The Zero Emissions Commitment and climate stabilization

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Abstract

How do we halt global warming? Reaching net zero carbon dioxide (CO_2) emissions is understood to be a key milestone on the path to a safer planet. But how confident are we that when we stop carbon emissions, we also stop global warming? The Zero Emissions Commitment (ZEC) quantifies how much warming or cooling we can expect following a complete cessation of anthropogenic CO_2 emissions. To date, the best estimate by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report is zero change, though with substantial uncertainty. In this article, we present an overview of the changes expected in major Earth system processes after net zero and their potential impact on global surface temperature, providing an outlook toward building a more confident assessment of ZEC in the decades to come. We propose a structure to guide research into ZEC and associated changes in the climate, separating the impacts expected over decades, centuries, and millennia. As we look ahead at the century billed to mark the end of net anthropogenic CO_2 emissions, we ask: what is the prospect of a stable climate in a post-net zero world?

KEYWORDS

Zero Emissions Commitment, ZEC, net zero, warming in the pipeline, locked in warming, climate neutrality, climate stabilization, uncertainty

Key points

- Substantial uncertainty remains in both the sign and magnitude of the Zero Emissions Commitment (ZEC): the expected additional change in global surface temperature once we achieve net zero CO_2 emissions.
- Uncertainty in ZEC has implications for the remaining carbon budget to stay below the temperature limits of the Paris Agreement: a positive ZEC reduces the remaining budget; a negative ZEC opens the door for more ambitious targets or more time to reach net zero.
- The prospect of additional warming after net zero is both plausible and significant, with a chance that ZEC could exceed 15% of total global warming.
- While a ZEC of 0 means no further change to global surface temperatures, other aspects of the Earth system, such as sea levels, will continue to change in a net zero world due to warming realized previously. These changes should be factored into the assessment of safe warming limits and adaptation plans.
- Current climate models do not adequately represent the full scope of complex and interdependent Earth system processes that determine ZEC. We present a structure for quantifying uncertainty in ZEC and propose a roadmap for future research into quantifying ZEC and reducing its uncertainties.

Introduction and definitions

As we advance into the 21st century, a drumbeat of climate-related disasters is sounding an ever-louder alarm. Be they floods, heatwaves, or hurricanes, their impacts are projected to increase in regularity and intensity as global warming continues (1). Tackling the climate crisis is one of the defining societal challenges of this century. In recent decades, the geophysical requirements for halting global warming have been subject to intense research (2–6). Our current models and understanding of relevant processes support the argument that if global carbon dioxide (CO_2) emissions from human activities are brought back to 'net zero' (i.e., we emit into the atmosphere no more than our activities absorb from it), the increase in global surface temperature may be halted. In other words, by no longer adding CO_2 to the atmosphere, we may cautiously expect that global warming can be stopped. The sixth assessment (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (7) supports this key geophysical insight, and this understanding underpins the many 'net zero' targets that countries and companies have announced over recent years.

The Zero Emissions Commitment (ZEC) describes the net change to global surface warming after a complete cessation of anthropogenic emissions, in many cases with a focus on CO_2. In combination with the transient climate response to cumulative emissions (TCRE), it defines the total amount of global surface warming for a given amount of CO_2. In turn, this total expected

warming determines the carbon budget: the amount of carbon dioxide that can be released before reaching a certain temperature threshold. A positive ZEC indicates additional surface warming after net zero, a negative ZEC a drop in surface temperature, and a zero ZEC no further averaged surface temperature change (Figure 1). Emerging literature on this topic (4, 8) led the IPCC to conclude that global surface temperatures 50 years after a complete cessation of CO_2 emissions (referred to as ZEC_{50}) would stabilize with no substantial further warming, but this assessment came with an important uncertainty range (9). Total surface warming could still increase or decrease once we stop adding CO_2 to the atmosphere, with a non-negligible chance that the change would exceed 15% of total warming. IPCC AR6 estimated that the absolute magnitude of ZEC is less than 0.3°C (9) for an initial warming of approximately 2°C.

For global surface temperatures to become and remain stable, the behavior of large-scale planetary sub-systems must cancel each other out and equilibrate at similar timescales (10). However, halting global warming does not mean that all Earth system components will stabilize at the same time. Many components of the system will continue to adjust to the perturbation that human activities have caused, including deep ocean warming, sea level rise, and changes in glacier-fed river systems (11).

In this article, we first present key definitions and the current high-level scientific understanding of the ZEC concept. We delve into the processes that determine the ZEC outcome and their uncertainties to better understand what to expect in a world that manages to bring its carbon emissions to net zero. We describe our current best understanding as well as key unknowns and reflect on the implications of these insights for climate policy today.

Definitions

Net zero CO_2 emissions are defined by the IPCC as the "condition in which anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals over a specified period" (12). In this article, net zero anthropogenic emissions are considered equivalent to zero anthropogenic emissions, while recognizing that net zero achieved via substantial CO_2 removal may be inequivalent to true zero emissions due to impacts on Earth system processes, such as changes to the land carbon sink. Ongoing research exploring the potential difference in warming response between positive and negative emissions is also acknowledged (13).

The Zero CO_2 Emissions Commitment is the estimated amount of *additional* change in global warming we can expect following zero anthropogenic emissions of CO_2 and is referred to in this article as ZEC. ZEC is defined by two dimensions: the time since the onset of net zero CO_2 emissions, and the global surface temperature change that occurs over this period. Though prone to false equivalence in wider climate communications, ZEC is distinct from the 'constant composition commitment', which describes the temperature change expected when atmospheric composition and hence radiative forcing (14, 15) is kept fixed at its present-day
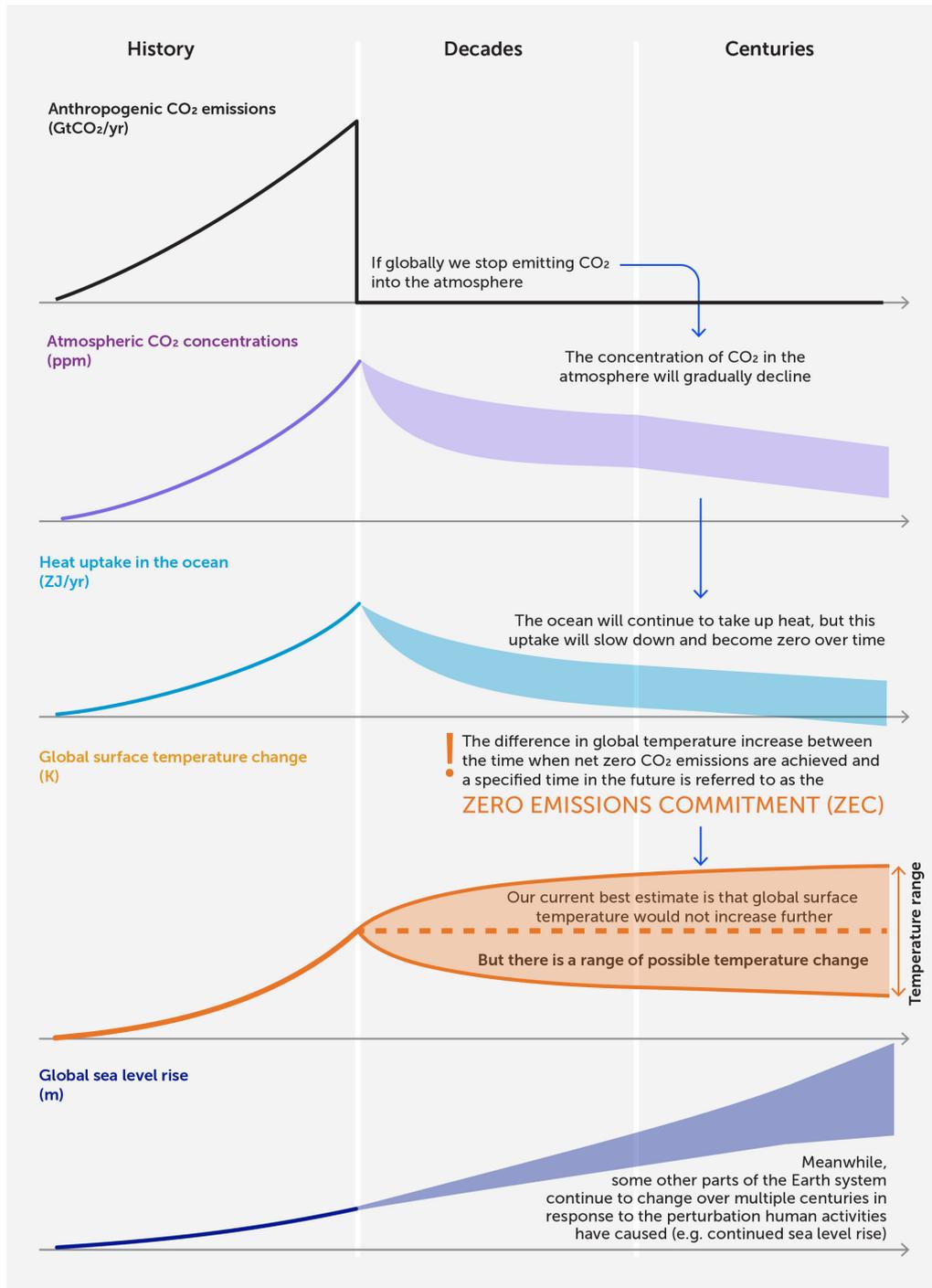
FIGURE 1

