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Quantifying the regional to global climate impacts of individual fossil fuel projects to inform decision-making

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Every additional tonne of carbon dioxide emissions adds to global warming[1]. This means that decisions to approve new fossil fuel projects represent pivotal moments in shaping Earth's future climate trajectory. Yet, the specific additional global warming caused by project-level CO_2 emissions, and the impacts of that warming, are rarely incorporated into decision-making on the acceptability of new fossil fuel projects. Here, we show how quantifying this additional warming enables concrete, foreseeable consequences to be identified and evaluated in a formal risk assessment framework. This approach reveals that major socioeconomic and environmental consequences can be attributed to CO_2 emissions associated with individual fossil fuel projects, contrary to the pervasive unquantified claims of negligible risks by project proponents. Furthermore, as countries pursue rapid decarbonisation aligned to their Nationally Determined Contributions, the CO_2 emissions from individual fossil fuel projects can, within decades, dominate and even exceed legislated national emission limits. The practical, future-focused approaches demonstrated here offer a critical bridge between climate science and decision-making, with immediate relevance to choices that will shape Earth's climate for decades to centuries to come.

Earth's climate over the coming decades to centuries will be determined by cumulative global emissions of carbon dioxide (CO_2)[1] (Fig.1a). Limiting global CO_2 emissions, and thereby limiting global warming, relies on cooperation, commitments and actions towards emission reductions that are implemented at national and sub-national scales[2]. Within these jurisdictions, the approval/permitting of new or extended fossil fuel extraction occurs on a project-by-project basis. This means that decisions with long-term commitments to future CO_2 emissions and their consequences are made at a project-level, which on their own can appear to be too small to significantly influence global climate change. This raises a fundamental question in the nexus between science and decision-making: if every project is considered too small to matter, does that imply that no individual project bears responsibility for any climate change consequences?

Approval of new or extended fossil fuel projects considers many factors, including their anticipated greenhouse gas emissions. For example, in Australia, one of the world's major fossil fuel producers[3], the proponents of new fossil fuel projects are required to submit project proposals that detail their anticipated greenhouse gas emissions and associated impacts. There are established protocols for calculating and reporting greenhouse gas emissions of fossil fuel production and use[4]. However, there is no required or best-practice framework for quantifying the consequences of these anticipated emissions. Across a range of project proposals under various

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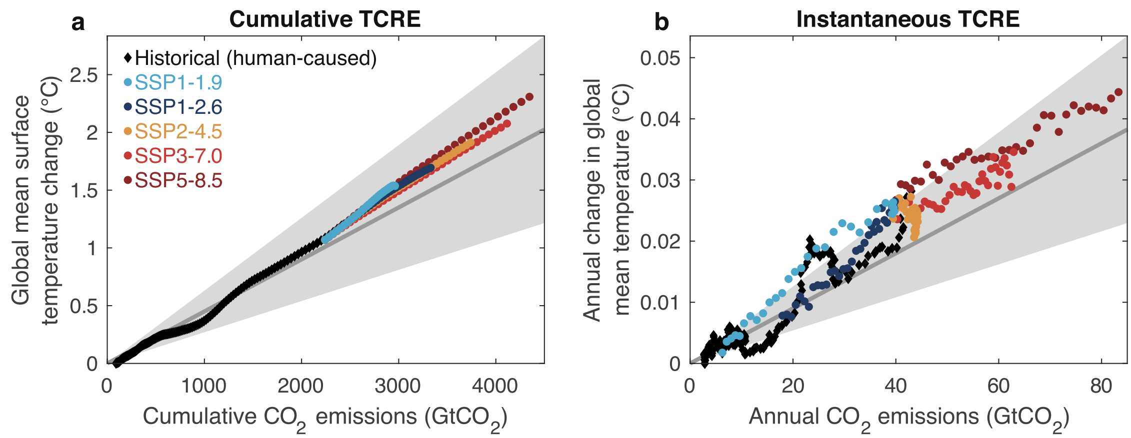

Fig. 1 | The transient climate response to CO_2 emissions (TCRE). a The near-linear relationship between cumulative CO_2 emissions and human-caused global warming demonstrated for historical data (1850–2019) and future emission scenarios synthesised across the multi-model mean of CMIP6 simulations (2014–2050). Future scenarios are based on Shared Socioeconomic Pathways (SSPs) ranging from very low emissions (SSP1-1.9) to very high emissions (SSP5-8.5) futures. Data are from Fig. SPM.10 of ref. 1. **b** The same near-linear relationship is also evident for annual CO_2 emissions and the additional human-caused warming each year, derived from the same datasets. Grey line in both panels shows the IPCC best estimate of the TCRE (0.45 °C of warming caused by 1000 $GtCO_2$) and grey shading shows the 66–100% likelihood range of the TCRE (0.27 °C to 0.63 °C of warming caused by 1000 $GtCO_2$).

Australian jurisdictions, and multiple proponents including global carbon majors[5,6], we demonstrate three pervasive areas where a climate-science basis is currently lacking in fossil fuel project proposal documents (Supplementary Table 1). Firstly, proponents consistently describe their project-level greenhouse gas emissions as negligible in the context of global emissions and as having an unquantifiable contribution to global warming. Secondly, because their global warming contribution is unquantified and assumed negligible, the climate change impacts of individual projects are also unquantified and assumed to be inconsequential. And thirdly, descriptions of project contributions to national or global emissions inventories fail to incorporate committed decarbonisation trajectories over the lifecycle of the proposed projects. Given the immediate risks of climate change, and the deep emission reductions required to meet national and international climate mitigation commitments, there is an urgent need for science-based tools that can support decision-making. Specifically, science-based approaches are needed to quantify the context and consequences of new fossil fuel projects at the point of their approval.

Bridging the divide between scientific evidence and decision-making requires frameworks that link greenhouse gas emissions to tangible consequences. The historical responsibility for climate warming, and its economic damages, has been established for nations[7] and major fossil fuel companies[6]. The economic costs of future climate warming and associated changes in climate variability and extremes have also been projected[8,9], and are expected to disproportionately impact poorer, low-latitude countries that are also often the least responsible for climate change. Scientific progress in quantifying and attributing climate change consequences is underpinning litigation claims worldwide[6,10]. But there remains a divide in bringing actionable scientific evidence into decision-making at a level that can play a role in reducing future climate harms. Using a case study approach, we demonstrate a simple and robust method for quantifying the additional global warming that can be anticipated from the CO_2 emissions of individual fossil fuel projects. This is a critical step that then enables the specific, tangible consequences of a project to be quantified, which in turn can be used to assess whether the project's risks are acceptable. We further illustrate the time-evolving context of project-level CO_2 emissions with respect to Nationally Determined Contributions (NDC) to climate change mitigation, which enables proposals for new or extended fossil fuel projects to be evaluated alongside concurrent commitments to rapid emission reductions. The novelty and potential impact of our future-focused, project-level framework is that it brings the best-available scientific evidence into decision-making at the point where decisions are being made now that will commit future CO_2 emissions for many decades to come. These are the decision points that will be critical to setting the world's future climate trajectory.

Results

Quantifying CO_2-induced warming

The IPCC 6th Assessment Report states that *every additional tonne of CO_2 emissions adds to global warming*[1]. Following IPCC protocols, this statement in the Summary for Policymakers has been approved by all 195 IPCC member governments as an accurate representation of the scientific evidence assessed by the IPCC[11]. The statement is made in the context of evidence for the 'Transient Climate Response to CO_2 Emissions' (TCRE); a simple yet robust metric that connects the primary cause of climate change (CO_2 emissions) to its principal measure (the change in global mean surface temperature)[12] (Fig. 1a). The IPCC assesses that the best estimate of the TCRE is that every 1000 billion tonnes (gigatonnes; Gt) of CO_2 emissions causes 0.45 °C of additional warming, with a 66–100% likelihood of warming between 0.27 °C to 0.63 °C[1]. The robust evidence for this TCRE relationship spans process understanding, direct observations and climate model simulations[11]. The TCRE has been defined based on global cumulative CO_2 emissions since 1850. It is the primary basis for determining the remaining carbon budgets that must not be exceeded if global warming is to be limited to particular policy relevant thresholds[2,13,14], including the 1.5 °C ambition and the well-below 2 °C goal of the Paris Agreement[15].

