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Assessing the remaining carbon budget through the lens of policy-driven acidification and temperature targets

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Abstract

Basing a remaining carbon budget on warming targets is subject to uncertainty due to uncertainty in the relationship between carbon emissions and warming. Framing emissions targets using a warming target therefore may not prevent dangerous change throughout the entire Earth system. Here, we use a climate emulator to constrain a remaining carbon budget that is more representative of the entire Earth system by using a combination of both warming and ocean acidification targets. The warming targets considered are the Paris Agreement targets of 1.5 and 2 °C; the acidification targets are −0.17 and −0.21 pH units, informed by aragonite saturation states where coral growth begins to be compromised. The aim of the dual targets is to prevent not only damage associated with warming, but damage to corals associated with atmospheric carbon and ocean acidification. We find that considering acidification targets in conjunction with warming targets narrows the uncertainty in the remaining carbon budget, especially in situations where the acidification target is more stringent than, or of similar stringency to, the warming target. Considering a strict combination of the two more stringent targets (both targets of 1.5 °C warming and −0.17 acidification must be met), the carbon budget ranges from −74.0 to 129.8PgC. This reduces uncertainty in the carbon budget from by 29% (from 286.2PgC to 203.8PgC). This reduction comes from reducing the high-end estimate of the remaining carbon budget derived from just a warming target. Assuming an emissions rate held constant since 2021 (which is a conservative assumption), the budget towards both targets was either spent by 2019 or will be spent by 2026.

Plain language summary The relationship between atmospheric CO_2 and warming is uncertain, which means that we do not know precisely how much carbon we have left to emit until we reach the Paris Agreement warming targets of 1.5 and 2 °C. However, the relationship between atmospheric CO_2 and ocean acidification is better understood, so by considering targets for acidification rather than warming alone, we can narrow down our estimate of how much emitted carbon is acceptable. Including acidification targets as well as warming targets means that we can directly address the issue of ocean acidification, which poses a threat to corals and the ecosystems reliant on them. By considering acidification and warming targets together, we can lower uncertainty in acceptable carbon emissions by 29%.

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1 Introduction

Climate change is one of the defining issues of the twenty-first century. The Paris Agreement (UNFCCC 2015), has been politically adopted by 196 parties and commits countries to an effort to "limit global warming to well below 2 [°C], preferably to 1.5 °C, compared to pre-industrial levels". Therefore, a central aim in climate science is to establish carbon emissions pathways or budgets that are consistent with these warming goals. The concept of a remaining carbon budget (RCB – the allowable carbon emissions remaining before a given climate target is met) is particularly meaningful in this context, as it allows for easy communication between the science and policy spheres regarding the impact of emissions on a complex system (Messner et al. 2010; Rogelj et al. 2019). Conventionally, the RCB is defined with respect to a single target of global mean warming (Rogelj et al. 2016, 2018), which is possible because the relationship between cumulative emissions and global mean warming is approximately linear (Allen et al. 2009; Matthews et al. 2009; Zickfeld et al. 2009; Goodwin et al. 2015). Exploiting this linear relationship allows for the simple calculation of a RCB towards a warming target.

Although calculating the RCB towards a warming target is a useful starting point, it has weaknesses. There is uncertainty in the value of the RCB due to uncertainty in the constant of proportionality (the transient response to climate change, TCRE), and uncertainty in non-CO_2 related warming. Uncertainty in the TCRE (with a likely range of 1.0 to 2.3 K EgC^{-1} (1000 to 23,000 K PgC^{-1}) in IPCC AR6, 2021 (Forster et al. 2021)) leads to an RCB for 1.5 °C ranging from of 0.65 to 1.5 EgC (650 to 1500 PgC). Political or sociological uncertainties increase this range even further (Rogelj et al. 2016). As well as this, the UNFCCC definition of the climate system is 'the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions' (UNFCCC 1992). The stated aim of avoiding dangerous climate change therefore, by definition, includes the protection of sustainable oceans, food production and ecosystems. Following this logic, the uncertainty associated with carbon emission pathways towards a 2 °C temperature change could mean carbon emissions that are on track with the Paris goals, but that would still cause dangerous change to the climate system as a whole (Steinacher et al. 2013), with carbon-associated changes predicted to ocean acidity and net primary production on land. Further, even if warming is restricted to 1.5 °C, at least 90% of all reef areas will be at risk of long-term degradation due to both ocean warming and ocean acidification caused by CO_2 uptake (Schleussner et al. 2016). In particular, the reef-building coral *Siderastrea sidera* has been found to react negatively to warming and acidification (with the impacts of both stressors being worse than the impacts of just one), with acidification impacting calcification and skeletal morphology (Horvath et al. 2016). As well as warm water corals, species in high latitude oceans face negative impacts from acidification, with seasonal aragonite undersaturation predicted in the Southern Ocean at 450ppm (McNeil and Matear 2008). Hauri et al. (2016) find that by 2060, surface aragonite undersaturation events will impact ~ 30% of the Southern Ocean following RCP8.5, increasing to more than 70% by 2100. Undersaturation harms the growth of calcifying plankton (for example Limanica helicina (McNeil and Matear 2008)), which has potential knock-on effects for the wider ecosystem.

An ensemble of simulations from a climate emulator (WASP: Goodwin (2016)), using scenarios that restore to either defined warming or defined acidification, finds that the resultant acidification from following warming targets within the range of the Paris Agreement targets (from 1.5 to 2.1 °C of warming) is between -0.135pH (less acidification) and -0.2pH (more acidification). Figure 1a shows the full range of achieved pH from pathways that stabilise at different warming targets. The variation across the ensemble is due to the uncertainty in the

Fig. 1 a The resultant surface ocean acidification from emissions pathways consistent with warming targets between the Paris Agreement warming targets of 1.5- and 2-degrees C. **b** The resultant warming from acidity targets ranging from −0.3 to −0.1

relationship between a given amount of warming and the associated carbon emissions, leading to uncertainty in how much acidification occurs.