Stylised schematic of how atmospheric carbon dioxide (CO_2) concentrations, ocean heat uptake, and global surface temperature can evolve under net zero CO_2 emissions. Process timescales are illustrative.

value for multiple centuries. Several commonly used phrases such as 'warming in the pipeline' (4), 'committed warming' (16), and 'unrealized warming' (17) risk further conflating the two concepts when insufficiently defined. Unless otherwise specified, in this article, "net zero" will refer to anthropogenic CO_2 emissions and removals, and "warming" to the near-surface global mean temperature change.

The broader Zero Emissions Commitment concept can also be applied to non-CO_2 gases and wider CO_2 inclusive groups, with studies considering ZEC for all anthropogenic forcing agents combined (12, 18–21), individual forcing agents (5, 6, 22–25), or for select combinations of these agents (3, 26). The latest assessments of the current global warming contributions of non-CO_2 greenhouse gases and aerosols show that they are of

approximately the same magnitude (7). Owing to the relatively short atmospheric lifetime of most anthropogenic greenhouse gases and aerosols compared to the atmospheric lifetime of CO_2 on centennial timescales, ZEC for all anthropogenic forcing agents largely depends on the response to CO_2 (3, 27). Recent model experiments designed to quantify ZEC have thus focused on CO_2 emissions only (28). In addition, while strategies to reduce global CO_2 emissions to net zero have been identified in the broad climate change mitigation scenario literature, no existing pathways show a complete elimination of methane (CH_4), nitrous oxide (N_2O), or aerosol emissions (29, 30). Reflecting this context, we consider ZEC for CO_2 only.

ZEC overview

Outline of the ZEC mechanism

ZEC is a function of the geophysical properties of the interconnected Earth system (Figure 2) and how these change as new th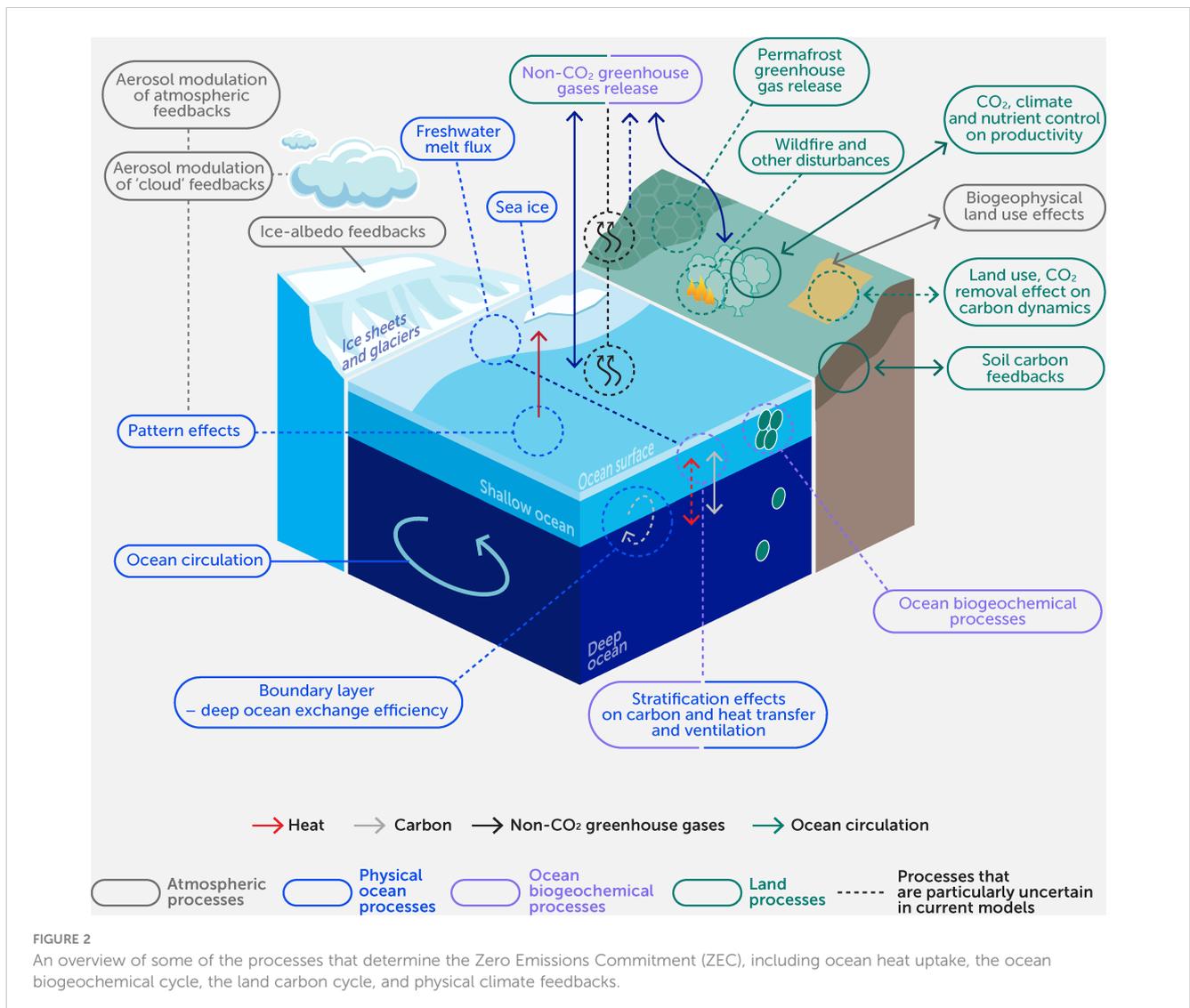ermal and biogeochemical steady states are established. ZEC can be thought of as a measure of the lag of the global warming response to a total cessation of net emissions, which results in either additional warming (positive ZEC), cooling (negative ZEC), or a stable temperature (zero ZEC). After emissions of CO_2 are reduced to net zero, both atmospheric CO_2 concentration (31) and ocean heat uptake are expected to decline (4, 32, 33). In isolation, the drop in atmospheric CO_2 concentration has a cooling effect on the climate, while the reduction in ocean heat uptake has a warming effect (4, 33, 34). In Earth system model (ESM) simulations, the drop in atmospheric CO_2 concentration is determined by carbon cycle processes that redistribute carbon between the atmosphere, ocean, land, and geological reservoirs. In its simplest form, ZEC can thus be thought of as a surface energy balance relationship in a zero-dimensional model: if, after emissions cease, Earth's surface and atmosphere absorb more energy than they emit back to space or is stored in the deep ocean, ZEC will be positive; if, on the other hand, Earth's surface and atmosphere emit more energy than the planet absorbs, ZEC will be negative. Under this simple relationship, temperature stabilization is reached when energy out equals

FIGURE 2

An overview of some of the processes that determine the Zero Emissions Commitment (ZEC), including ocean heat uptake, the ocean biogeochemical cycle, the land carbon cycle, and physical climate feedbacks.

energy in (Figure 3). Changes to feedback mechanisms affecting clouds and surface albedo (or reflectivity), patterns of warming, and exchanges of heat with the deep ocean may modify how Earth absorbs and emits energy in the future compared to the recent past, adding uncertainty to the ZEC outcome.

Even a zero ZEC scenario will not stop regional temperature change (35), long-timescale environmental consequences of climate heating, and Earth's natural long-term climate variability. For example, global sea level rise will continue owing to mass input from ice sheet dynamics and volume expansion from deep ocean warming driven by past anthropogenic emissions, with centennial to millennial time-lags until ocean heat uptake and ice sheet mass adjustment reach new steady states (11).