The near-linear increase in global temperatures due to ongoing CO_2 emissions is expected (with high confidence) to continue over this century and for global warming up to at least 2 °C[11]. This is regardless of the intensity of future emissions, and includes the emission reduction pathways required to limit warming to well-below 2 °C (e.g., SSP1-1.9 and SSP1-2.6 emission scenarios; Fig. 1a). CO_2 is well-mixed and long-lived in the atmosphere (Methods), and zero-CO_2 emission scenarios demonstrate that the global warming caused by past CO_2 emissions persists over many centuries, even after net CO_2 emissions cease entirely[16–19]. The TCRE reflects the near-immediate climate warming response to CO_2 emissions that persists for centuries, while over millennial and longer timescales the equilibrium response of the climate to elevated atmospheric CO_2 concentrations results in further atmospheric surface warming as the energy budget balances across different parts of the Earth system, including the ocean[20]. In the future, the TCRE could become higher than current assessments if positive feedbacks within the Earth system are activated, amplifying the warming caused by anthropogenic CO_2 emissions. For example, if human-generated CO_2 emissions cause enough warming to exceed the tipping point for rapid permafrost thaw[21], releasing large quantities of additional greenhouse gases into the atmosphere, then the resulting global warming would exceed expectations based solely on the TCRE relationship for anthropogenic CO_2 emissions[11]. The TCRE is applied indiscriminately to all human-caused CO_2 emissions, however in reality the relationship is more nuanced for CO_2 emissions associated with land use change as these also involve associated changes in the land carbon sink and planetary surface albedo[7].

The TCRE relationship provides a simple approach, based on robust scientific evidence, to quantify the additional global warming that can be anticipated due to individual fossil fuel projects. There is no assessed minimum emissions level where the TCRE relationship ceases to persist between CO_2 emissions and the global warming they cause[11]. Process-based understanding of how CO_2 acts as a greenhouse gas to cause climate warming extends down to the molecular level[22–26]. This implies that the near-linear relationship quantified for cumulative global CO_2 emissions and total global warming should apply to any level of CO_2 emissions that are made within the context where there is high confidence in the TCRE (i.e., fossil CO_2 emissions made this century, and for global warming up to at least 2°C). Indeed, an equivalent near-linear relationship exists between annual anthropogenic CO_2 emissions and additional human-caused warming each year[14] (Fig. 1b). The TCRE has been used to quantify the annual and total contributions to historical global warming attributable to individual nations[7]. The application to quantify the additional warming caused by CO_2 emissions from individual fossil fuel projects is equivalent in method and scale to this previously established use. This is consistent with the IPCC assessment that every additional tonne of CO_2 emissions adds to global warming, and underpins the application of the TCRE at emission levels far smaller than the gigatonne scale used to quantify cumulative global CO_2 emissions.

Additional warming from project-level emissions

Quantification of the additional warming caused by individual fossil fuel projects is a critical evaluation tool. To illustrate this, we use a case study of the Scarborough gas project that has recently been approved for development offshore of northwest Australia[27] (Fig. 2). Liquified Natural Gas (LNG) production from the Scarborough and North Scarborough fields is currently expected to start in 2026 and continue for 31 years, with potential for further expansion or extension to other gas fields in the Greater Scarborough resource. The Scarborough Offshore Project Proposal[27] defined the anticipated scope and environmental outcomes of the project as part of the regulatory approval process. This included estimates for routine greenhouse gas emissions related to the production, processing and consumption of Scarborough LNG. In its detailed impact evaluation, the report states that "*it is not possible to link greenhouse gas emissions from Scarborough with climate change or any particular climate-related impact given that the estimated emissions associated with Scarborough are negligible in the context of existing and future predicted global greenhouse gas concentrations*" (Supplementary Table 1)[27]. The consequence of greenhouse gas emissions from the Scarborough project was therefore evaluated by the project proponents as "*negligible for all receptors*".

The estimated greenhouse gas emissions from the Scarborough project total 876 million tonnes (Mt) of CO_2 emissions over the anticipated lifetime of the project[27]. This incorporates CO_2 emissions associated with offshore production, onshore processing and domestic and international use of Scarborough gas (Methods). Equation 1 quantifies the best estimate of the additional global warming caused by CO_2 emissions from this project, based on the TCRE, as:

$$Additional\ warming(^{\circ}C) = Emissions(Mt\ CO2) \times \frac{0.45\,(^{\circ}\mathrm{C})}{1,000,000\,(Mt\ CO2)} \quad (1)$$

The best estimate is that the 876 Mt of CO_2 emissions from this project will cause 0.00039 °C of additional global warming, with a 66–100% likelihood of causing global warming of between 0.00024 °C and 0.00055 °C (Fig. 2; Methods). While direct measurement of global mean temperature changes is not possible with this level of precision, the agreement across multiple, consistent and independent lines of high-quality evidence (i.e., robust evidence using IPCC calibrated language[28]) gives high confidence in the near-linear relationship between CO_2 emissions and global warming that is quantified through the TCRE[11]. Thus, the additional warming that will be caused by CO_2 emissions from the Scarborough project (or any other fossil fuel project) is knowable and can be quantified based on the anticipated CO_2 emissions of the project.

Quantifying consequences

Quantification of the additional warming caused by individual fossil fuel projects enables tangible consequences of this additional warming to be quantified and evaluated in a risk assessment framework. A range of human, environmental and economic impacts are attributable to human-caused global warming. This includes evidence for severe impacts on human and natural systems that have already occurred at current levels of global warming[29,30], and projected future warming that will continue to worsen the frequency and intensity of many climate change-related hazards[1]. These regional consequences in many cases scale with global warming levels, and hence, with CO_2 emissions. They can therefore provide more relatable and relevant measures of climate change risks for decision-makers than quantification of additional global warming alone[31]. Here, we use examples of impacts that are known to be strongly associated with global warming to demonstrate a framework for quantifying tangible consequences of the additional warming caused by an individual fossil fuel project.

The human cost of global warming can be quantified by considering the number of people who will be left outside of the "human climate niche"[32]. The human climate niche describes the climate conditions in which human societies have historically thrived and is defined by the distribution of the human population with respect to mean annual temperature. This distribution is shaped by the effects of climate on people, and on the species and resources that sustain or challenge us, and has been highly consistent for millennia[32,33]. Unlike economic impact measures, the human climate niche framework for quantifying the human cost of global warming considers all lives as equal, regardless of wealth and is inclusive of those already alive and yet to be born[32]. The anticipated global population by the mid-21st century under middle-of-the-road socioeconomic pathways is around 9.5 billion people[34]. In a world with 9.5 billion people, every 1 °C of additional global warming is projected to cause a 13.8 ± 1.6% increase in the global population exposed to a local climate shift where the mean annual temperature exceeds 29 °C and is beyond the hot edge of the human climate niche[32] (Fig. 2a; Supplementary Fig. 1a). Considering the full cold-to-hot distribution of the climate niche, as well as anticipated demographic change, allows for further quantification that 9.5 ± 1.0% of the global population will be left outside of the human climate niche for every 1 °C of additional global warming[32]. Based on these relationships, the 0.00039 °C (0.00024 °C–0.00055 °C likely range) of additional global warming caused by CO_2 emissions from the Scarborough project will result in a best estimate of 516,000 people (308,000–732,000 likely range) being exposed to unprecedented heat, and 356,000 people (213,000–504,000 likely range) being left outside of the human climate niche (Fig. 2a; Methods).