Some previous studies have examined ways to create more a representative RCB, including by using targets based on regional extreme temperatures and precipitation (Seneviratne et al. 2016). The relationship is not 1:1 and varies spatially, which has the effect of lowering the RCB by differing amounts depending on which region is being considered. This method does avoid undesirable outcomes related to global mean warming but does not address issues that are related to carbon emissions and not to warming (for example, ocean acidification). The practice of scaling local temperature or precipitation extremes to global mean temperatures is also subject to limitations related to uncertainty in the scaling process, model biases and issues to do with exploring scaling on a local or regional basis. Many of these issues do not apply in the case of this study because the scale

is global, and we are exploiting a well-constrained relationship (i.e., between atmospheric carbon and ocean acidity).

Other studies have examined the RCB under combinations of climate targets, rather than solely (scaled) global mean warming (Steinacher et al. 2013). This is a manageable way to reduce the likelihood of dangerous change to multiple aspects of the climate system, and, like the study by Seneviratne et al. (2016), the use of combinations of climate targets reduces the allowable carbon emissions remaining before these targets are met. The study by Steinacher et al. (2013) is carried out using a set of illustrative targets relating to atmospheric warming, steric sea level rise, ocean aragonite saturation and terrestrial productivity. They find that the RCB is lower for combined targets than for the most restrictive single target in the set, especially in the long term.

Here, we extend an algorithm for generating emissions pathways to reach warming-only targets (Goodwin et al. 2018) to include an additional ocean acidification target, and explore the impact on the RCB of incorporating another climate target. Acidification is used as the accompanying climate target for a few reasons. Firstly, it has been identified as a key issue that impacts many aspects of the ocean ecosystem. Ocean acidification caused by anthropogenic carbon emissions is already causing damage to coral reefs (Kleypas et al. 1999; Hughes et al. 2003; Bruno and Selig 2007), and these impacts are projected to increase as acidification continues (Pelejero et al. 2010; Pandolfi et al. 2011). As well as acidification, ocean ecosystems are facing the impacts of ocean warming, which has the potential to worsen the impact on species and ecosystems. For example, the combination of ocean warming and acidification is predicted to reduce the habitable area for tropical and subtropical corals around Japan by half by 2020–2030 (Yara et al. 2012). The impact of the two stressors together is highly species specific and can also vary with developmental stage, with studies showing that the impacts of the two stressors combined is sometimes synergistic, sometimes antagonistic (Talmage and Gobler 2011; Duarte et al. 2014; Ong et al. 2017).

Also, it is possible to create an acidification target that is relevant to ocean ecosystems. Elevated CO_2 in seawater will increase acidification (via chemical reactions that result in larger concentration of H^+ ions) and reduce aragonitic calcium carbonate ($CaCO_3$) saturation – so ocean pH can be linked to aragonite saturation (Ridgwell and Zeebe 2005; Cao and Caldeira 2008). The saturation state with respect to aragonite is an important modulator of coral growth (Martindale et al. 2012; Guan et al. 2015), the general consensus being that modern shallow water corals require a consistent aragonite saturation state $\Omega_{arag} > 3.4$ to be able to grow. Cao and Caldeira (2008) find that stabilising atmospheric CO_2 at 450ppm will mean only 8% of existing coral reefs will inhabit waters that satisfy these conditions. The link between increased atmospheric CO_2, ocean acidification and aragonite saturation makes it possible to decide on a communicable acidification target that prevents damage to ocean ecosystems that are in danger from acidification. The well-constrained relationship between cumulative emissions and ocean acidification (Steinacher and Joos 2016) will aid in reducing uncertainty in the RCB that is caused by the uncertain relationship between carbon emissions and warming.

Although discussion concerning the impacts of ocean acidification is wide-ranging, there has been little successful effort to address ocean acidification in climate policy (Harrould-Kolieb and Herr 2012; Galdies et al. 2020). In the existing legal framework under the UNFCCC there is no explicit mention of ocean acidification. The Paris agreement, which is arguably the most prominent aspect of climate policy in global discourse, focuses solely on limiting global warming (Oral 2018). There have been multiple proposed ways to ensure that ocean acidification is properly addressed by the UNFCCC mandate (Lamirande 2011; Harrould-Kolieb and Herr 2012; Kim 2012), including the possibility of framing

ocean acidification as an effect of warming-related climate change, rather than a concurrent problem (Harrould-Kolieb and Herr 2012). Putting ocean acidification under the umbrella of warming does mean increased discourse around ocean acidification as an issue and goes some way towards encouraging policy that effectively addresses acidification. However, it is possible to address warming without addressing acidification (e.g., through geoengineering (Zhang et al. 2015)), so the approach is not watertight. An RCB based on an ocean acidification target and a warming target provides a basis to incorporate marine issues into global policy, which have so far been underrepresented in global efforts to mitigate dangerous climate change (Harrould-Kolieb and Herr 2012; Oral 2018; Galdies et al. 2020).

The aim for this study is to quantify carbon emission pathways that are consistent with both warming and ocean acidification targets, and then use these pathways to explore the impact of multiple climate targets on the RCB. To examine this, we propose a pair of mean ocean pH targets that are analogous with the Paris Agreement targets for global mean warming (1.5 and 2 °C warming).

The scientific questions for the study follow these aims, and can be summarised as:

1. What are two pH targets that are analogous to the 1.5 and 2 °C warming targets of the Paris Agreement in terms of feasibility and impacts avoided?
2. How does including these acidification targets change the remaining carbon budget?

2 Methods

The WASP model uses an 'Adjusting Mitigation Pathway' algorithm (AMP) to create carbon emissions pathways that restrict global mean warming to a single policy-driven target (Goodwin et al. 2018). Here, this algorithm is extended to include the option of restricting surface ocean acidification to an additional pre-set target of similar stringency to the Paris Agreement temperature thresholds, to be used either instead of, or in conjunction with, a warming target. Every 10 years until 2150, the algorithm chooses an emissions rate to stabilise towards the more stringent target (here termed a strict scenario), the less stringent target (lenient), or to take the mean of the emissions rate towards each target (a weighted scenario). After 2150, the algorithm removes carbon if it is above the given target and allows carbon emissions if not, but the scale of carbon emissions or drawdown is no longer calculated using the relationship between warming/acidification and cumulative emissions. The rate of carbon drawdown is greater for a greater overshoot. For more details on the algorithm structure, see Section 2.1.