ZEC modeling

Studies of how much warming could be expected under particular conditions originated in the 1980s with early analyses of response timescales by Hansen et al. and Wigley and Schlesinger (36, 37) strengthened by constant composition runs in the third phase of the Coupled Model Intercomparison Project (CMIP3) (38). The IPCC Fourth Assessment Report in 2007 included a section on long-term changes (38), presenting results from multiple Earth system models of intermediate complexity (EMICs) specifically running a zero emissions scenario. The Fifth Assessment Report in 2013 featured a "Frequently Asked Question" titled "12.3: What Would Happen to Future Climate if We Stopped Emissions Today?" (10), alongside results from ZEC simulations with EMICs (19). Nevertheless, uncertainty in ZEC remains and contemporary modeling exercises have been designed to structure and expand these investigations to determine the sign and magnitude of ZEC with increased confidence.

The ZEC Model Intercomparison Project (ZECMIP) (28) is the largest ZEC modeling exercise to date, performing coordinated idealized experiments in 18 ESMs and EMICs. ZECMIP considered two types of emissions pathways. The first pathway involved "1pctCO$_2$" simulations in which atmospheric CO$_2$ concentrations increase by 1% per year. For ZECMIP, these "1pctCO$_2$" simulations were run until their diagnosed cumulative CO$_2$ emissions reached a certain value and were then suddenly switched to an emission-driven zero emissions case. The second type of ZECMIP experiments were "bell-shaped" pathway experiments, in which emissions evolved gradually from zero to a peak, and then decreased gradually again to zero. While both experiments converged to roughly equal global mean temperature anomalies, in the latter much of ZEC is already realized by the time zero emissions is reached (4), owing to the slower forcing trajectory in the bell curve experiment.

ZECMIP (4) found a surface temperature change ranging from –0.36 to +0.29°C across participating models 50 years after emissions cease (ZEC$_{50}$) for cumulative emissions of 1000 PgC, increasing to –0.40 to +0.52°C for 2000 PgC. These models suggest that substantial delayed warming or cooling could occur after emissions are curtailed and that ZEC is state-dependent, meaning that the (relative) magnitude of ZEC can differ depending on the level of anthropogenic cumulative emissions (4). The ESM and

EMIC modeling results assessed in IPCC AR6 showed a slightly negative ZEC$_{50}$ smaller than –0.1°C (–0.34°C to +0.28°C) (4, 9, 28). This informed the latest IPCC assessment, which concluded that the absolute magnitude of ZEC$_{50}$ for emissions of 1000 PgC is <0.3°C with >66% probability (9). As 1000 PgC emissions leads to approximately 2°C of global warming (39), this implies a ZEC$_{50}$ of approximately ±15% of realized warming at zero emissions. IPCC AR6 provided no assessment of ZEC on longer timescales and expressed low confidence in the sign of ZEC.

Simple models have also been used to explore what values of ZEC are consistent with observations. The results suggest that industrial-era temperatures alone do not strongly constrain ZEC, but paleoclimate records and independent evidence about equilibrium climate sensitivity could lead to potential further constraints (40). These findings depend on the structural assumptions within the models used and the inclusion of independent degrees of freedom for carbon and thermal climate processes.

Two significant caveats apply to the current modeling evidence relating to ZEC. First, ZECMIP features only a subset of available ESMs, and the 100-year zero emission extensions for ESMs cannot inform us about the potential for carbon-climate, deep ocean, and ice sheet dynamics, which occur on longer timescales. Multi-century simulations with individual ESMs have revealed markedly different behaviors, with an increase in warming after a century-long decrease despite zero CO$_2$ emissions (27, 32, 33, 41), whereas earlier experiments with EMICs did not show such multi-century behavior (19). Second, while there is consensus on a near-zero ZEC as a model mean in the participating ZECMIP models, further research to elucidate the carbon and climate process decomposition is needed to determine if this result arises from common or oversimplified structural underpinnings, from model calibration, or simply by chance—especially given that intermediate complexity models exhibit more diverse behavior (4).

Earth subsystems post net zero

To assess the potential for significant warming or cooling post net zero emissions, we consider the evolution of key Earth subsystem processes that both drive and respond to changing carbon concentrations and heat gradients under net zero CO$_2$ emissions. The shifting dominance of processes from decadal to millennial timescales is discussed, building a picture of interconnected Earth system elements and the changes to global mean temperature these can bring. Some processes require or result in temperature changes, while others are set to evolve even in a world with stable global temperature.

Evolution of Earth subsystems post net zero

Ocean heat uptake

The ocean is the largest reservoir of accumulated energy as a result of anthropogenic climate forcing, having stored roughly 91% of Earth's additional retained heat since 1971 compared with approximately 1% stored in the atmosphere (4, 5, 33, 42). After

net zero CO_2 emissions are reached, ocean heat uptake is expected to decline as the ocean approaches a thermal steady state relationship with the atmosphere (4, 5, 33). However, the rate and amount of this decline may be sensitive to processes not well understood, and models are sensitive to the ways in which these processes are represented.

Two parameters are particularly important to understand the role of the ocean in global surface temperature: the *efficiency* of ocean heat uptake, which is a measure of the ability of the ocean to transport upper ocean waters to depths away from the atmosphere; and the *efficacy* of ocean heat uptake, which is a measure of the global surface temperature response per unit of heat taken up by the ocean, and which depends on climate feedbacks in response to ocean heat uptake (43).

Efficiency

While most of the energy in recent decades has been absorbed by the upper ocean, the link between the upper and deep ocean is important to understand the ocean temperature of an ocean thermal steady state, and the time needed to reach it. One simple model that accounts for a surface energy reservoir (effectively the upper ocean) and a deeper reservoir (taking surface energy down to greater depths) is the "two-layer energy balance model" (44–47), where heat transfer is assumed to be proportional to the temperature difference (48). Other simple models, which comprise more ocean layers, include an additional structural element that provides a slightly modified long-term response, i.e., the inclusion of polar sinking water and upwelling. This leads to longer response timescales compared with diffusive-only models and replicates general circulation model (GCM) ocean heat uptake relatively well (49–53).

On diurnal to seasonal timescales, the evolving upper 200 m stratification and turbulent mixed layer govern the uptake of energy, where deeper mixed layers have a higher heat capacity and thus the sea surface temperature warms less per unit of energy taken up (54). On decadal timescales, the tropical oceans continue to operate as a mixed layer, while the subtropical oceans and their gyres overturn in subtropical cells, subducting surface waters and their energy anomalies into the pycnocline. On still longer timescales, the polar oceans form subsurface water masses by deep convection that overturns the surface waters into North Atlantic Deep Water (NADW) via the Atlantic Meridional Overturning Circulation (AMOC) and Southern Ocean waters near the Ross and Weddell Seas to form Antarctic Bottom Water (AABW). These water masses will remain away from the surface for centuries and millennia, respectively (55).

Efficacy

The specific patterns of surface heat uptake and surface warming affect the marine boundary layer and thus the atmosphere, leading to complex cloud feedbacks that affect radiative and atmospheric warming and cooling of the oceans (56). For instance, ocean heat uptake at high latitudes is thought to be more effective at cooling the atmosphere than ocean heat uptake at low latitudes (43, 57, 58), which is suspected to originate from shortwave radiation cloud feedback (56).

Biases where the tropical ocean mixed layer depth is excessive tend to increase the short timescale heat capacity of the ocean, while excessive mixed layer depths in the North Atlantic deep convection region tend to warm the NADW, and excessive mixed layer depths in the Southern Ocean deep convection tend to cool the NADW and warm the upper tropical oceans. The CMIP6 ensemble spread in observable indicators of these water formation processes is much larger than that which is supported by observational uncertainty. Thus, the efficacy and climate sensitivity of the CMIP6 ensemble, and two-layer models trained to match it, can likely be improved substantially through better ocean process representation (Hall and Fox-Kemper, 2022)[1]. While all ESMs have deep oceans that warm during emissions and continue to do so long after emissions cease and surface exchanges stabilize, the rate at which the surface ocean loses heat to the deep ocean (and the strength of feedbacks on surface ocean temperature anomalies) varies among models, affecting the precision of ZEC estimates on the multi-decadal scale and longer.

Longer term change

The timescales of the deep and bottom oceanic overturning are on the order of centuries to millennia. Neither the NADW nor AABW have yet been fully equilibrated to the surface climate changes of the last century, let alone modern changes. That means that the deep ocean will continue to warm, acidify, and deoxygenize over the coming centuries and millennia even if net zero CO_2 emissions are reached (11). We expect continued warming and volume adjustment in the deep-water masses, which implies a continuing global mean thermosteric sea level rise of roughly 0.25 m/°C of surface warming after 2000 years, along with continued mean ocean temperature and heat content change. As the cryosphere is also slow to adjust, the total global mean sea level rise is expected to be closer to 0.6 m/°C of surface warming after 100 years, or 4 m/°C after 2000 years and 7 m/°C after 10,000 years. During the last interglacial period, for example, temperatures were 0.5°C to 1.5°C warmer, and the sea level was 5–10 m higher (11, 59).