One of the many consequences of exposure outside the human climate niche is increased mortality. At current levels of human-caused global warming, there has already been an observable and rapidly escalating rise in heat-related excess deaths[35–37], including mass mortality events[38]. In many of the worst-affected regions of the world, principally developing nations with tropical (hot and humid) climates, robust data to quantify the human mortality burden of global warming is not yet available. In Europe, where suitable health data is available across 854 cities[36], recent work has quantified that under a low mitigation and low adaptation scenario (SSP3-7.0), the death burden of climate change will increase by 49% this century[39]. Using the middle-of-the-road emissions and demographic scenario (SSP2-4.5) for projected European deaths (Fig. 2b, Supplementary Fig. 2a), it can be estimated that in Europe alone the additional climate warming caused by the Scarborough project will result in an additional 484 heat-related deaths by

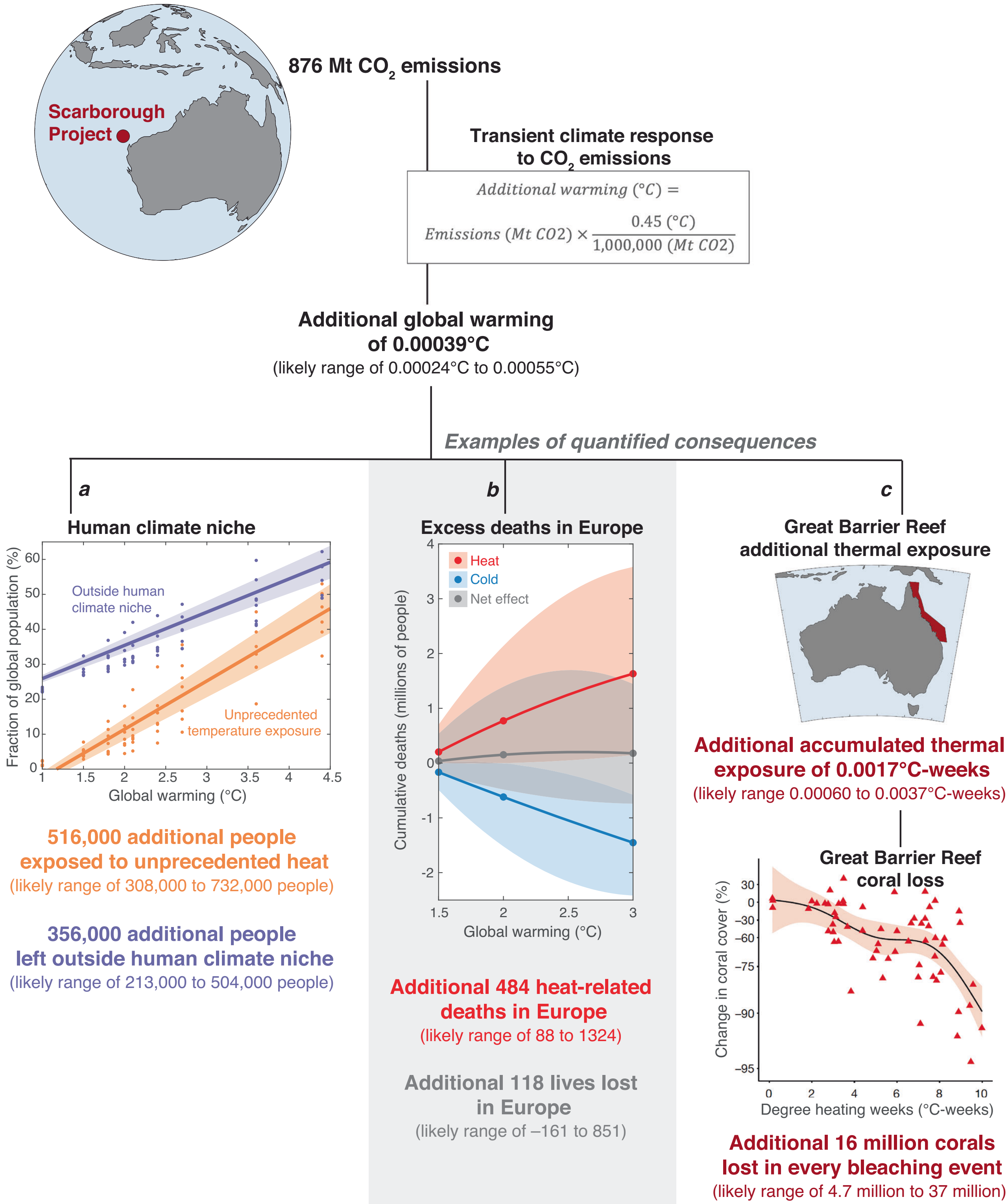

Fig. 2 | Example of the quantification of the consequences of project-level CO_2 emissions. The approach is illustrated using the Scarborough offshore gas project as a case study but is applicable to any fossil fuel project. Emissions from the Scarborough project of 876 Mt CO_2 can be anticipated (based on the TCRE) to cause a best estimate of 0.00039 °C of additional global warming. The consequences of this additional warming are expected to result in best estimates of, **a** an additional 516,000 people globally exposed to unprecedented heat and 356,000 left outside the human climate niche in a world with 9.5 billion people[32] (Supplementary Fig. 1 also quantifies impacts for global populations of 6.9 billion and 11.2 billion people); **b** an additional 484 heat-related deaths in Europe, and a total of 118 additional lives lost in Europe (net effect) by the end of this century under a middle-of-the-road emissions pathway (SSP2-4.5)[39] (Supplementary Fig. 2 also quantifies impacts under the high emissions SSP3-7.0 scenario); and, **c** additional thermal exposure in the Great Barrier Reef Marine Park (Supplementary Fig. 3) that results in an additional 16 million coral colonies lost in every future bleaching event on the Great Barrier Reef (lower panel after ref. 43). See Methods for calculation details, and text in the "quantifying consequences" section for more detailed descriptions of the examples illustrated in this figure.

the end of this century (with a likely range of 88 to 1324 additional heat-related deaths; Methods). Heat-related excess deaths in Europe are projected to be most common in southern regions[39], and when taking into account reduced cold-related deaths primarily in northern Europe, the net effect of additional warming caused by Scarborough project emissions is estimated to cost 118 lost lives (−161 to 851 likely range) in Europe alone.

Human-caused climate warming is also having detrimental consequences for natural systems that people value and depend upon. The Great Barrier Reef (GBR) is a UNESCO World Heritage site that is protected under Australian environmental laws[40]. The severe impact of human-caused global warming on coral reefs is evident in the newly emerging phenomenon of mass coral bleaching and mortality events[41]. The GBR has experienced six mass bleaching events during the last decade (2016, 2017, 2020, 2022, 2024, and 2025), caused by heat extremes that are beyond the range of natural climate variability[42]. These repeated bleaching events mean that the existential threat to the GBR ecosystem from human-caused climate warming is now being realised[41–44]. Back-to-back mass bleaching events have already occurred twice in consecutive summers, and with further global warming, mass bleaching of corals will soon occur every summer. The severity of coral bleaching and mortality depends on the intensity of marine heatwaves (positive sea temperature anomalies relative to the long-term average) and their duration (usually measured in weeks), which are combined in the 'Degree Heating Week' (DHW) thermal exposure metric[45]. During the 2016 mass bleaching event on the GBR an accumulated heat exposure of 5 °C-weeks–6 °C-weeks resulted in an average loss of 60% of corals, and 8 °C-weeks–10 °C-weeks increased the average loss to 90% of corals[43]. Each increase in heat exposure of 1 °C-weeks resulted in the death of 2–5% more corals[43]. The 0.00039 °C (0.00024 °C–0.00055 °C likely range) of additional global warming caused by CO_2 emissions from the Scarborough project would increase accumulated thermal exposure on the GBR by 0.0017 °C-weeks (0.00060 °C–0.0037 °C-weeks likely range; Methods; Supplementary Fig. 3). Over the entire GBR, this would result in the death of an additional 16 million coral colonies (4.7 to 37 million likely range) during every future mass bleaching event (Fig. 2c, Methods).

The additional global warming attributable to a single fossil fuel project has quantifiable consequences for people and the environment (Fig. 2), and these can be robustly evaluated in a risk assessment framework. Risk assessments typically use the likelihood of an outcome, and the consequence of that outcome, to determine whether the risk of an activity is acceptable (Supplementary Fig. 4). The "*negligible (level F) for all receptors*" impact level of greenhouse gas emissions that was reached in the proponent's risk assessment of the Scarborough project (Supplementary Table 1)[27] is assigned where consequences are expected to be localised and have no lasting effect (Supplementary Fig. 4). The quantified, evidence-based approach that we demonstrate here does not support this assessment of a negligible impact. We quantify additional warming, and examples of its consequences, with an uncertainty range that encompasses a likelihood of 66% or higher. In the Scarborough risk assessment framework these constitute a "likely" (51 to 80% chance) to "highly likely" (>80% chance) outcome (Supplementary Fig. 4a). The additional warming caused by CO_2 emissions from the Scarborough project will persist for multiple decades to centuries and cause long-term impacts across a range of environmental and social receptors, as illustrated by the examples developed above (Fig. 2a–c). In the Scarborough risk assessment framework these long-term impacts to communities and highly valued ecosystems equate to the highest levels (levels A and B) of consequence (Supplementary Fig. 4b). When these quantified assessments of likelihood and consequence are combined, the result is a risk rating of "severe" (Supplementary Fig. 4c). In an approval process, a severe risk rating should necessitate actions to reduce residual risk to an acceptable level.