2.1 The WASP model and AMP algorithm

The Warming, Acidification and Sea-level Projector is an 8-box model of the heat and carbon flux between atmosphere (1 box), land (2 boxes) and ocean (5 boxes). 19 parameters describing the climate response to radiative forcing from CO_2, other greenhouse gases and aerosols, and the exchange of carbon and heat between the 8 boxes, are varied randomly within a prescribed range according to Goodwin et al. (2018). Variation of these parameters causes variation between ensemble members. A visual representation of heat and carbon exchange between these boxes is available in Fig. 2.

The model generates a prior Monte Carlo ensemble of 2.5×10^6 simulations with Earth system parameters varied independently according to our current understanding
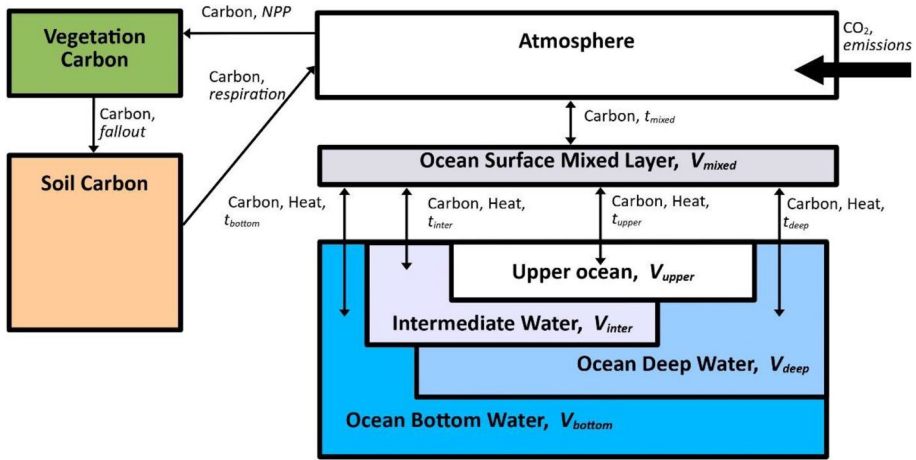
Fig. 2 Schematic of WASP model, adapted from Goodwin 2016

of the climate system (parameters are varied after Goodwin et al. 2018). Of this initial ensemble, only the model runs that are consistent with historical observations of climate characteristics such as surface warming (Ciais et al. 2013; Hartmann et al. 2013; Rhein et al. 2014), ocean heat uptake (Rhein et al. 2014) and ocean carbon uptake (Ciais et al. 2013) are used in projections into the future. This provides a posterior ensemble of around $\sim 10^3$ members out of the original 2.5×10^6. Simulations are allowed into the posterior ensemble if they lie within the 90% range of at least 7 out of 8 of the historical observation checks (see Goodwin et al. 2018 for more detailed explanation).

Uncertainty in processes impacting warming is represented in the model via variations in, e.g., climate sensitivity and ocean heat uptake, and uncertainty in processes impacting acidification are represented via variations the timescale of equilibration between atmosphere and surface ocean, and timescales of ventilation between ocean layers. These parameters are kept constant throughout a simulation but are varied across the ensemble members.

One of the functions of the WASP model is to create adjusting mitigation pathways towards a given climate target. In its original form, the Adjusting Mitigation Pathways (AMP) algorithm (Goodwin et al. 2018) creates pathways towards just a warming target. Here, we expand the AMP algorithm to aim for a warming target and an acidification target. In this section we outline how the AMP algorithm creates pathways towards a target.

The key principle of the AMP algorithm is to calculate a carbon budget ($I_{remaining}$) based off a pre-set climate target, then set the emissions rate (C_{rate}) at time t such that carbon budget described by $I_{remaining}$ is linearly reduced to zero:

$$C_{rate}(t) = C_{rate}(t_n)\left(1 - \frac{t - t_n}{t_{C=0}}\right) \qquad (1)$$

Until $t - t_n = t_{C=0}$, where $t_{C=0}$ is the time at which the carbon emissions rate is reduced to zero (i.e., the carbon budget is used up). This process is repeated every 10 years, to allow for adjustments in the emissions rate that may become necessary in the event of over- or under-estimation of $I_{remaining}$.

$I_{remaining}$ for a given target quantity, X, is defined as

$$I_{remaining}\left(t_n\right) = \left[\Delta X_{target} - \Delta X_{obs}(t_n)\right] / \left[\frac{\Delta X}{\Delta I}\right]\bigg|_{obs} \tag{2}$$

where $\frac{\Delta X}{\Delta I}$, the response of quantity X to emissions, is assumed constant over the 10-year assessment period. For warming, this is the transient climate response to emissions. For acidification, further explanation is given in Section 2.2.