Ocean carbon uptake and marine emissions of other biogeochemical cycles

The processes governing the ocean carbon response to the cessation of CO_2 emissions result from the same processes and mechanisms that drive the sign and magnitude of the ocean carbon sink during rising emissions (60). Anthropogenic CO_2 accumulates in the surface ocean via enhanced air-sea gas exchange, which is then transported to depth by ocean currents and mixing (61, 62). This newly accumulated CO_2 alters the chemistry in the ocean, acidifying it through carbonic acid (63). Climate change-induced perturbations to ocean temperature, circulation, and biological processes then act to further alter the ocean carbon cycle (64, 65). The relative contribution of each process in setting the regional and global response to emission cessation remains largely uncertain,

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1 Hall G and Fox-Kemper B. Regional mixed layer depth as a climate diagnostic and emergent constraint. (submitted to) *Geophys Res Lett* (2022).

however, and may depend on the state (i.e., the level of warming and atmospheric CO_2) at which emissions are brought to net zero.

Current knowledge, mostly based on multi-model assessment, suggests that the role of the ocean carbon cycle varies substantially across timescales. On annual to multi-decadal timelines after net zero CO_2, the magnitude of ocean carbon uptake is projected to be similar to that absorbed by the terrestrial biosphere (4, 31). On centennial to millennial timescales, the role of the ocean becomes increasingly prominent. The results of ESM simulations (4, 31, 41, 66) indicate that while the cumulative land carbon sink stops growing within about a century after reaching zero emissions, and even begins to decrease thereafter, the ocean continues to absorb carbon. Joos et al. (31) reported that, after 1000 years of simulation, on average 59% of the 100 GtC of emitted carbon (under present-day conditions) will have been transferred to the ocean and 16% to the land, with 25% remaining in the atmosphere.

Beyond the ocean carbon cycle, many other ocean processes may influence the overall ocean carbon contribution to ZEC, including mesoscale eddies, melting from ice sheets, sea ice cover, and CH_4 release—all of which add to the uncertainty in defining the outcome of ZEC.

Land carbon

The land carbon contribution to ZEC is dominated by three types of processes: those that govern the carbon response to CO_2 concentrations in terrestrial ecosystems; those that govern the response to climate change; and anthropogenic land use and land use change. Each of these processes may also interact with one another.

Land carbon response to CO_2

In a world with excess CO_2 emissions, the magnitude of the land carbon sink increases via CO_2 fertilization of leaf photosynthesis, which is one of the most important drivers of current land carbon uptake (67). Increased ecosystem productivity, resulting from increased CO_2 fertilization, leads to the accumulation of carbon in biomass and soil organic matter as ecosystem respiration is exceeded, at least temporarily. This land carbon accumulation in response to CO_2 tends to be limited, however, by the availability of nutrients, especially nitrogen and phosphorus (68, 69). Over time, decomposition also increases and balances the increased production. Thus, declines in CO_2 fertilization, due either to increased nutrient limitation or declines in the growth rate of atmospheric CO_2, lead to a reduction of the land carbon sink (70). When CO_2 emissions reach net zero, the speed with which terrestrial ecosystems respond to the change from rising to falling atmospheric CO_2 concentrations (by slowing or potentially stopping their net carbon uptake) will strongly influence the land contribution to ZEC.

Land carbon response to climate change

The land carbon sink capacity is further modulated by climate feedbacks (60, 71, 72). Cumulative carbon emissions result in persistent global warming after reaching net zero emissions, and the committed long-term land response to this warming represents a key set of processes that in turn will govern the magnitude of ZEC. Processes such as the loss of carbon from peatland and permafrost soils, which are currently not well represented in most ESMs, are likely to increase the magnitude of a positive ZEC as time progresses (73). Changes to biome distributions and ecosystem structures may also continue long after temperatures have stabilized, thus representing a long-term committed carbon stock change (74). Since many of the CMIP6 ESMs do not account for vegetation dynamics, these changes are also likely underrepresented throughout the CMIP6 ensemble and in the ensemble mean. Pugh et al. (74) suggest that the long-term committed sink from vegetation expansion offsets the loss from permafrost, but both are highly uncertain. Other processes, such as the committed ecosystem response to changed disturbance processes, such as fire and drought, lead to large carbon losses in forests and wetlands, and may also increase ZEC (75). Interactions between processes should not be neglected. For example, thawing permafrost not only liberates carbon but also nutrients that may stimulate plant growth and thereby locally and partially counterbalance the carbon loss from permafrost thaw (76).

Land use

To date, ZEC has been quantified in idealized scenarios that do not include historical or potential future land use dynamics. ESM results predicting continued carbon uptake by terrestrial ecosystems post zero emissions should therefore be qualified; this carbon sink may rely in part on substantial contributions from regions where historical land use, or future changes, may preclude such uptake owing to deforestation (which reduces sink capacity) and continued carbon emissions from agricultural lands. However, comparing idealized ZECMIP runs with simulations of the SSP5-3.4-overshoot scenario that include land use (77) suggests that the idealized scenario does not substantially change the magnitude of the committed land carbon response (41). Further, the coupled carbon-climate responses to a net zero state that is characterized by substantial gross fossil-fuel emissions mitigated by land-based CO_2 removal may differ from those of idealized zero gross fossil-fuel emissions because of the biophysical responses to land-based mitigation. A wider diversity of ESM experiments using emissions-driven net zero scenarios that vary in their land-based mitigation methods and contributions are required to understand these dynamics.

Physical climate feedbacks

Physical climate feedbacks involve the responses of clouds, surface albedo, water vapor, and temperature via their effects on the global energy balance. A challenge in predicting the long-term evolution of global warming is that these feedbacks vary over time. Indeed, under sustained CO_2 forcing, most coupled atmosphere-ocean climate models predict more amplifying feedbacks as time progresses (56). This feedback time dependence may result in ZEC being positive. For example, one ESM experiment revealing a positive ZEC featured a change in the magnitude of the physical climate feedback acting to enhance surface warming (33). This long-term evolution of physical climate feedbacks is poorly understood, particularly in a scenario of carbon emissions declining to net zero.

On all timescales relevant to ZEC, much of the feedback time-dependence comes from low clouds via their impact on solar reflection and thus the global energy balance (78). The amount and distribution of low clouds strongly depend on the spatial pattern of sea surface temperatures (SST), a phenomenon known as the "SST pattern effect" (79). Of particular importance is the SST differential between regions of deep atmospheric convection (e.g., the Indo-Pacific warm pool) and other regions; this controls the stability of the atmosphere and thereby the amount of marine low clouds (80). Under sustained CO_2 forcing, coupled climate models typically simulate a decrease in this SST differential, resulting in more amplifying low cloud feedback over time (albeit with large uncertainty), acting to enhance surface warming. How the SST pattern and clouds evolve under a scenario of net emissions declining toward zero is unknown, meaning that the impact of cloud feedback on ZEC is poorly understood.

In addition to the SST pattern effect, additional drivers of time-dependence in low cloud feedback include state-dependent cloud responses, for example, in mixed-phase clouds where the feedback depends on the initial ratio of liquid versus ice phase (81) and in regime transitions resulting from coupled ocean-atmosphere feedbacks (82). Furthermore, deep convective clouds may also exhibit regime transitions between different levels of spatial aggregation (83), affecting the global energy balance by modulating the greenhouse effect of high clouds.

On millennial timescales, the melting of ice sheets will fundamentally alter the global radiative budget, both via local changes in surface albedo and via remote climate impacts mediated by changes in ocean overturning and global sea level. Ocean circulation changes would likely interact with the SST pattern effect, allowing clouds to modulate the global climate response to ice sheet melting. The coupling of ice sheets with global climate allows for a potentially large impact on ZEC, but we currently have no confidence in the sign or magnitude of this effect.

Earth subsystem processes assessed by uncertainty

In this section, we outline the processes in each Earth subsystem that drive uncertainty in ZEC. This uncertainty can be organized into five categories:

- processes known or suspected to impact ZEC, but currently missing in models
- processes with high uncertainty, whose uncertainty and interactions are not sufficiently represented in models
- common structural biases in current modeling frameworks that tend to bias ZEC estimates to the upper or lower ranges
- the possibility of abrupt change or irreversible tipping of system dynamics, and
- the potential of state and pathway dependence for all these subsystem processes.