Climate change mitigation context

In addition to assessing the acceptability of the consequences of CO_2 emissions from new fossil fuel projects, another important policy consideration is how these proposed emissions relate to national emission reduction commitments. Fossil fuel projects span multiple decades, meaning that approval of new or newly extended fossil fuel projects today typically commit additional CO_2 emissions through to and beyond 2050 (Supplementary Table 1). Frequently, the context of annual emissions of these individual fossil fuel projects is quantified to be only a small percentage of today's CO_2 emissions relative to state, national or global emissions levels (Supplementary Table 1). For example, the anticipated annual domestic emissions of the Scarborough project of 6.2 Mt CO_2 per year (based on scope 1 emissions and 15% of production that is reserved for domestic consumption; Methods) are equivalent to 1.6% of Australia's fossil CO_2 emissions in 2024. However, the rapidly depleting remaining carbon budgets available to limit global warming to well-below 2 °C[11,13] necessitate deep and rapid CO_2 emission reductions this decade, and achieving net-zero emissions by around mid-century[46]. This means that an appropriate emissions context of new fossil fuel projects should encompass a rapidly decarbonising world.

National Determined Contributions (NDCs) provide an unambiguous, policy-aligned target for assessing the emissions context of proposed fossil fuel projects. Remaining carbon budgets for limiting global warming are determined at the global level[11,13], but emission reduction commitments and actions are implemented at national and sub-national levels. Principles of fairness that encompass capability, equality and responsibility have been discussed for guiding national allocations of the remaining global carbon budget[2,47]. The Australian Government has previously determined that a national allocation of 0.97% might be considered as Australia's fair share of the remaining global carbon budget to guide national emission reduction targets[48]. Australia's 2022 NDC[49] is a legislated commitment to reduce national greenhouse gas emissions by 43% below 2005 levels by 2030, and to achieve net-zero emissions by 2050. This is broadly equivalent to Australia doing its fair share to limit global warming to 1.7 °C with around a 50–67% likelihood of success (Fig. 3a; Supplementary Fig. 5; Supplementary Fig. 6).

Scarborough project emissions can be anticipated to constitute a rapidly increasing fraction of the national CO_2 emissions budget under Australia's committed climate change mitigation pathway (Fig. 3b). The expected annual CO_2 emissions from production, processing and domestic consumption of Scarborough gas (i.e., emissions covered under Australia's national greenhouse gas inventory; Methods) will be around 1.9% of the national annual CO_2 budget at the commencement of production in 2026. This proportion rises to 2.5% by 2030 and 4.9% by 2040. By 2049, the anticipated Australian emissions from the Scarborough project alone will comprise half (49%) of Australia's entire annual CO_2 emissions budget. Beyond 2050, all CO_2 emissions from the Scarborough project would require durable CO_2 removal from the atmosphere of an equivalent quantity to be consistent with Australia's NDC.

CO_2 removal is necessary in net-zero pathways to compensate for hard-to-abate emissions, but should not be employed to avoid the rapid, near-term emission reductions required to achieve Paris Agreement goals[50,51]. In 2023, human activities to move CO_2 from the atmosphere into durable geological storage (i.e., effectively reversing the carbon flux caused by fossil fuel combustion) amounted to only 0.04 Mt CO_2 globally[52], which is equivalent to only 0.6% of the planned annual Australian emissions from the Scarborough project. The context illustrated here for Scarborough emissions represents a single project. However, the reality is that many approved and proposed fossil fuel projects, both in Australia (Supplementary Table 1) and globally[3], now have life spans that extend through the time when nations have committed to substantially reducing emissions and achieving net zero. The context of project-level and aggregated fossil fuel emissions commitments relative to climate change mitigation commitments, as well as the significant financial burdens, technological limitations and environmental risks of durable CO_2 removal at scale[50,51,53], will become increasingly pressing factors as the remaining carbon budgets for limiting global warming continue to decline.

Discussion

Our analysis demonstrates how tangible and quantified examples of socio-economic and environmental consequences, across regional to global scales,

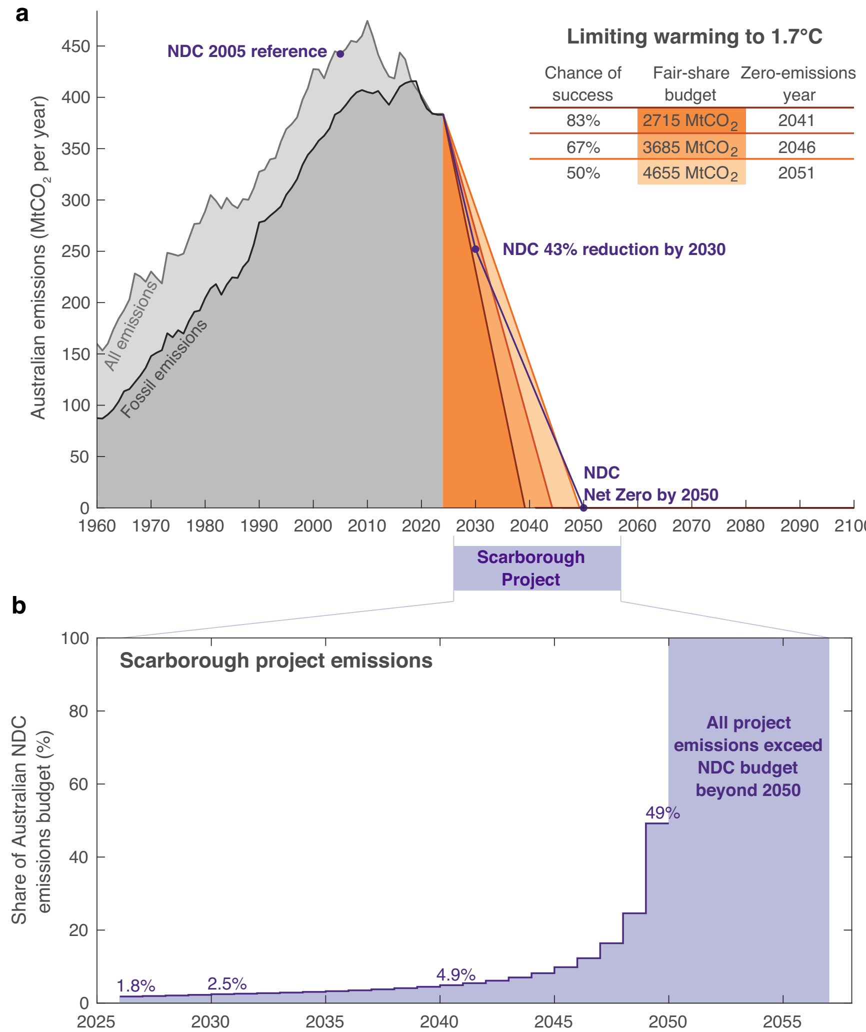

Fig. 3 | Australia's emission reduction pathway commitment and the changing context of Scarborough project emissions. a Australia's historical CO_2 emissions from 1960 to 2024 are shown for fossil (black line) and total (grey line) emissions, along with Australia's 2022 Nationally Determined Contribution (NDC; purple line) for emission reductions of 43% by 2030 (relative to 2005 levels) and net-zero emissions by 2050. Orange shading and table details show linear emission reduction pathways from the start of 2025 that are consistent with Australia's fair share of the remaining global carbon budget for limiting warming to 1.7 °C (Methods; See Supplementary Figs. 5 and 6 for the equivalent analyses for remaining carbon budget pathways to limiting warming to 1.5 °C and 2.0 °C, respectively). **b** Demonstration of the rising contribution of Scarborough project CO_2 emissions that fall under Australian carbon reporting (production, processing and domestic consumption) relative to Australia's NDC emissions reduction pathway.

can be brought into science-informed decision-making in ways that recognise that every fraction of a degree of additional warming matters. The most pressing concerns of decision-makers related to future CO_2 emissions may vary depending on the climate change vulnerabilities and values of the jurisdiction where new fossil fuel projects are being approved, or of the groups and nations where future emissions will have particularly dangerous and costly consequences. These factors may determine decisions on which consequences to prioritise when quantifying the impact of future CO_2 emissions[54]. For example, in Australia a range of nationally significant animals, plants, habitats, water resources or places, including the GBR Marine Park (Fig. 2c), are protected by national legislation through the Environmental Protection and Biodiversity Conservation Act[40]. Significant impacts on these Matters of National Environmental Significance[40] can be addressed in environmental approvals for proposed fossil fuel projects under Australia's jurisdiction. In other jurisdictions, human rights laws may provide instruments for climate change litigation, such as recent high-profile examples in Europe[54]. In these settings the quantification of consequences for people (Fig. 2a), including excess mortality (Fig. 2b), may have the greatest relevance for decision-making. The International Court of Justice (ICJ) recently concluded in a unanimous Advisory Opinion that States have binding legal obligations under international law to prevent significant harm to the climate system and to reduce emissions to levels capable of achieving the 1.5 °C Paris Agreement goal (para. 457 of ref. 55). States must apply best available science to all their climate-related decision-making (paras. 278, 284, 298, and 347 of ref. 55). The ICJ Advisory Opinion is highly relevant for national decision-making on the compatibility of proposed fossil fuel projects with achieving a State's climate change mitigation commitments for rapid decarbonisation over the coming decades (Fig. 3), including the ICJ conclusion that Developed States may be committing internationally wrongful acts by granting new fossil fuel project licences (para. 427 of ref. 55).