An example pathway resulting from this algorithm is shown in Fig. 3. After 2150 (marked with a vertical line) the algorithm changes so that a linear rate of negative emissions is prescribed if the target has been overshot.
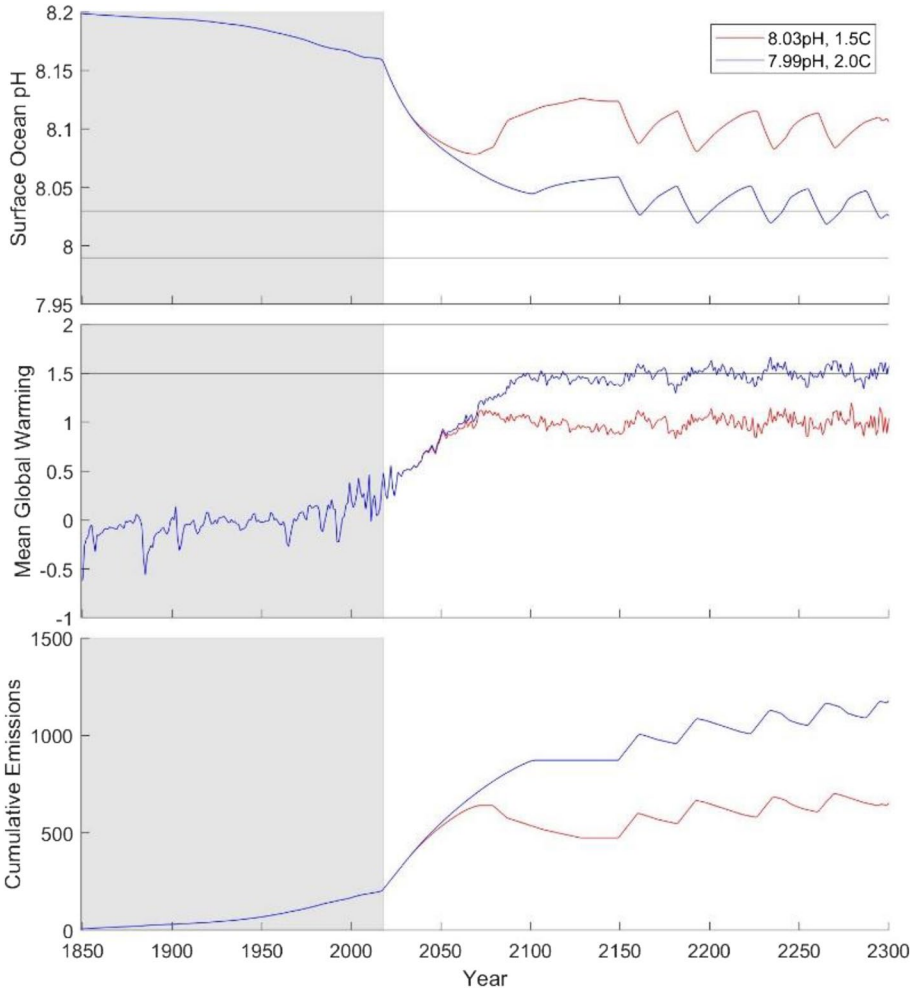
Fig. 3 Example acidification, warming and cumulative emissions pathways following the strict scenario in the AMP algorithm (i.e. the most stringent carbon emissions rate is chosen at each 10-year checkpoint). The red line stabilises towards a warming target of 1.5 (since preindustrial), and a pH target of 8.03. The blue line stabilises towards a warming target of 2.0 (since preindustrial), and a pH target of 7.99. The grey box covers the historical period, where the AMP algorithm is not applied. The vertical line at year 2150 shows where the algorithm changes from an emissions rate calculated using the response of warming or acidification to emissions, from prescribing a rate of emissions based on whether (and by how much) the target is being overshot. Note that the warming appears lower than the target because the algorithm outputs warming relative to zero radiative forcing, rather than relative to the 1850-1900 baseline

2.2 Relating Ocean pH to atmospheric CO_2

Surface ocean pH is closely tied to atmospheric CO_2, since there is an approximately annual timescale for CO_2 exchange between the atmosphere and ocean mixed layer, and seawater pH reduces with ocean CO_2 uptake (Zeebe and Wolf-Gladrow 2001). Thus, any given minimum surface ocean pH target can be accurately expressed as the maximum atmospheric CO_2 that corresponds to that surface ocean pH. However, because of the lag of around a year between a change in atmospheric CO_2 and the corresponding change in surface ocean pH, tuning CO_2 emissions directly to a surface acidification target could lead to acidification stabilising just above the set target. To avoid this issue, we express the ocean acidification (minimum surface pH) target in the algorithm as a maximum atmospheric CO_2, corresponding to that ocean surface pH value once the atmosphere and surface ocean have reached chemical equilibrium. The corresponding atmospheric CO_2 is calculated online using the pre-existing equation within the WASP model relating surface ocean pH to atmospheric carbon:

$$\Delta lnCO_2(limit) = \frac{\Delta pH(target) - C_{pH1}(-\Delta C_{sat})}{C_{pH1}} \tag{3}$$

where ΔC_{sat} is the difference between the current dissolved inorganic carbon concentration, and the dissolved inorganic carbon that brings the surface ocean into equilibrium with atmospheric CO_2. and C_{pH1} and C_{pH2} are coefficients calculated using a perturbation experiment in an explicit numerical carbonate chemistry solver (Follows et al. 2006).

This CO_2 target is then used in the AMP algorithm as a proxy for the surface pH target, with the assumption that the atmospheric fraction of emitted CO_2 (the amount of total emissions that remain in the atmosphere, $\Delta CO_{2.atmos}/I_{em}$), remains roughly constant over the duration of each 10-year assessment period (Friedlingstein et al. 2006), such that the allowable remaining emissions at the beginning of each assessment period is given according to Eq. 2.

2.3 Developing acidification targets analogous to Paris Agreement targets

We begin by considering changes to regional aragonite saturation that would be considered dangerous to local ecosystems—in the tropics, this would most likely be $\Omega_{arag} < 3.4$ as this is the point where coral growth is compromised (Kleypas et al. 1999). It is worth noting that in higher latitudes, $\Omega_{arag} < 1$ is a more pressing threshold, as this is the point at which other calcifying organisms struggle to build their shells (Kleypas et al. 1999). For this exercise we focus on the $\Omega_{arag} < 3.4$ threshold at the tropics, which here we define as the band between 30 degrees North and South of the equator. To create a pair of acidification targets, we use the climate projections of the Hadley Centre UKESM1.0-LL (Good et al. 2019) to find the global mean pH when the area of the tropics that is habitable to corals (where aragonite saturation is above 3.4) reduces to 75% and 50% of the habitable area in 2020. We use projections following SSP245, because the amount of warming in this scenario is great enough to have a favourable signal to noise ratio, and still comfortably within the range of forcing the WASP emulator can simulate (Goodwin 2016; Goodwin et al. 2018).

