC. All significant linear regressions are plotted ($p < 0.05$; grey solid line) with equation and regression coefficient (R^2). Data used to develop a model are also plotted (open circles) but were excluded from the regression analysis to preserve data independence.

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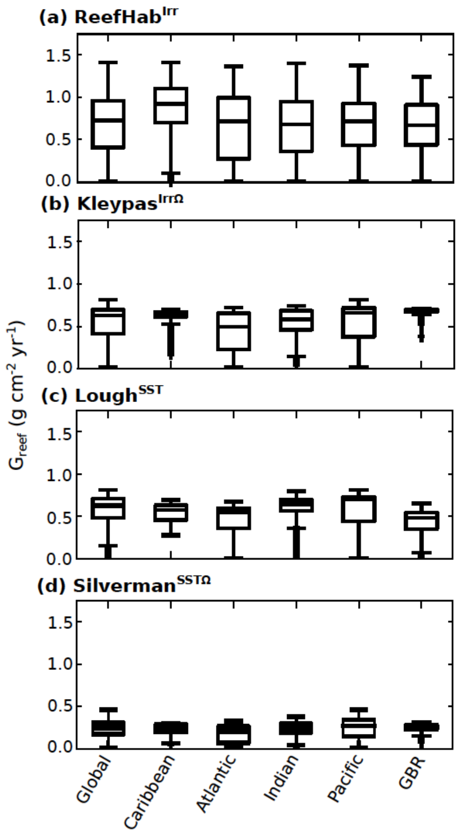

Figure 7. Box and whisker plots of model estimates for global and regional $CaCO_3$ production. A live coral cover (LCC) of 30 % is applied. Range (whiskers), 25th and 75th percentiles (boxes), median (red line), and data outliers (+) are plotted.

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