The approaches demonstrated here provide a science-based foundation that can be employed by companies, governments, decision-makers, governance boards, climate consultants and legal practitioners in quantifying the consequences of continued fossil fuel production and use, and in assessing whether these projects fall within acceptable levels of environmental and societal risk. In particular, we argue that companies proposing new or extended fossil fuel projects must better account for the impacts of their projected emissions. It is no longer defensible to simply state that their consequences will be negligible (Supplementary Table 1) when scientific evidence allows significant impacts to be anticipated and quantified (Fig. 2; Supplementary Fig. 4). A science-based approach also allows for a more explicit assessment of the financial burdens that result when new fossil fuel projects are approved, including through implicit assumptions and dubious feasibility[50,53] of rapidly increasing large-scale CO_2 removal as continued fossil fuel production and use coincide with national decarbonisation commitments (Fig. 3). This work has developed the quantification process for a small number of example consequences, but many other consequences of additional warming can also be anticipated. Future work will broaden the quantified consequences so that the best-available scientific evidence is able to more readily be incorporated into climate-relevant decision-making globally. The future-focused framework developed here reinforces that every tonne of CO_2 emissions adds to global warming, and that every fraction of a degree of additional warming matters[1].

Methods

All datasets and documents used for the analyses in this paper are derived from publicly available sources. These data sources are specified in the Methods text below, and in the analysis source code (https://doi.org/10.5281/zenodo.16516964).

Transient climate response to CO_2 emissions (TCRE)

The TCRE relationship used in this study is derived from the IPCC 6th Assessment Report of Working Group 1. The IPCC assessed that the *best estimate* is that 0.45 °C of global warming results from every 1000 Gt CO_2 emissions, with a *likely range* of global warming between 0.27 °C and 0.63 °C for every 1000 Gt CO_2 emissions[1].

Following established protocols for IPCC calibrated language[28], the *best estimate* represents the most likely value of the TCRE, and the *likely range* quantifies the possible range of TCRE values around the best estimate that are assessed to have a 66–100% likelihood (i.e., greater than 66% likelihood). IPCC assessments of likelihood involve statistical approaches to quantify uncertainty used alongside expert judgement. In the case of the TCRE, the *likely range* was derived from the statistical 90–100% likelihood of the TCRE (i.e., the 5th to 95th percentiles that statistically define a *very likely range* around the *best estimate*) in combination with expert judgement to account for incomplete coverage of all Earth system components in the approaches that were used to statistically define the TCRE. This consolidated assessment thus conservatively uses the statistical 5th–95th percentile range to describe a *likely range* (66–100% likelihood) of the TCRE[11].

It is well established that CO_2 is a well-mixed and long-lived gas in the atmosphere. This means that human-caused CO_2 emissions from fossil fuel combustion influence global climate in the same way, regardless of where these emissions are made. It also means that the climate warming impact of CO_2 emissions is sustained over timescales of multiple centuries to millennia. Short-lived greenhouse gases, notably methane (CH_4), cause warming that is sustained only over decadal timescales and for which an analogous TCRE relationship is not expected[11]. For this reason, this study only quantifies the additional warming and consequences of project-level CO_2 emissions. For fossil fuel projects, CO_2 emissions are the dominant greenhouse gas that is produced (typically >99%; see example for Scarborough emissions below).

Scarborough emissions

Greenhouse gas emission data is derived from the Scarborough Offshore Project Proposal[27]. Anticipated routine greenhouse gas emissions from the project are summarised in units of CO_2-equivalent. To facilitate application of the TCRE to determine the additional global warming caused by the Scarborough project, the CO_2-equivalent emission estimates are converted to CO_2 emissions using available information as follows:

Offshore production: Emissions (scope 1) from offshore production are derived from Table 7–14 and Table 7–15 of ref. 27. These are used to determine that fuel gas emissions of 9.88 Mt CO_2-equivalent are comprised of 99.7% CO_2, and flaring emissions of 1.38 Mt CO_2-equivalent are comprised of 95.4% CO_2. Scarborough gas has a CO_2 composition of 0.1 mol% (page 378 of ref. 27), and so offshore fugitive emissions of 0.26 Mt CO_2-equivalent (primarily CH_4) are omitted from the CO_2 emission estimates. Emissions from installation, construction and decommissioning of the offshore production infrastructure are estimated at 1 Mt CO_2-equivalent (page 378 of ref. 27), and are converted to CO_2 using 99.3% CO_2 composition derived from Australian Government national greenhouse gas accounting guidelines for heavy duty diesel fuel used for transport[4].

Onshore processing: Emissions (scope 1) from onshore processing of Scarborough gas are derived from Tables 7–17 of ref. 27. Reservoir CO_2 emissions of 0.55 Mt CO_2-equivalent are assumed to be 100% CO_2. Processing emissions of 87.42 Mt CO_2-equivalent use the fuel gas emissions composition of 99.7% CO_2.

Consumption: End use emissions (scope 3) for Scarborough gas are derived from Table 7-19 of ref. 27. Under the domestic gas reservation policy of Western Australia, 15% of Scarborough gas production is required to be marketed in Western Australia (p. 387 of ref. 27). This amounts to 92.69 Mt CO_2-equivalent emissions from domestic consumption. International use amounts to 685.84 Mt CO_2-equivalent. The CO_2 composition of these emissions is estimated at 99.7%, based on Australian government greenhouse gas reporting for gas distributed by pipeline[4].

Scarborough project emissions are provided[27] as fixed estimates without uncertainty values. As such, any uncertainty associated with emissions from the project are not incorporated in error calculations in this study.

Anticipated CO_2 emissions from Scarborough gas total 876 Mt CO_2 over the life of the project. Total CO_2 emissions are used in this study to quantify the additional warming and consequences of the Scarborough project. Of the total emissions, 192 Mt CO_2 fall under Australian jurisdiction for carbon accounting purposes (i.e., the emissions from production, processing and domestic consumption). The component of Australian emissions is used to demonstrate the time-evolving context of the Scarborough project relative to Australia's Nationally Determined Contribution to emission reductions.

The following text describes the methods used to quantify consequences and context of emissions from the Scarborough project, however, these are applicable in the same way to any project-level fossil fuel emissions. As such, in the following text we refer simply to the Project, rather than continuing to specify the Scarborough project.

Quantifying additional warming

The additional global warming that will be caused by CO_2 emissions from the Project is quantified using the TCRE through Eq. 1:

$$Additional\ warming(^{\circ}C) = Emissions(Mt\ CO2) \times \frac{0.45\ (^{\circ}C)}{1,000,000\ (Mt\ CO2)}$$

This results in a *best estimate* of 0.00039 °C of additional global warming that will be generated by the 876 Mt CO_2 emissions from the Project. To calculate the *likely range* of additional global warming, the best estimate constant of 0.45 °C is substituted with 0.27 °C and 0.63 °C in the equation above, generating the *likely range* of 0.00024 °C–0.00055 °C of additional global warming.

Quantifying consequences

For each of the quantified consequences demonstrated here, we use a Monte Carlo approach to fully propagate uncertainty. Errors are propagated using 100,000 realisations that randomly sample the uncertainty distributions of each variable used in quantifying consequences. Following the same approach used by the IPCC in determining the TCRE (see TCRE methods text above), we quantify a conservative *likely range* of consequences by calculating the 5th and 95th percentiles across the 100,000 realisations that sample the uncertainty distributions.