We use projections of dissolved inorganic carbon, pH, total alkalinity, ocean surface temperature and salinity from UKESM1.0-LL in an offline carbonate solver (Follows et al. 2006) to calculate aragonite saturation for every grid point between 30 degrees north and south of the equator. This calculation is initially done for the years 2015, 2050 and 2100 (maps shown in Online Resource 2). From just these three time points a significant area of ocean with $\Omega_{arag} > 3.4$ is lost by 2050 following SSP245. The global mean pH values that we wish not to exceed therefore lie somewhere in this range. To find them, we count the number of grid squares where $\Omega_{arag} > 3.4$ for several years from 2015 to 2050. Plotting these values against the global mean pH for that year (averaging all grid squares from UKESM1.0-LL), we find that the number of grid squares with $\Omega_{arag} > 3.4$ decreases to 75% of its initial value when global mean pH is 8.03, and to 50% of its 2020 value when global mean pH is 7.99 (Fig. 4). This yields acidification targets of -0.17 (75% area remaining) and -0.21 (50% area remaining) for initial ocean pH of 8.2. It is important to note that this relationship is subject to some uncertainty (shown in the shaded areas of the graph in Fig. 4) so the derived targets are also subject to a small amount of uncertainty. Because the uncertainty is small, we continue the study with just one set of targets rather than examining the impact of uncertainty here, to match the discourse around the warming targets of the Paris Agreement.
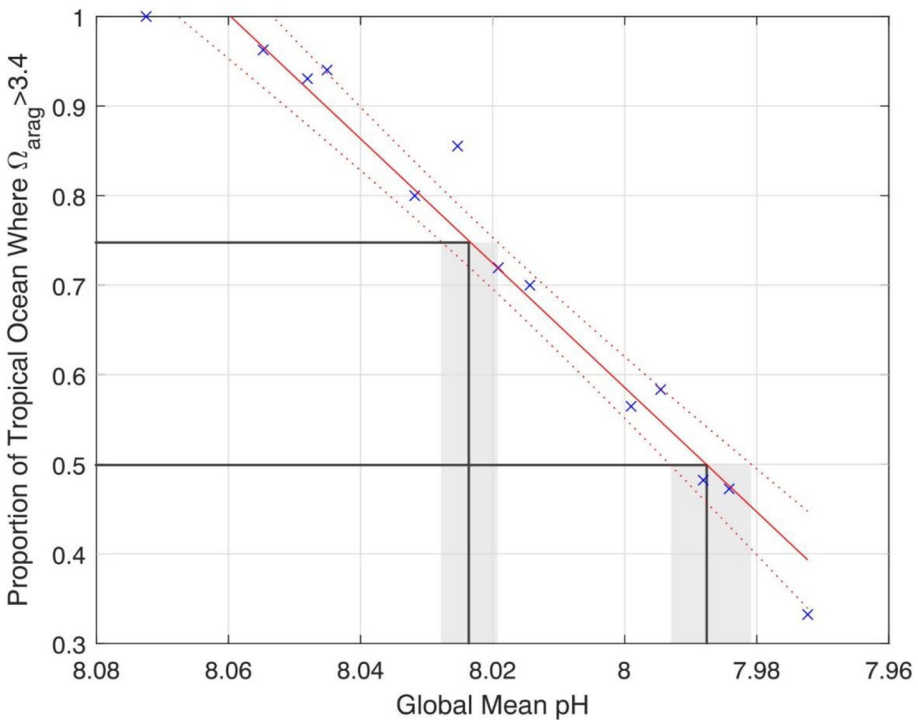

Fig. 4 The global average ocean acidity vs proportion of tropical ocean area where aragonite saturation is sufficient for tropical corals to survive. Red dotted lines indicate confidence intervals, which introduce minimal uncertainty to the resulting acidification targets

2.4 Evaluating the achieved vs actual acidification and warming for each combination scenario

We run the AMP algorithm for a range of targets around the Paris Agreement targets and the acidification targets proposed in Section 2.3—for warming, this range is 1.5–2.1 °C; for acidification this is -0.225 to −0.1 units. To simplify analysis in later sections, we will assess the performance of each combination scenario in terms of whether the four climate targets of interest are met and discard scenarios that do not consistently meet enough of the targets considered.

Figure 5 shows the resultant median warming and acidification for the strict, lenient and weighted scenarios. Figure 6 shows the difference between the target and resultant warming and acidification for the same scenarios. Here it is clear that in the lenient scenario, the warming targets are not reliably met for any combination of targets, and only the less stringent acidification targets are met. The stipulation for the lenient scenario is that the carbon trajectory for the next 10 years should be consistent with at least one target, but it is possible for both targets to be missed by 2100. This outcome can occur if the algorithm overestimates the allowable carbon budget by underestimating the climate sensitivity to emissions, or by underestimating the zero emissions commitment of warming. While this can happen regardless
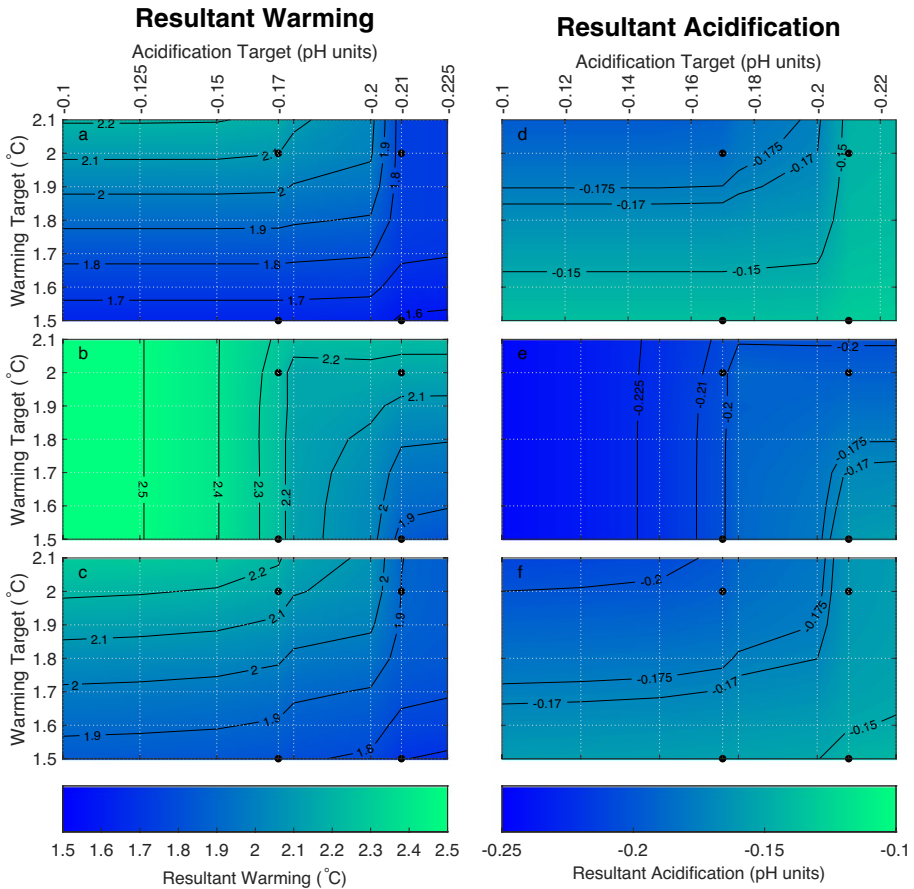
Fig. 5 The resultant warming (right column) and acidification (left column) from strict (top row), lenient (middle row) and weighted (bottom row) combinations of warming and acidification targets
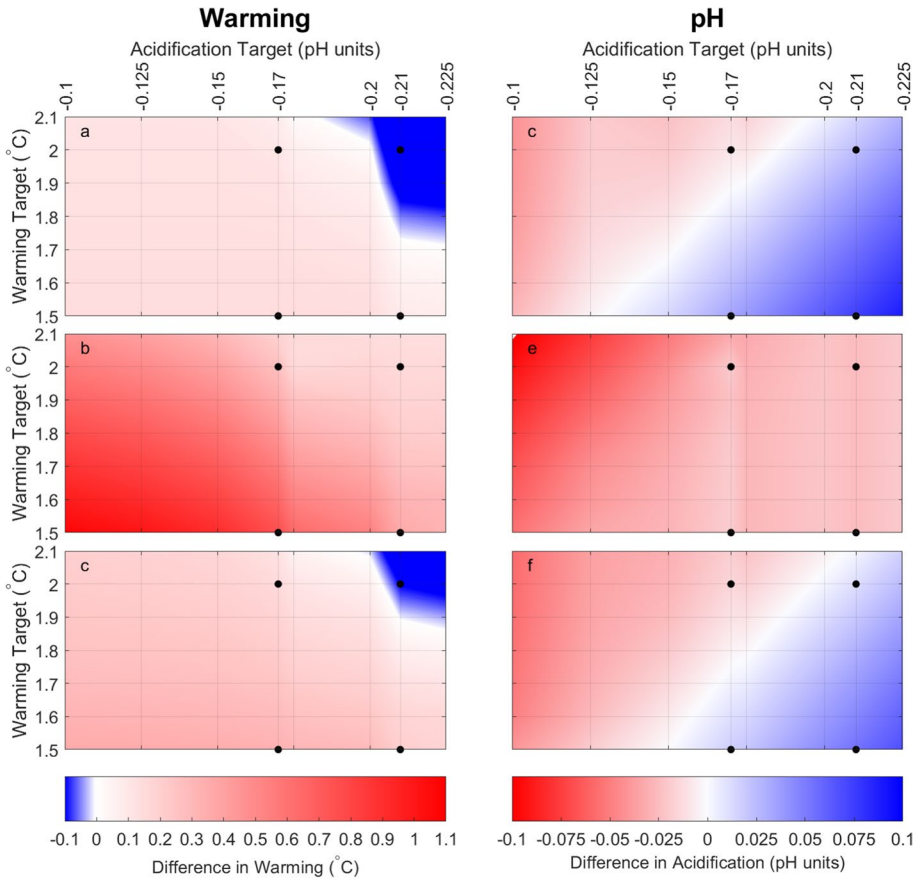
Fig. 6 The difference between resultant and target warming (right column) and acidification (left column) from strict (top row), lenient (middle row) and weighted (bottom row) combinations of warming and acidification targets. Red indicates target has not been met. Based on this, we discard lenient combinations of targets for analysis as they consistently fail to meet warming targets