These uncertainties warrant caution in two aspects. First, temperature stabilization could take longer than anticipated and

be both pathway- and state-dependent. Second, a world that reaches net zero emissions will still be locked into long-term changes for which we must prepare.

Many of the uncertainties in ZEC are related to uncertainties in the transient climate response to cumulative carbon emissions (TCRE) as they are driven by similar processes whose response is correlated over time. For example, MacDougall et al. (4) showed that the natural carbon uptake at net zero is correlated with the ongoing carbon uptake after net zero [(4) see figure 9 therein]. For ZEC on millennial timescales, processes that contribute more prominently to uncertainty in the equilibrium response also start to emerge.

Ocean heat and carbon uptake: drivers of uncertainty

Heat and carbon are absorbed by the ocean via the mixed layer. They are then transported and distributed vertically at a rate determined by layer depths, turbulence, convection, overturning, and detrainment. These ocean physical processes therefore control both excess heat and anthropogenic carbon and their relative uptake and transport to the deep ocean, which is a major determinant of ZEC. However, uncertainty remains in the quantification and modeling of these processes (84–86). Currently, we can only assess if an increase or decrease in each process would increase or decrease ZEC, not whether a more realistic model tends toward increasing or decreasing each process. The impact of these activities on ZEC is the approach shown in Table 1.

Uncertainty caused by processes affecting ocean heat and carbon, as well as physical climate feedback
Air-sea fluxes

In general, atmospheric anomalies in temperature and carbon concentration are well mixed and thus largely uniform across the air-sea surface, meaning the ocean uptake for heat and carbon behave similarly. However, in some regions and processes, they differ; for example, polar amplification results in increased regional warming affecting only heat uptake (and not carbon), while seawater carbonate chemistry and biological processes affect only carbon. These may lead to subtle long-term differences in ZEC. Separately, upper ocean processes involved in air-sea fluxes, such as mixing and submesoscale, change the rates and sensitivity of large-scale processes such as overturning.

Large-scale overturning

The North Atlantic and Southern Ocean overturning cells are critical for the transport of carbon and heat at depth, and hence small changes in the overturning strength affect ocean storage of heat and carbon. Overturning also impacts the rate of change in ocean surface temperature, and hence physical climate feedback via the pattern effect and associated cloud response (58, 94). AMOC is projected to weaken in the coming century owing to anthropogenic climate heating (11). After the cessation of emissions, it is expected to continue weakening and then stabilize on a multi-decadal timescale, recovering on a multi-century timescale (95, 96),

TABLE 1 Future research to improve the sign and magnitude of the Zero Emissions Commitment (ZEC) must strengthen couplings between the relevant Earth system components (both physical and biogeochemical) to determine their responses to rising carbon dioxide and climate change. This table poses research questions and suggests modeling experiments to address the uncertainty of the processes listed in Figure 4.

Topic	Corresponding label in Figure 4	Process	Research question	Experiment/analysis to quantify effect on ZEC	Actionability (1: start immediately; 2: start within known timeframe; 3: timeframe to start unknown)	Guidance for prioritization
Land carbon	A	Land response to CO_2	What are the long-term ecosystem responses to elevated CO_2 and the direct responses to declining CO_2 concentrations following net zero?	Increased evaluation of land models against free-air CO_2 enrichment (FACE) experiments. Dependent on site experiments, but plenty exist and new ones are coming online [see, e.g., AmazonFACE (67) and "MESI" (87)].	1: Can begin now. Requires more synthesis of data and use to evaluate land models, but this exists and is ongoing. A systematic land model protocol and evaluation could be made, e.g., as part of GCP budget or TRENDY (see: https://blogs.exeter.ac.uk/trendy/) analysis every year. This also applies to B and C.	Potential for > ±10% impact on ZEC. Can be actioned now and included in systematic land evaluation. Processes A–C are all related and could be a single ongoing activity to evaluate land model response to CO_2, nutrients and climate.
	B	Nutrient limitation on carbon-concentration and carbon-climate interactions	What is the role of nutrient limitation in the ecosystem response to elevated CO_2?	Climate model ZEC experiments with carbon-only, carbon-nitrogen and carbon-nitrogen-phosphorous, and also land model experiments compared to manipulation (nutrient addition) experiments [e.g., Amazon fertilisation experiment (AFEX)]. This could be piloted with one model.	1: Can begin now, with some experiments already underway using UVic ESCM. Systematic nutrient evaluation could be carried out with a common protocol as per (88). This could be included as part of a regular GCP evaluation of land models.	Potential for ±10% impact on ZEC. Can be actioned now and included in systematic land evaluation.
	C	Decomposition response to climate	What are the long-term timescales of soil decomposition responses to warming?	Increased evaluation of land models against soil warming experiments, e.g., (89) database.	1: Can begin now and be included in systematic land model evaluation, as above.	Potential for ±10% impact on ZEC. Can be actioned now and included in systematic land evaluation.
	D	Permafrost response to climate	How can thawing permafrost be better/more widely included in Earth system models, and what are the timescales of permafrost responses, including processes such as abrupt thaw?	Offline land model runs can be done to quantify timescale and magnitude of carbon release, then coupled into ESMs in the longer run. See (73) for a possible protocol. Requires ESMs to be ready for permafrost land models.	1: Offline runs can be done now with some land models; 2: Some ESMs may have permafrost for CMIP7; 3: Need for more ESMs in the long term to include permafrost models.	Potential for +1% impact on decadal ZEC, and > +10% impact on millenial ZEC. Offline runs can be actioned now, and plans can be made to assess permafrost impact for models available in CMIP7. Processes D–I are all related and concern processes that are not yet widely included in models.

(Continued)

TABLE 1   Continued

Topic	Corresponding label in Figure 4	Process	Research question	Experiment/analysis to quantify effect on ZEC	Actionability (1: start immediately; 2: start within known timeframe; 3: timeframe to start unknown)	Guidance for prioritization
Land carbon (Continued)	E	Boreal ecosystem response to climate	What are the timescales of forest range shifts and disturbance shifts with warming?	Offline land model runs can be done to quantify timescale and magnitude of vegetation dynamics. In the longer run these can be coupled into ESMs and evaluated with observed evolution, particularly after disturbance/extremes. Requires more ESMs to include vegetation dynamics.	1: Offline runs can be done now with some land models; 2: Some ESMs already have vegetation dynamics and will do for CMIP7; 3: Need for more ESMs in long term to include vegetation dynamics.	Impact on ZEC quantified only speculatively due to lack of evidence. Assessed potential of -1% impact on decadal ZEC, and -10% impact on millenial ZEC. Some models may be available for CMIP7, but there is a need for more ESMs to prepare now to include vegetation dynamics for future CMIPs.
	F	Tropical ecosystem response to climate	What are the long-term implications of warming on tropical forests?	Offline land model runs can be done to quantify timescale and magnitude of vegetation dynamics. In the longer run these can be coupled into ESMs. These can be used to identify the role of disturbance and extremes in observed and modeled transitions. Requires more ESMs to include vegetation dynamics.	1. Offline runs can be done now with some land models; 2: Some ESMs already have vegetation dynamics and will do for CMIP7; 3: Need for more ESMs in long term to include vegetation dynamics.	Potential for ±10% impact on ZEC. Can be actioned now in offline land models. There is a need for more ESMs to prepare now to include vegetation dynamics for future CMIPs.
	G	Fire disturbance to ecosystems	What is the impact of wildfire on the land carbon flux?	Offline land model runs can be done to quantify timescale and magnitude of fire, then in the longer run coupled into ESMs. Requires more ESMs to include vegetation dynamics.	1. Offline runs can be done now with some land models; 2: Some ESMs already have fire or vegetation dynamics, but few have both that interact. Some may do for CMIP7; 3: Need for more ESMs in the long-term to include vegetation and fire dynamics.	Potential for ±1% impact on ZEC. Can be actioned now in offline land models. There is a need for more ESMs to prepare now to include vegetation and fire dynamics for future CMIPs.
	H	Wetland methane	How will natural methane emissions evolve after cessation of emissions?	Offline land model runs can be done to quantify timescale and magnitude of wetland methane, then in the longer run coupled into ESMs. Requires more ESMs to include wetlands and interactive methane cycle.	1: Offline runs can be done now with some land models; 2: For some ESMs, wetland methane diagnosis is already possible but no interactive methane runs are likely in CMIP7; 3: Need for more methane coupling in ESMs in the long term.	Potential for -1% impact on ZEC. Can be actioned now in offline land models. There is a need for more ESMs to prepare now to include methane coupling.
	I	Potential release of nitrous oxide from land	How will nitrous oxide emissions evolve after cessation of emissions?	Offline land model runs may already be able to quantify timescale and magnitude of N_2O. Inclusion in ESMs needed in the longer term. Dependent on ESMs planning N_2O cycle (both land and ocean).	1: Offline runs can be done now with some land models; 2: ESMs might be developed to be able to do this, but no interactive N_2O runs in CMIP7; 3: Need for more N_2O coupling in ESMs in the long term.	Impact on ZEC quantified only speculatively due to lack of evidence. Assessed potential of ±1% impact on ZEC. Some offline runs can be actioned now, but there is a need for ESMs to prepare interactive N_2O runs for the next CMIP.