To propagate uncertainty in additional warming, we randomly sample a normal distribution[11] around the mean TCRE (mean = 0.45 °C, σ = 0.11 °C) and use this to calculate 100,000 realisations of the additional warming that can be anticipated for CO_2 emissions from the Project. The 5th and 95th percentiles of this distribution correspond to additional warming of 0.00024 °C and 0.00055 °C, consistent with the IPCC-defined *likely range* of the TCRE.

Human climate niche: Quantification of the impacts of additional global warming caused by the Project are derived from the relationships developed in ref. 32, and the associated code archive[56]. We quantify impacts based on a world with 9.5 billion people, which represents a middle-of-the-road shared socioeconomic pathway (SSP2) by the middle of the 21st century.

Two aspects of how global warming will affect people in relation to the human climate niche are quantified[32] (Supplementary Fig. 1a).

Unprecedented heat exposure quantifies the proportion of the global population whose local climate shifts to be beyond the upper limit of the human climate niche (i.e., above a mean annual temperature of 29 °C). In a world with 9.5 billion people this increases linearly by 13.8 ± 1.6% (mean and 95% confidence interval) per °C of global warming. The number of people left outside of the human climate niche takes into account the full temperature distribution of the human climate niche, with the proportion of the global population left outside the human climate niche increasing linearly by 9.5 ± 1.0% per °C of global warming in a world with 9.5 billion people. The uncertainty in these relationships is randomly sampled 100,000 times assuming a normal distribution around the mean.

Supplementary Fig. 1a shows the data used to calculate the number of people moved outside of the human climate niche through additional global warming for the middle-of-the-road (SSP2 in 2070) scenario of a world with 9.5 billion people. Supplementary Fig. 1b, c, further demonstrate the consequences for scenarios with lower (6.9 billion) and higher (11.1 billion) global population scenarios, as quantified in ref. 32.

Excess mortality in Europe: Quantification of excess deaths in Europe due to the additional warming caused by the Project is based on relationships determined across 854 European cities and quantified for various future climate scenarios[39,57]. We note that this example is used due to the availability of data from Europe to be able to quantify the excess deaths associated with additional warming. Some other parts of the world will be more severely impacted than Europe by excess deaths as a result of additional global warming, but data availability currently precludes quantification of these consequences.

Consistent with our approach for the human climate niche, we quantify excess climate change-related deaths in Europe using a middle-of-the-road (SSP2-4.5) future climate scenario. We extract data for cumulative excess deaths using a climate-change only option that has removed the effects of changing demographics under a no climate change scenario. Cumulative deaths are based on all age groups and a 0% adaptation scenario. The dataset quantifies cumulative deaths between 2015–2099, and so may slightly overestimate deaths caused by the Project where CO_2 emissions will occur over the 2026–2057 period. However, this should be countered by our approach of calculating additional deaths above 1.5 °C of global warming, which is near to today's climate warming level and so discounts any intensification of the impact of emissions on European deaths as global warming worsens over the lifetime of the Project.

Using the parameters described above, we extract Europe-wide information for cold-related deaths, heat-related deaths and total deaths at 1.5 °C, 2.0 °C, and 3.0 °C global warming levels (Supplementary Fig. 2a). Information for cumulative deaths at 4.0 °C is omitted as this level of global warming is poorly constrained in the SSP2-4.5 scenario of future climate simulations. Cumulative deaths data is provided as a best estimate, as well as lower and upper bounds that represent a 95% confidence interval. To estimate the additional deaths in Europe caused by the Project, we fit polynomials to the best estimate and 95% confidence interval data across the 1.5 °C to 3.0 °C global warming levels. We then use these polynomial functions to calculate the consequences of additional warming caused by the Project above 1.5 °C (e.g., the additional deaths at 1.50039 °C global warming level for the best estimate of additional warming, compared to deaths at 1.5 °C). The 95% confidence interval is not symmetrically distributed around the best estimate of cumulative deaths, and varies based on the level of additional warming. To account for this, the uncertainty distribution is randomly sampled 100,000 times based on a normal distribution that is defined by the 95% confidence interval at the level of additional warming above 1.5 °C caused by the Project, and the midpoint of this confidence interval.

The quantification of additional deaths in Europe is also repeated using the same methods, but for the impact of global warming levels defined in a high emissions (SSP3-7.0) scenario (Supplementary Fig. 2b).

Coral loss on the GBR: The consequences of additional warming caused by the Project for coral loss on the GBR requires first determining how global warming relates to thermal stress in the Great Barrier Reef Marine Park (GBRMP). Thermal exposure is measured using the Degree Heating Weeks (DHW) parameter that is indicative of conditions that lead to coral bleaching and mortality[41,58]. We examine the relationship between DHW and global warming using global mean surface temperature anomalies from the Berkeley Earth global temperature record (monthly resolution)[59] and the 5km-resolved DHW dataset from the NOAA Coral Reef Watch product (daily resolution)[45,58]. These datasets illustrate that the annual, summer-centred maximum of accumulated DHW averaged over the GBRMP has been increasing at 4.4-times (± 1.0 standard error; °C-weeks per °C) the rate of annual (July–June) global mean surface temperature (Supplementary Fig. 3a, b). This relationship is based on fitting a linear model, which is expected to be an appropriate estimate for the small magnitudes of additional warming being examined in this study. However, over larger magnitudes of additional global warming it is expected that the increase in DHW will be non-linear, as demonstrated by the lognormal distribution of the spatial relationship between the 5 km grid level (12222 individual grid cells) annual maximum of accumulated DHW over the GBRMP with annual (July–June) global mean surface temperature (Supplementary Fig. 3c, d). The linear model (Supplementary Fig. 3b) estimates that 0.00039 °C of additional global warming will result in a best estimate of additional thermal exposure in the GBRMP of 0.0017 °C-weeks, and 100,000 random samples of a lognormal distribution of uncertainty on this relationship based on the spatial relationship across the GBRMP (Supplementary Fig. 3d) results in a 5–95% range of 0.00060 °C-weeks to 0.0037 °C-weeks.

Determining how increasing thermal stress relates to anticipated coral loss on the GBR uses information on the observed relationship between heat exposure and coral cover losses, alongside estimates of the area of coral reef habitats within the GBRMP and the density of coral colonies within these habitats.

The empirical relationship between heat exposure and observed losses of corals on the GBR during the 2016 mass bleaching event estimates that each increase in heat exposure of 1 °C-weeks resulted in the death of 2–5% more corals (Fig. 2c)[43]. This defines a best estimate of 3.5% coral cover loss per °C-weeks, and an uncertainty around this central estimate that has a normal distribution with $\sigma = 0.91$.

The GBRMP includes an estimated 1.06 million hectares of coral habitat (hard substrate) at depths of 0–20 m[60]. This is used as a conservative fixed estimate in our calculations and may underestimate total reef area. For example, another study that also measured deeper reefs estimated reef area to be more than 3-times larger (3.47 million hectares)[61].

The number of corals per hectare is highly variable and poorly documented because coral abundance is typically measured as percent cover. Approximately 270,000 colonies larger than 9 cm^2 in size were counted per hectare on a Pacific reef[62]. Counts like this are highly sensitive to cutoffs in the minimum size of individuals recorded (e.g., the smallest size visible underwater to the naked eye, or in photographs or videos), and it is not feasible to count the youngest corals at the scale of hectares because newly recruited corals are microscopic. Their densities can exceed thousands per square metre[63] and far outnumber older and larger corals[64]. Consequently, we conservatively assume that, on average, 250,000 individual coral colonies larger than 1 cm in diameter currently occur per hectare on each of the 1.06 million hectares of coral habitat on the GBR (i.e., an average density of 25 corals per m^2 of reef habitat). This average fixed estimate of density discounts many billions of juvenile corals that are smaller than 1 cm.

Based on the relationship between DHW and coral cover, each increase in heat exposure of 1 °C-weeks results in a loss of 2–5% of corals, which represents an average decline per hectare of 5000 to 25,000 individual coral colonies (from an original average of 250,000). Consequently, across all 1.06 million hectares of shallow coral habitat on the GBR, a further increase in accumulated thermal exposure of 0.0017 °C-weeks (*likely range* of 0.00060 °C to 0.0037 °C-weeks) would result in the loss of 16 million corals (*likely range* of 4.7–37 million corals) during every future mass bleaching event. Within a decade or two, mass bleaching on the GBR, and elsewhere, is likely to occur every summer[41,42].