of strict or lenient scenario, overshoot in a lenient scenario is likely to result in both targets being missed, because the algorithm is already choosing to aim towards the climate target that will likely result in the other climate target being missed. The purpose of the multiple targets framework is to prevent additional damage to the climate system, so it is not useful in this case to consider lenient combinations of targets going forward because this does not represent an improvement on current climate discourse.

Figure 1b shows the resultant warming from following carbon trajectories towards just acidification targets, with the black horizontal lines showing the Paris Agreement warming targets of 1.5 and 2 °C. For acidification targets that allow 0.2 units or more of acidification, the median resultant warming exceeds 2 °C. We conclude that, although acidification is important, it must be considered in combination with warming targets otherwise it is possible for the warming targets to be exceeded. It is therefore also not worth considering emissions pathways that stabilise at just acidification targets, as this does not constitute an improvement to current political efforts. We will therefore mainly present RCBs for the strict and weighted target combinations in the results section.

2.5 Remaining carbon budget (RCB)

The nature of the AMP algorithm (creating a cumulative emissions pathway that stabilises to be in line with a given climate target) means it is straightforward to calculate a carbon budget for the future. This can be done by subtracting the cumulative emissions (CE) for the start year (2020) from the cumulative emissions at a policy relevant and/or time-stable point (*t*) in the model:

$$RCB = CE_t - CE_{2020} \qquad (4)$$

Here, the RCB will be evaluated using $t = 2100$, a policy-relevant point as most policy focuses on changes in the nearest century.

3 Results

3.1 Remaining carbon budgets towards two climatic targets

Figure 7 shows the RCB for a strict combination of warming and acidification targets. To examine uncertainty in projections, we present the 5th, 50th and 95th percentiles. Here, horizontal contours indicate that the choice of pH target has no impact on the RCB (i.e., the algorithm favours the warming target-consistent emission rate at each ten-year interval), and vertical contours the opposite. From these contours we can find the median, 95th and 5th percentiles of the carbon budget consistent with a strict combination of the Paris Agreement warming targets and the pH targets chosen in this study. For a combination of 8.03pH and 1.5 °C warming (the two more stringent targets) the median (5th–95th percentile) RCB is 24 (−73.8 to 129.8) PgC. For the two less stringent targets of 7.99pH and 2 °C warming, the RCB is 315.2 (114.4 to 502.4) PgC.