(Continued)

TABLE 1 Continued

Topic	Corresponding label in Figure 4	Process	Research question	Experiment/analysis to quantify effect on ZEC	Actionability (1: start immediately; 2: start within known timeframe; 3: timeframe to start unknown)	Guidance for prioritization
Land carbon (Continued)	J	Legacy effects of land use change	How does ZEC in idealized no-land-use scenarios differ from a net zero characterized by both widespread land-based carbon sequestration and prior land use legacies?	Emissions-driven ESM scenarios, including historical land use and a net zero characterized by both gross fossil fuel emissions and land- and ocean-based sequestration. Requires wider diversity of emissions-driven climate mitigation scenarios in CMIP7.	2: Can be undertaken in CMIP7 timeframe.	High confidence in a ±10% potential impact on decadal ZEC. Can be actioned for CMIP7.
Ocean heat and biogeochemical cycles	K	Potential release of non-CO_2 greenhouse gases from the ocean (e.g., methane and nitrous oxide)	How can marine biogeochemical processes responsible for non-CO_2 GHG emissions be included in ocean models?	Both offline simulation/reconstruction and emission-driven runs as ZECMIP would be useful to quantify their impact. Requires: a larger array of observational data, including mesocosms experiments; greater computational resources to properly resolve open and coastal oceans; hybrid resolution numerical schemes to decrease modeling costs; machine learning to accelerate modeling and/or reduce costs necessary to improve performance; reduced complexity models.	2 or 3: Timeframe depends on the trace GHG being investigated.	Potential for ±10% impact on ZEC. If the level of non-CO_2 GHG is subject to change because of Earth system feedbacks, it is important to bound it.
	L	Ocean-ice sheet interactions—change in ocean stratification affecting carbon uptake	How will global and regional ocean stratification evolve after reaching net zero emissions, in particularly in polar regions with ice sheet meltwater release; how will this influence carbon uptake?	Improve the representation of ocean-ice coupling by simple parameterization or ocean-ice sheet coupling, and run ESM in warming stabilization scenarios. Investigate impact of different warming targets and pathways, which will (1) determine the level of ocean-ice inertia after net zero emissions and (2) provide different level of stratification to assess their impact once net zero is reached.	1: All tools are available for such assessment. Simple ocean-ice parameterization exists; 2: coupling ocean-ice sheet requires more development and process understanding but will probably become efficiently actionable in the next decade.	Potential for ±10% impact on ZEC. Some aspects are actionable now, with ocean-ice sheet coupling possible in the next decade.
	M	Mesoscale eddies and filaments affecting ocean carbon uptake	What are the impacts of unresolved and poorly represented mesoscale and submesoscale processes in the current generation of Earth system models, and how can these affect air-sea flux of carbon as well as carbon transfer between the sea surface and the deep ocean?	See processes O, P and Q below.	See processes O, P and Q below.	Potential for ±1% impact on ZEC with only speculative confidence due to lack of evidence.

(Continued)

TABLE 1 Continued

Topic	Corresponding label in Figure 4	Process	Research question	Experiment/analysis to quantify effect on ZEC	Actionability (1: start immediately; 2: start within known timeframe; 3: timeframe to start unknown)	Guidance for prioritization
Ocean heat and biogeochemical cycles (Continued)	O, P, Q	Ocean surface boundary layer (OSBL) mixing, OSBL submesoscales, subduction by mesoscales	What are the key processes driving mixing of the OSBL missing in the current generation of Earth system models, and how can those affect heat and carbon flux across the sea surface? What is the impact of unresolved and poorly represented submesoscale processes in the current generation of Earth system models, and how can those affect upper ocean stratification, and heat and carbon transfer between the sea surface and the deep ocean?	Recently, the community established an ensemble of submesoscale-permitting models (90) that differ in OSBL approaches. Such an ensemble can be used to provide insight into the OSBL and submesoscale aspects of this problem. Furthermore, at this moment the NASA S-MODE campaign and other "Adopt-a-Crossover" experiments during the initial period of the surface water and ocean topography (SWOT) mission are providing a near-global view of submesoscale observations. While these experiments are short-duration (weeks to years) rather than climate-duration (decades to centuries) experiments, there should be an explosion of process understanding triggered. This process understanding will aid in the improvement of parameterizations and climate model treatment of these processes and their consequences.	1: Already underway.	Potential for ±10% impact on centennial ZEC from process O. Some work already underway.
	R	Ocean stratification	How will global and regional ocean stratification evolve after reaching net zero emissions, particularly in the polar region with ice sheet meltwater release; how will this influence heat uptake?	See process L.	See process L.	Impact on ZEC only speculative over centennial-millenial timescales due to lack of evidence. Some aspects actionable now, with ocean-ice sheet coupling possible in the next decade.
	S	Changing Atlantic meridional overturning circulation (AMOC)	What are the key processes driving the AMOC mean strength and depth, and controlling its future change? How can we better represent them in Earth Sytem Models to quantify the impact of AMOC decline on ZEC?	RAPID and OSNAP and other similar monitoring systems are already in place [e.g., (91, 92)]. These observations challenge the representation and variability of present climate models. In addressing these discrepancies, AMOC should be better simulated in time for CMIP7.	1: Already underway.	Potential for +10% impact on centennial ZEC. Some work already underway.

(Continued)

TABLE 1 Continued

Topic	Corresponding label in Figure 4	Process	Research question	Experiment/analysis to quantify effect on ZEC	Actionability (1: start immediately; 2: start within known timeframe; 3: timeframe to start unknown)	Guidance for prioritization
Ocean heat and biogeochemical cycles (Continued)	T	Changing Southern Ocean overturning circulation (SMOC)	What are the key processes driving the SMOC mean strength and depth, and controlling its future change? How can we better represent them in Earth Sytem Models to quantify the impact of SMOC decline on ZEC?	One key limitation of the study of the Southern Ocean overturning is the poor process understanding of dense water formation and overflows, which hampers our confidence in the current generation of Earth system models to address this specific question. Representation of bottom water formation, export, and consumption urgently needs to improve observation of key overflow processes and develop modeling strategies to improve the representation of such processes (e.g., increase horizontal or vertical resolution, change coordinate system, develop specific parameterization). Impact of changing SMOC on ZEC can be assessed by modeling sensitivity experiments such as virtually freezing ocean circulation in a climate model, or by freshwater hosing experiments in a warming stabilization scenario. Requires national operators to target surveys in ways that are best aligned to models. International cooperation is key here, and may be a feature of the buildup to and legacy of the planned 5th International Polar Year (2032-33).	1 or 2: Some modeling aspects are readily available; the observation part will require years to advance further.	Potential for +10% impact on ZEC over centuries. Requires international cooperation, with opportunities for this in the upcoming International Polar Year.
	misc.	misc.	How can Earth system components (rivers, ice shelves, aerosols) be coupled more completely in Earth System Models?	Factorial experiments including or not including the coupling across components. Depends on the level of readiness of ESMs.	2: Several modeling groups are progressing in this direction currently.	Quantitifying ZEC implies conducting holistic simulations, where couplings are the glue of the represented components of the model. As such, novel couplings might affect the sign or the magnitude of ZEC in both directions, depending on how the coupling will affect the radiative budget of the Earth.