This quantification of consequences of Project emissions focuses only on losses of corals due to additional warming worsening the intensity of marine heatwave events. It discounts the compounding impacts of diminishing return-times between mass coral bleaching events, and of concurrent ocean acidification and intensified flooding that also degrade reef ecosystems[65]. The calculation of coral loss assumes that the relationship between DHW and coral losses on the GBR remains constant in the future. However, it is plausible that mortality rates in response to DHW could increase if the proportion of weedy, heat-susceptible corals increases over coming decades. Weedy corals are the first to rebound after bleaching events, despite their susceptibility to heat stress, and their prevalence may rise in response to repeated mass bleaching events[44]. Our quantification focuses only on losses of corals, without quantifying the impacts of worsening heat stress on other climate-sensitive species in the GBRMP such as mangroves, sea grasses, turtles, dugongs and sea birds. The loss of millions of corals will also reduce the population sizes of many species that depend on corals and the habitat they provide, including juveniles and adults of many fish species[66]. Many critical ecological processes, including calcification, reef growth, predation, and symbiosis will be further diminished throughout the GBR.

Climate mitigation context

Australia's 2022 Nationally Determined Contribution[49] is for a 43% reduction in greenhouse gas emissions by 2030 (relative to 2005 emissions), and net-zero emission by 2050. The emissions reduction pathway of Australia's NDC from actual emission levels at the start of 2025 is calculated using a linear reduction rate (Fig. 3a).

To give context to these emission reduction commitments we demonstrate them relative to historical emissions data from the Global Carbon Budget 2024[52] (data accessed: https://globalcarbonbudget.org/gcb-2024/). The Global Carbon Budget 2024 provides annual CO_2 emissions datasets at global and national scales to the end of 2023, along with published estimates for global emission in 2024[52]. Australia's emissions for 2024 are assumed to be equivalent to 2023 emissions, which is a valid approximation based on Australian Government reporting[67].

The historical emissions data for Australia are based on annual fossil CO_2 emissions, as well as land-use change (LUC) emissions, which we take as the average of two accounting methods (OSCAR and HN23 datasets; the BLUE and LUCE datasets were excluded as they are highly variable at national scales, making them inconsistent with national emissions reporting). We note that the emission reduction and negative emission trends (i.e., reforestation) in Australian LUC emissions from the Global Carbon Budget are not as strong as for Australian Government emissions reporting[67], due to government-reported inventories also including the natural land sink in managed forests[52].

To demonstrate how Australia's NDC relates to the remaining carbon budget for limiting warming to policy-relevant thresholds (Fig. 3a; Supplementary Figs. 5 and 6), we use the remaining global carbon budgets from the start of 2024[13] adjusted for estimated 2024 emissions[52] to reflect the remaining carbon budget from the start of 2025. In 2013, the Australian Government determined that Australia's "fair share" of the remaining global carbon budget should be 0.97%[48]. From 2013–2024 (inclusive) Australia's total CO_2 emissions were 1.03% of global CO_2 emissions, based on global and national inventories of the Global Carbon Budget[52]. We adjust for Australia's proportion of actual global emissions between 2013 and 2024 in determining Australia's fair share of the remaining carbon budget from the start of 2025. This approach sets Australia's fair-share budget relative to 2013 (i.e., when the fair-share was established by the Australian Government) and adjusts for both changes in scientific evidence for the remaining global carbon budget[13] and for Australia's actual emission rate since the fair-share was established. Linear emission reduction pathways[49] are used to show the pathways that would be consistent with Australia achieving its fair share to limit warming to 1.5 °C (Supplementary Fig. 5), 1.7 °C (Figs. 3a) and 2.0 °C (Supplementary Fig. 6) with a 50, 67, and 83% chance of success. Australia's 2022 NDC is broadly consistent with a fair-share emission reduction pathway to limit global warming to 1.7 °C with between a 50% and 67% chance of success.

For each year of the Project, we calculate the proportion of Project emissions (using only CO_2 emissions that fall under Australia's jurisdiction for carbon reporting) relative to anticipated annual total Australian emissions based on a linear reduction of emissions from the start of 2025 that achieves Australia's NDC (Fig. 3b).

Software

All analysis and figure panels were generated with MATLAB 2024b software. This included using the M_Map mapping package[68].

Data availability

All datasets and documents used for the analyses in this paper are derived from publicly available sources. These data sources are specified in the Methods text, and in the analysis source code.

Code availability

MATLAB code for the analyses performed in this study is available at Zenodo: https://doi.org/10.5281/zenodo.16516965. Future work will be linked to this Zenodo archive, including development of a Python version of the code, and an interactive app that can be utilised for proposed project-level fossil fuel emissions that are made anywhere in the world. Future work will also extend the quantified consequences across a greater range of examples to aid translation of the methods demonstrated here into applications across various sectors and locations.

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References

1. IPCC. Summary for Policymakers, in *Climate Change 2021. The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds V. Masson-Delmotte et al.) pp. 3-32, Cambridge University Press. (IPCC, 2021).
2. Matthews, H. D. et al. Opportunities and challenges in using remaining carbon budgets to guide climate policy. *Nat. Geosci.* **13**, 769–779 (2020).
3. Trout, K. et al. Existing fossil fuel extraction would warm the world beyond 1.5°C. *Environ. Res. Lett.* **17**, 064010 (2022).
4. Australian Government. *Australian National Greenhouse Accounts Factors: For individuals and organisations estimating greenhouse gas emissions*. https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-factors-2024. (Australian Government, 2024).
5. Heede, R. Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010. *Clim. Change* **122**, 229–241 (2014).
6. Callahan, C. W. & Mankin, J. S. Carbon majors and the scientific case for climate liability. *Nature* **640**, 893–901 (2025).
7. Jones, M. W. et al. National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Sci. Data* **10**, 155 (2023).
8. Waidelich, P., Batibeniz, F., Rising, J., Kikstra, J. S. & Seneviratne, S. I. Climate damage projections beyond annual temperature. *Nat. Clim. Change* **14**, 592–599 (2024).
9. Kotz, M., Levermann, A. & Wenz, L. The economic commitment of climate change. *Nature* **628**, 551–557 (2024).
10. Beggs, P. J. et al. The 2024 report of the –Lancet Countdown on health and climate change: Australia emerging as a hotspot for litigation. *Med. J. Aust.* **222**, 272–296 (2025).
11. Canadell, J. G. et al. Global Carbon and other Biogeochemical Cycles and Feedbacks, in *Climate Change 2021*: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the*