Figure 8 shows cumulative emissions of carbon over time since 2018 for a select combination of pH and temperature targets. In these panels, stable cumulative emissions indicate that yearly emissions have been reduced to 0. A 'combined target' trajectory corresponding with a 'single target' trajectory indicates that the model is favouring the emissions rate consistent with the same target at every 10-year interval. The shaded area shows the 5-95th percentile range: a narrower plume indicates more certainty in the cumulative emissions consistent with
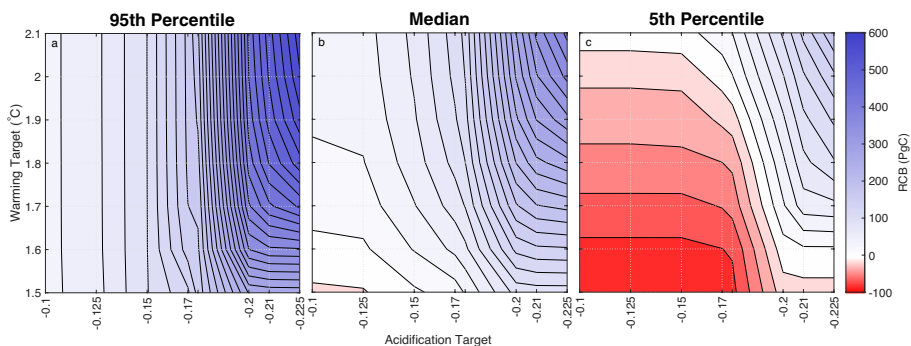
Fig. 7 Contours of the 95th, 50th and 5th percentile RCB (panels a, b, c respectively) for a strict combination of all warming and pH targets considered in the study
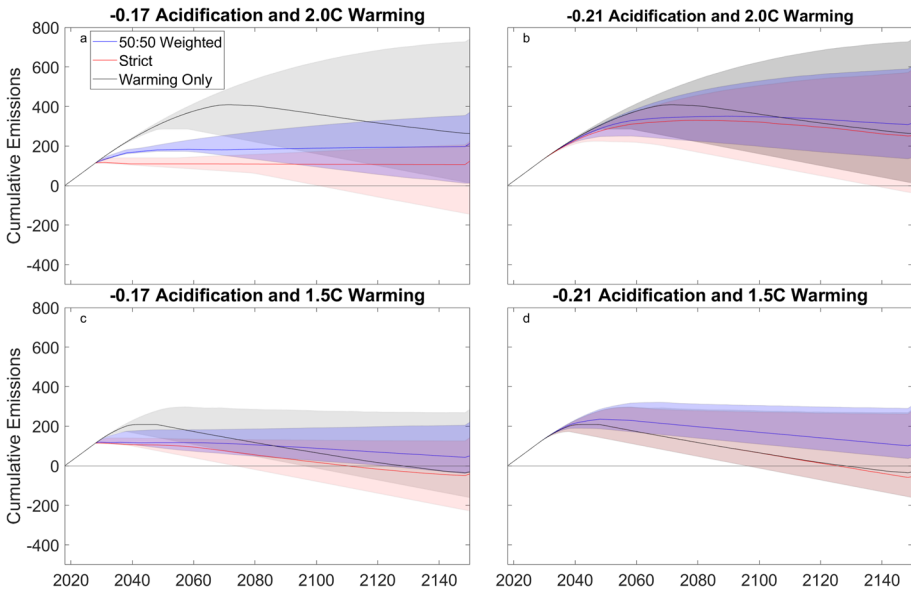
Fig. 8 Plumes of cumulative emissions since 2010 for warming and pH targets of 1.5/2 °C and 7.99/8.03pH respectively. Here we present strict, warming only and 50:50 weighted, as these are the more likely to hit both targets. Solid line = median, shading = 5–95 percentile

the set target(s). Note that the uncertainty is noticeably narrower for the trajectories towards combined targets (strict and weighted), than when towards just a warming target. In all panels, we see a peak-and-decline pattern in cumulative emissions to stay on track towards the given combination of targets. This prompts us to consider the benefit of considering the extra target of acidification in terms of the difference in emissions reductions necessary to stay on target between the peak in cumulative emissions and 2150, when the 10-year checks for re-assessing carbon emissions rate cease. For the more stringent acidification target (−0.17) and less stringent warming target, the necessary emissions reduction reduces from 145PgC for just a warming target to 10PgC for both: a 93% change (top right panel). Although this change is smaller in other panels (and non-existent in 8d, where the warming target is more stringent than the acidification target), there is still a change of 58% and 32% in 8b and c respectively.

In Fig. 9, we see the impact on the parameter space of taking a 50:50 weighting of the two potential emission rates. Note that this is not necessarily a weighting of the strict and lenient scenarios, but a weighting of the temperature-only and the pH-only scenarios.

The RCB for the pH targets is generally larger than the RCB for warming targets (Figs. 5 and 6, respectively). For the pH targets of 8.03 and 7.99pH, the median (5-95th percentile) RCB is 140.2 (59.2 to 192.1) PgC and 377.9 (218.3 to 519.2) PgC, respectively. For the warming targets of 1.5 and 2 °C, the RCBs are 92.4 (−7 to 297.2) PgC and 378.2 (165.7 to 618.7) PgC, respectively.

Figure 10 shows the probability distribution of RCB for the Paris Agreement warming targets and the pH targets generated in this study. This indicates when uncertainty in the RCB is reduced by introducing another climatic target. For combinations of targets where one target is obviously more stringent than the other (panel d), the RCB consistent with a strict combination of the two targets matches the more stringent target (consistent with the nature of the algorithm) and therefore there is no reduction in uncertainty. In cases where
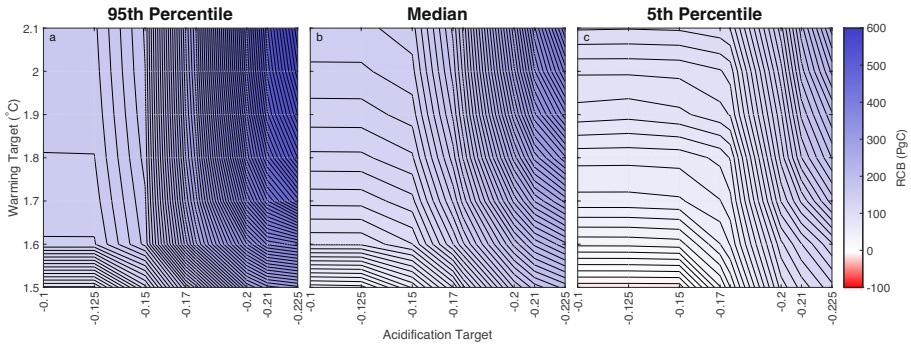
Fig. 9 Contours of the 95th, 50th and 5th percentile RCB (panels **a**, **b**, **c** respectively) for a weighted combination of all warming and pH targets considered in the study