(Continued)

TABLE 1 Continued

Topic	Corresponding label in Figure 4	Process	Research question	Experiment/analysis to quantify effect on ZEC	Actionability (1: start immediately; 2: start within known timeframe; 3: timeframe to start unknown)	Guidance for prioritization
Ocean heat and biogeochemical cycles (Continued)	misc.	Ocean-ice sheet interactions— change in sea level	How will global sea level change after net zero is achieved?	We note that the Southern Ocean and Antarctic ice sheet remain poorly surveyed and observed to the level needed for reliable prognostic evaluations of change. Guided by satellite observations of present change, and evaluations of past change, basic data gathering on surveys designed for models may allow us to better constrain predictions. Critical to data gathering, and modeling are ice shelf cavities and also the boundary between water and the grounded ice sheet. Both aspects are data and knowledge sparse yet appear critical to the interaction between the ocean and ice sheets from a sea level prespective. Requires national operators to target surveys in ways that are best aligned to models. International cooperation is key here, and may be a feature of the build-up to, and legacy of, the planned 5th International Polar Year (2032-33).	1: Assembling existing data (Southern Ocean Observing System) Ocean bathymetry (GEBCO) and Antarctic subglacial topography (upcoming Bedmap3). 2: Using this information, with modeling in mind, to target high-precision survey and observations. 3: Using drones, AUVs and UAVs to collect data in a systemic continental-wide manner. Modeling can begin immediately and would be improved in time with such data gathering. Work in the polar regions is notoriously time-limited, due to the field season being around 3-4 months per year. The 5th International Polar Year, in 2032-33, may offer an acceleration of plans and projects. The Scientific Committee on Antarctic Research could act as a convenor of nations and programs related to such work.	A long-term effect of current and expected global warming, with significant implications for policy and planning.
Physical climate feedbacks	U	Sea surface temperature pattern effect affecting low cloud and lapse-rate feedbacks	What physical drivers control the time-evolution of SST patterns in response to a climate forcing?	Develop observational constraints on forced SST patterns and track particularly tropical Pacific gradients. Requires analysis of SST patterns and climate feedbacks in global high-resolution coupled climate model experiments. Depends on availability of decadal-scale 3D timeseries of ocean and atmosphere variables for climate analysis.	1: Activity is ongoing.	Potential for +10% impact on decadal ZEC. Some work already underway.
	V	State-dependence of the cloud response to warming	How does cloud feedback depend on the climate state?	Analyze cloud feedbacks in model experiments for different climate states e.g., paleo, historical, future. Depends on availability of paleo, historical and future climate model experiments (e.g., from CMIP).	1: Activity is ongoing.	Potential for +10% impact on decadal ZEC. Some work already underway.

(Continued)

TABLE 1 Continued

Topic	Corresponding label in Figure 4	Process	Research question	Experiment/analysis to quantify effect on ZEC	Actionability (1: start immediately; 2: start within known timeframe; 3: timeframe to start unknown)	Guidance for prioritization
Physical climate feedbacks (Continued)	W	High cloud aggregation	How do clouds and convection respond to climate change?	Assess the drivers of convective aggregation in convection-permitting simulations and in observations. Depends on availability of convection-permitting climate model experiments and availability of decadal-scale satellite observations of clouds.	1: Activity is ongoing, primarily on a regional scale.	Potential for ±10% impact on decadal ZEC. Some work already underway.
	X	Nonlinear cloud response to warming	How do nonlinear climate responses control cloud feedback?	See process Z.	See process Z.	Potential for ±10% impact ZEC. Some work already underway.
	Y	Snow and sea ice changes affecting albedo feedback	How do snow- and ice-albedo feedbacks depend on the spatial pattern of climate change?	Assess snow- and ice-albedo feedbacks in high-resolution ocean-ice model simulations of climate change. Depends on availability of high-resolution ocean-ice model simulations and correct representation of ocean–shelf heat exchange.	2: Ocean-ice sheet coupling requires more development and process understanding but will probably become efficiently actionable in the coming decade.	Potential for +10% impact on decadal ZEC. Some work already underway, with further development of ocean-ice sheet coupling needed.
	Z	Ice sheet changes affecting albedo and ocean circulation	How do ice sheets respond to climate change on centennial to millenial timescales?	Analyze climate feedbacks in coupled ice sheet–ocean–atmosphere models on millennial timescales. Depends on availability of coupled ice sheet models with millenial-scale climate change simulations.	2: Partly underway with a new generation of active ice sheet climate models (93), but further development of active ice sheet models is needed.	Potential for > ±10% impact on millenial ZEC. Some work already underway, with further development of ice sheet models needed.

Abbreviations:

AMOC, Atlantic meridional overturning circulation

CMIP, Coupled Model Intercomparison Project

ESM, Earth system model

N_2O, nitrous oxide

OSNA, Overturning in the Subpolar North Atlantic Program

SST, sea surface temperature

UVic ESCM, University of Victoria Earth System Climate Model

AUV, autonomous underwater vehicle

CO_2, carbon dioxide

GCP, global carbon budget

OSBL, ocean surface boundary layer

SMOC, Southern Ocean overturning circulation

UAV, unmanned aerial vehicles

ZECMIP, Zero Emissions Commitment Model Intercomparison Project

though many uncertainties remain. Deep convection in the Southern Ocean is also expected to decline in the coming century (11, 97), though changes after net zero emissions remain poorly understood (98). Over the same timescale, changes in the lateral redistribution of heat and carbon are expected because of alterations in the properties of the water masses (58, 86, 99, 100), though the overall response to emission cessation is poorly understood. The combination of uncertainties may be greater than the uncertainty in each isolated process owing to the interplay between physical and chemical processes (101, 102).

Ice sheets

Changes in glacial meltwater from polar ice sheets have important consequences for upper ocean stratification, and hence the strength of the global ocean overturning (103–106). Important uncertainties remain in the future of ice sheet mass loss at different timescales (from decades to millennia) and in the consequences of meltwater-induced feedbacks that may affect the overall Earth energy balance. Additional uncertainty exists due to state dependency on global temperatures when net zero is reached. Long-term committed ice mass loss will be larger for higher CO_2 levels than for lower levels (11). In addition, there may be non-linear behaviors via which too much glacial meltwater could entirely curtail bottom water convection, at least temporarily, with consequences for ocean transport of heat and carbon and the SST pattern effect (94, 106). Instabilities in the ice sheet system have a particularly important impact in Greenland (where surface albedo change can lead to enhanced melting and further albedo impacts) and Antarctica (where the ice sheet rests on a bed well below sea level and retreats into deeper terrain). In both cases, ice-loss processes triggered by emissions may now act in isolation, potentially supplying freshwater to the ocean over the coming centuries after net zero is reached. Current ESMs do not represent ice sheets interactively (4, 107) and hence do not capture the impact of their melt and feedback on the ocean. These knowledge gaps prevent us from properly quantifying the combined uncertainty.

Meso and submesoscale processes

Most climate models do not resolve the small-scale (10–100 m) turbulence that mixes the boundary layer of the ocean and the submesoscale (1–10 km) and mesoscale (10–100 km) turbulent eddies that influence the boundary layer, deep convection, and transport of water out of the boundary layers and convection zones into the global overturning (108). This is because such simulations would require unattainably high horizontal and vertical ocean model resolutions, especially at high latitudes. Beyond differences in ocean forcing, the ensemble spread can largely be related to differences in the treatment of these turbulent processes (84). The role of mesoscale eddies for anthropogenic carbon and heat uptake remains unclear. Consideration of small-scale processes suggests a reinforcement of anthropogenic carbon uptake (109). However, the influence of mesoscale eddies through eddy-driven circulation may counteract large-scale circulation features, impacting the overall capacity of the Southern Ocean to take up CO_2 over the long term (110, 111). In the ocean interior, deep-reaching submesoscale

processes might be central to a correct representation of vertical heat distribution and, therefore, stratification (112, 113), with consequences for carbon uptake and ocean surface temperature.

Uncertainty caused by processes affecting ocean carbon only

Carbonate chemistry

While the circulation determines the volume of anthropogenic CO_2 transported into the deep ocean, the carbonate chemistry, which is well understood, determines the concentration of anthropogenic CO_2 in these water masses (114). CO_2 is a weak acid, and seawater dissociates most of it into bicarbonate, while the seawater carbonate ion concentration is reduced and the proton concentration rises (115). However, current climate models have difficulties in correctly representing the surface ocean carbonate chemistry (e.g., accounting for the Revelle factor), especially in regions with the largest anthropogenic carbon uptake, such as in the Southern Ocean and the North Atlantic (116).

Biological processes

The role of biological processes in long-term carbon storage, especially the transport and transformation of living and dead particulate matter in the mesopelagic zone (117), is highly uncertain (118). It remains unclear how the hard-tissue pump responds to ocean acidification (119). Biological processes missing in current ESMs may impact ZEC in various ways. Although small, these contributions are tightly linked to highly climate-responsive components of the Earth system (e.g., coastal sediments, sea ice, and permafrost), which makes their contribution uncertain. For instance, sediment and weathering interactions are often ignored on very long timescales (66). Sea ice biogeochemistry may lead to important dimethylsulfide (DMS) emissions with respect to the proportion controlled by the open-ocean biogeochemistry (120). We understand little about how these processes may contribute to ZEC, but, overall, the contribution of biological processes to the oceanic uptake of anthropogenic carbon is small, at least on the decadal to centennial timescales (121–123).