Intergovernmental Panel on Climate Change (eds V. Masson-Delmotte et al.) pp. 673-816, (IPCC, 2021).
12. MacDougall, A. H. The transient response to cumulative CO2 emissions: a review. *Curr. Clim. Change Rep.* **2**, 39–47 (2016).
13. Forster, P. M. et al. Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* **16**, 2625–2658 (2024).
14. Matthews, H. D., Solomon, S. & Pierrehumbert, R. Cumulative carbon as a policy framework for achieving climate stabilization. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **370**, 4365–4379 (2012).
15. United Nations. *Paris Agreement*. unfccc.int/sites/default/files/english_paris_agreement.pdf. (United Nations, 2015).
16. King, A. D. et al. Exploring climate stabilisation at different global warming levels in ACCESS-ESM-1.5. *Earth Syst. Dynam.* **15**, 1353–1383 (2024).
17. Matthews, H. D. & Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* **35**, L04705 (2008).
18. Palazzo Corner, S. et al. The Zero Emissions Commitment and climate stabilization. *Front. Sci.* **1** https://doi.org/10.3389/fsci.2023.1170744 (2023).
19. Eby, M. et al. Lifetime of anthropogenic climate change: millennial time scales of potential CO2 and surface temperature perturbations. *J. Clim.* **22**, 2501–2511 (2009).
20. Forster, P. et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity, in *Climate Change 2021*: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds V. Masson-Delmotte et al.) pp. 923-1054, Cambridge University Press. (IPCC, 2021).
21. Armstrong McKay, D. I. et al. Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 377, eabn7950 (2022).
22. Tyndall, J. On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction. *Philos. Trans. R. Soc.* **151**, 1–36 (1861).
23. Arrhenius, S. On the influence of carbonic acid in the air upon the temperature of the ground. *Philos. Mag. J. Sci.* **41**, 237–276 (1896).
24. Callendar, G. S. Can carbon dioxide influence climate? *Weather* **4**, 310–314 (1949).
25. Plass, G. N. Effect of carbon dioxide variations on climate. *Am. J. Phys.* **24**, 376–387 (1956).
26. Manabe, S. & Möller, F. On the radiative equilibrium and heat balance of the atmosphere. *Monthly Weather Rev.* **89**, 503–532 (1961).
27. Woodside. *Scarborough Offshore Project Proposal*. https://info.nopsema.gov.au/offshore_projects/41/show_public (2020).
28. Chen, D. et al. Framing, Context and Methods, in *Climate Change 2021*: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds V. Masson-Delmotte et al.) pp. 147-286 (Cambridge University Press, 2021).
29. Hoegh-Guldberg, O. et al. The human imperative of stabilizing global climate change at 1.5°C. *Science* **365**, eaaw6974 (2019).
30. IPCC. Summary for Policymakers, in *Climate Change 2022*: *Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds H.-O. Pörtner et al.) pp. 3-33 (Cambridge University Press, 2022).
31. Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R. & Wilby, R. L. Allowable CO2 emissions based on regional and impact-related climate targets. *Nature* **529**, 477–483 (2016).
32. Lenton, T. M. et al. Quantifying the human cost of global warming. *Nat. Sustain.* **6**, 1237–1247 (2023).
33. Xu, C., Kohler, T. A., Lenton, T. M., Svenning, J.-C. & Scheffer, M. Future of the human climate niche. *Proc. Natl. Acad. Sci. USA* **117**, 11350–11355 (2020).
34. Kc, S. & Lutz, W. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Change* **42**, 181–192 (2017).
35. Vicedo-Cabrera, A. M. et al. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Change* **11**, 492–500 (2021).
36. Masselot, P. et al. Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe. *Lancet Planet. Health* **7**, e271–e281 (2023).
37. Lüthi, S. et al. Rapid increase in the risk of heat-related mortality. *Nat. Commun.* **14**, 4894 (2023).
38. Matthews, T. et al. Humid heat exceeds human tolerance limits and causes mass mortality. *Nat. Clim. Change* **15**, 4–6 (2025).
39. Masselot, P. et al. Estimating future heat-related and cold-related mortality under climate change, demographic and adaptation scenarios in 854 European cities. *Nat. Med.* **31**, 1294–1302 (2025).
40. Australian Government. *Environment Protection and Biodiversity Conservation Act*. Federal Register of Legislation. https://www.legislation.gov.au/C2004A00485/latest/versions. (Australian Government, 1999).
41. Lough, J. M., Anderson, K. D. & Hughes, T. P. Increasing thermal stress for tropical coral reefs: 1871–2017. *Sci. Rep.* **8**, 6079 (2018).
42. Henley, B. J. et al. Highest ocean heat in four centuries places Great Barrier Reef in danger. *Nature* **632**, 320–326 (2024).
43. Hughes, T. P. et al. Global warming transforms coral reef assemblages. *Nature* **556**, 492–496 (2018).
44. Hughes, T. P. et al. Emergent properties in the responses of tropical corals to recurrent climate extremes. *Curr. Biol.* **31**, 5393–5399 (2021).
45. Liu, G. et al. Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA coral reef watch. *Remote Sens.* **6**, 11579–11606 (2014).
46. United Nations. *Glasgow Climate Pact*. unfccc.int/sites/default/files/resource/cop26_auv_2f_cover_decision.pdf. (United Nations, 2021).
47. Robiou du Pont, Y. et al. Equitable mitigation to achieve the Paris Agreement goals. *Nat. Clim. Change* **7**, 38–43 (2017).
48. Climate Change Authority. *Reducing Australia's greenhouse gas emissions: targets and progress review final report*. https://www.climatechangeauthority.gov.au/sites/default/files/Targets%20and%20Progress%20Review%20Final%20Report.pdf. (Climate Change Authority, 2014).
49. Australian Government. *Australia's Nationally Determined Contribution*. https://unfccc.int/sites/default/files/NDC/2022-06/Australias%20NDC%20June%202022%20Update%20%283%29.pdf. (Australian Government, 2022).
50. Gidden, M. J. et al. Chapter 8: Paris-consistent CDR scenarios, in *The state of carbon dioxide removal 2024 - 2nd Edition* (ed S. M. Smith), https://doi.org/10.17605/OSF.IO/8XK7H (2024).
51. Shindell, D. & Rogelj, J. Preserving carbon dioxide removal to serve critical needs. *Nat. Clim. Change* **15**, 452–457 (2025).
52. Friedlingstein, P. et al. Global Carbon Budget 2024. *Earth Syst. Sci. Data* **17**, 965–1039 (2025).
53. Schleussner, C.-F. et al. Overconfidence in climate overshoot. *Nature* **634**, 366–373 (2024).
54. Blattner, C. E. et al. How science bolstered a key European climate-change case. *Nature* **621**, 255–257 (2023).
55. International Court of Justice. *Advisory Opinion: Obligations of States in Respect of Climate Change*. *23rd July 2025*. https://www.icj-cij.org/sites/default/files/case-related/187/187-20250723-adv-01-00-en.pdf (2025).
56. Lenton, T. M. et al. Quantifying the Human Cost of Global Warming (Code). *figshare*, https://doi.org/10.6084/m9.figshare.22650760.v1 (2023).
57. Masselot, P., Mistry, M. N. & Gasparrini, A. Projection of temperature-related mortality in 854 European cities under climate change and

adaptation scenarios. *Zenodo*, https://doi.org/10.5281/zenodo.14004321 (2024).
58. Heron, S. F., Maynard, J. A., van Hooidonk, R. & Eakin, C. M. Warming trends and bleaching stress of the world's coral reefs 1985–2012. *Sci. Rep.* **6**, 38402 (2016).
59. Rohde, R. A. & Hausfather, Z. The Berkeley Earth land/ocean temperature record. *Earth Syst. Sci. Data* **12**, 3469–3479 (2020).
60. Roelfsema, C. M. et al. How much shallow coral habitat is there on the Great Barrier Reef? *Rem. Sens.* **13**, 4343 (2021).
61. Harris, P. T. et al. Submerged banks in the Great Barrier Reef, Australia, greatly increase available coral reef habitat. *ICES J. Mar. Sci.* **70**, 284–293 (2013).
62. Edwards, C. B. et al. Large-area imaging reveals biologically driven non-random spatial patterns of corals at a remote reef. *Coral Reefs* **36**, 1291–1305 (2017).
63. Hughes, T. P. et al. Global warming impairs stock–recruitment dynamics of corals. *Nature* **568**, 387–390 (2019).
64. Dietzel, A., Bode, M., Connolly, S. R. & Hughes, T. P. Long-term shifts in the colony size structure of coral populations along the Great Barrier Reef. *Proc. R. Soc. B Biol. Sci.* **287**, 20201432 (2020).
65. Hughes, T. P. et al. Coral reefs in the Anthropocene. *Nature* **546**, 82–90 (2017).
66. Pratchett, M. S., Thompson, C. A., Hoey, A. S., Cowman, P. F. & Wilson, S. K. Effects of Coral Bleaching and Coral Loss on the Structure and Function of Reef Fish Assemblages, in *Coral Bleaching: Patterns, Processes, Causes and Consequences* (eds Madeleine J. H. van Oppen & Janice M. Lough) pp. 265-293 (Springer International Publishing, 2018).
67. Australian Government. *Australia's National Greenhouse Accounts*. *Department of Climate Change, Energy, the Environment and Water*, https://www.greenhouseaccounts.climatechange.gov.au/ (Australian Government, 2025).
68. Pawlowicz, R. M._*Map: A mapping package for MATLAB (version 1.4m) [Computer software]* https://github.com/g2e/m_map (2020).

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Author contributions
N.J.A. conceived the study. N.J.A. and T.P.H. developed the analysis, with contributions from N.M., G.M.F., and S.P.K. N.J.A. wrote the analysis code and prepared the figures. N.J.A. led the writing, and all authors contributed to discussions and editing of the manuscript.

Competing interests
This manuscript builds upon consultancy work previously undertaken by N.J.A. and T.P.H. as independent experts for the Australian Conservation Foundation engaged through the Environmental Defenders Office.

Additional information
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