the targets are of a comparable stringency (panels b, c), the lines do not intersect because the algorithm is less likely to favour just one target, and may switch targets at the next check point. In these cases, the strict RCB has less uncertainty than the RCB towards just a warming target (see Online Resource 2 for the same PDFs for the highest, lowest and medium targets, where this is even more apparent). Also note the double peak in the strict scenario in 10c (the two more stringent targets in combination). This likely arises from the way the AMP algorithm handles overshooting each target—if the warming target is overshot, the algorithm prescribes negative carbon emissions at a rate that is scaled to the level of overshoot. If the acidification target is overshot, the same rate of carbon removal is prescribed regardless of how much the target is overshot. The double peak will only exist for target combinations where overshoot of both targets is feasible, otherwise the algorithm would deal with the overshoot more consistently.
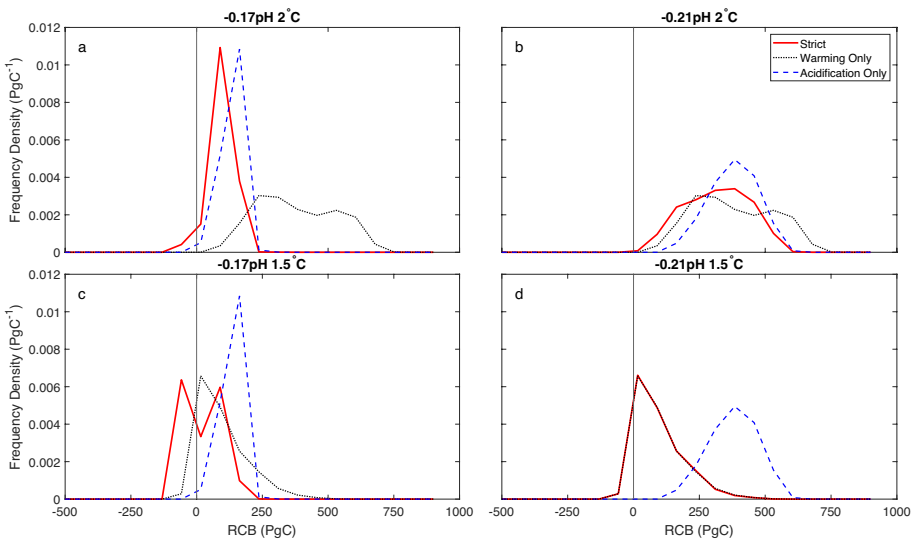
Fig. 10 probability density functions of the RCB for 2100 for warming and pH targets of 1.5/2 °C and 7.99/8.03pH respectively

4 Discussion and conclusions

A central goal in climate science is to create communicable carbon emissions trajectories and budgets that are consistent with a politically chosen climate goal. Conventionally, this is a single target of global mean surface warming, but emissions trajectories consistent with the political warming targets of 1.5 and 2 °C are not sufficient to prevent dangerous change in other aspects of the Earth system. The purpose of this study is to explore whether considering a second carbon-related target alongside warming makes a difference to the remaining carbon budget, and therefore to provide some impression of how comprehensive a single warming target is as a unifying goal in climate mitigation policy. To do this, we quantify the difference between carbon budgets consistent with one climate target and two climate targets. We examined the RCB for a range of temperature and pH targets between 1.5 and 2.1 °C and 8.1 and 7.9pH, respectively. Based on a strict combination of these targets (i.e., where emissions reductions take the pathway to the most stringent target as analysed every ten years), the median RCB for 2100 ranges from ~500PgC for the least amount of mitigation (2.1 °C warming, -0.3 acidification) to ~−100PgC for the most amount of mitigation (1.5 °C warming, −0.1 acidification). The median RCB and the year at which the budget will be spent (assuming a constant emission rate of 38.3PgC/year, equal to that in 2021 according to the IEA) is given in Table 1.

A key result from the study is the impact on the RCB of including a second target for ocean acidification. To illustrate, we consider the impact when running the AMP algorithm on a strict setting—i.e., both targets must be met. If the acidification target is considerably more relaxed than the warming target (see Fig. 10d), the AMP algorithm consistently favours the warming target, so there is no impact in this case. However, in cases where the acidification and warming targets are of a similar stringency (Fig. 10b, c), *uncertainty is reduced*—and this reduction comes from cutting off the high-end estimate of the RCB derived from just aiming for the warming target. If the acidification target is considerably more stringent (Fig. 10a), the difference in the median and spread of the RCB is more marked. Uncertainty in the combined RCB is lower than the carbon budget based on a single warming target, but the RCB with the highest certainty is framed using a single acidification target. This is due to the high level of certainty in the relationship between atmospheric carbon dioxide and ocean pH, caused by the short timescale of CO_2 exchange between atmosphere and ocean. We also find that the emissions trajectories towards combined targets are 'smoother', with less of a peak-and-decline shape—where declining cumulative emissions means that carbon is being removed from the atmosphere. This means a more urgent need to reduce emissions in the short term, with the benefit of needing less carbon dioxide removal (CDR) in the future. Given that CDR technology is still nascent, and its impacts on aspects of the climate system beyond warming are still uncertain, a scenario that commits us to less need for CDR is beneficial.

Table 1 Remaining carbon budget and year of expiry for strict and weighted combinations of the targets considered in this study

	Remaining carbon budget (PgC)				Year of expiry			
	1.5 °C		2.0 °C		1.5 °C		2.0 °C	
	Strict	Weighted	Strict	Weighted	Strict	Weighted	Strict	Weighted
−0.17	24.6	98.3	104.1	194	2023	2029	2030	2038
−0.21	91.5	182.7	315.2	354.4	2029	2037	2050	2053

The motivation for considering more than one climate target when calculating a remaining carbon budget is that the uncertainty in the relationship between warming and cumulative carbon emissions means that there is a range of potential allowable emissions that is consistent with one warming target. This means that there is a range of potential damage to the climate system that may be sustained, even if the warming targets of the Paris Agreement (for example) are met. We therefore wish to consider whether a second climate target will avoid additional damage to other aspects of the Earth System. We find that the adoption of the additional aim to limit ocean acidification reduces uncertainty in the remaining carbon budget by lowering the upper limit of the probability distribution. This decrease in allowable emissions (if honoured in global climate change mitigation policy) will increase the likelihood that the most dangerous effects of climate change can be avoided across multiple facets of the climate system.

Declarations

Informed consent N/A.

Competing interests The authors declare that they have no relevant financial or non-financial interests to disclose.

The authors declare no competing interests.

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