Potential release of non-CO_2 greenhouse gases from the ocean (e.g., CH_4 and N_2O)

It is well known that potential CH_4 emission sources in the coastal and open ocean (e.g., clathrates in marine sediments) are sensitive to climate change (124). Though the exact magnitude of future CH_4 emissions remains uncertain, its dependence on the magnitude of future warming is better supported. Despite polar amplification, substantial releases from the permafrost-embedded subsea clathrates are very unlikely during the 21st century (39) but cannot be ruled out under very high warming levels. Archer et al. (66), for example, showed that coastal CH_4 emissions may increase with ocean warming >3°C. They estimate that this would further burden total atmospheric carbon, with published estimates ranging between 35 and 940 PgC, leading to an additional 0.4–0.5°C warming. Further, large physical uncertainties remain in quantifying the magnitude of CH_4 release, particularly with respect to how gas migrates through the sediment column.

Individual studies suggest the ocean N_2O cycle might be one of the only biogeochemical cycles where climate change induces negative feedback, i.e., a decrease in ocean N_2O emissions (125). This is because of increased ocean stratification (which tends to counteract the vertical transfer of N_2O from the deep ocean to the surface), decreases in ocean productivity, and the impact of increasing atmospheric N_2O abundance on the air-sea flux. As such, potential cooling induced by emission cessation may reinforce N_2O emissions from the ocean to the atmosphere. However, current climate models often do not explicitly simulate N_2O and CH_4 cycles. Consequently, the resulting uncertainty associated with these processes cannot be assessed.

Land carbon: drivers of uncertainty

The response of the land biogeochemical cycle to net zero is tightly linked to the drivers and constraints of the current natural land carbon sink. Here, we provide an initial expert estimate of both the magnitude and direction of uncertainty in ZEC due to uncertainty in the underlying processes, and the timescales to which they apply. Some of these processes have already been included in ESMs but are uncertain, while others are still missing.

Land response to CO_2

The largest driver of the land carbon sink—the productivity and allocation response to CO_2—is also the largest contributor to its uncertainty. It is known that the uncertainty in the land response to CO_2 exceeds that for the ocean and that the response to CO_2 is more uncertain than the response to climate (39, 71). This remains true of the drivers of sink change contributing to ZEC. In ZECMIP, the land carbon sink decreases by approximately half after 20 years, nearly 90% after 50 years, and approaches close to zero after 100 years. These ESM assessments do not take into account committed responses of ecosystem recovery from historical disturbances due to land use and land management. The processes at play may lead to greater land uptake after net zero is achieved than is projected in the idealized ZECMIP framework, particularly if the recovery timescales are longer than those used to define the land-use emissions that partially define net zero (74). Land-use drivers that continue to act on longer timescales, such as committed peat loss due to hydrologic alteration of peatlands (126, 127), are not well integrated into ESMs and so may be missing from current assessments of committed land use dynamics and their role in governing ZEC.

As the majority of ESMs used to quantify ZEC are biased by not including nutrient constraints and processes that affect these over long timescales, there may be consequential biases in the calculated magnitude of ZEC (69, 128). In the small sample of ESMs contributing to ZECMIP, there is no systematic difference in ZEC between models with and without representation of the terrestrial nitrogen cycle although there is evidence that the nitrogen cycle reduces both the land carbon response to CO_2 and climate change (60). However, the nitrogen effect gradually diminishes with a decreasing atmospheric CO_2 growth rate (70), as organisms that engage in nitrogen fixation and other nitrogen cycle processes (such as losses due to leaching) gradually relieve ecosystem nitrogen limitations (70, 129, 130).

Phosphorus limitation on land is likely to further reduce the land carbon response to CO_2 and climate change (60). However, there is no clear evidence of how nutrient cycles affect the further response of the sink after net zero.

There is no evidence that the existing estimates would be biased, so this uncertainty (a) is large, (b) symmetrically impacts ZEC, and (c) operates on short to mid-term timescales. Confidence in this assessment is medium due to the relatively large body of literature and some experimental evidence but with a substantial spread in modeling results.

Decomposition response to climate (excluding permafrost soils)

As there is only a small change in global temperature following zero emissions, the expected response of land carbon to the climate post net zero will largely be the long-term continuation of its response to the climate change that had occurred during the period of rising CO_2. Warmer temperatures lead to accelerated decomposition of organic matter, and this remains stubbornly uncertain across CMIP6 models even with nutrient cycling considered, as it was in CMIP5. Therefore, this uncertainty (a) is moderate, (b) symmetrically impacts ZEC, and (c) operates on short timescales. Confidence in this assessment is medium due to the relatively large body of literature and some experimental evidence but with a substantial spread in modeling results.

Permafrost feedbacks to climate

Only represented in a small number of the models contributing to ZECMIP, permafrost thaw is a process that contributes to uncertainty in ZEC. It is virtually certain that large areas of permafrost will thaw under a warmer climate. However, the amount of carbon released with decomposition of previously frozen organic matter, the timescale of release and its form (CO_2 versus CH_4), and the potential compensation by plants growing in areas impacted by permafrost thaw are all uncertain. IPCC assessments (39, 131) suggest that carbon release during this century will likely be small, but if warming persists then the thaw of permafrost will lead to irreversible loss of frozen organic carbon. Abrupt permafrost thaw, which occurs in a narrow region of ice-rich permafrost, has the potential to increase the magnitude of permafrost feedback to the climate, accelerate the timing of those losses, and lead to higher fluxes of CH_4 (132). However, the role of abrupt thaw is not addressed by large-scale models, and there is little understanding of emissions after net zero. Overall for permafrost emissions, we assess that the uncertainty will (a) be small initially but grow to be large, (b) lead to a higher ZEC as more CO_2 is released, and (c) operate on long (>100-year) timescales. Confidence in this assessment is low due to limited modeling results and the substantial spread of results between studies.

Boreal ecosystems response to climate

Converse to permafrost loss of carbon from high latitude regions, woody encroachment and boreal forest expansion represent potentially long-term committed carbon sinks, while at the same time altering the biogeophysical properties of the surface

and therefore the local climate (133). Pugh et al. (74) suggest that these could be of comparable magnitude to permafrost loss, although both are highly uncertain. While some ESMs include dynamic vegetation, it is still relatively rare. We therefore assess this uncertainty will (a) be small initially but grow to be large, (b) lead to a lower ZEC as more CO_2 is taken up, and (c) operate on long (>100-year) timescales. Confidence in this assessment is speculative due to a very limited literature base.

Tropical ecosystem response to climate

Tropical ecosystems respond to elevated temperatures and associated changes in rainfall by potentially reducing productivity and wood growth. Research is heavily focused on the Amazon forest, which is seen as especially vulnerable to future climate change (134) and additional pressures from human activity (135). Recently observed increases in mortality (136), decreased sink (137), and changes in variability suggesting decreased resilience (138) all point toward the credible risk of an Amazon forest tipping point occurring if global warming reaches 2°C (77, 139).

Conversely, assessing tropics-wide carbon sinks (140) provides quantitative constraints on tropical temperature sensitivity (across productivity and decomposition), which indicates that smaller rather than larger carbon cycle sensitivities are consistent with observed variability. Therefore, for ZEC, the contribution of tropical ecosystems to uncertainty is (a) moderate to large, (b) possibly biased toward a smaller contribution, but with potential for abrupt changes releasing carbon, and (c) operates on short timescales. Confidence in this assessment is low due to competing observational and modeling constraints on different spaces and timescales and at different levels of global warming.

Fire disturbance to ecosystems

Fire may increase CO_2 (and other) emissions from land. It may also reduce equilibrium carbon storage for a given ecosystem. If global climate change is small following zero emissions, then further changes in fire disturbance may also be small, but this process is missing in most ESM models and no studies have assessed the response of fire disturbance after zero emissions. Therefore, this uncertainty (a) is moderate, (b) symmetrically impacts ZEC, and (c) operates on short to mid-term timescales. Confidence in this assessment is low due to limited literature and poor model agreement.

Wetland CH_4

Wetland CH_4 emissions are driven by both climate (temperature and moisture) and vegetation productivity and therefore are directly responsive to CO_2. Warming generally tends to increase emissions (39). However, as CO_2 declines post net zero, wetland productivity and thus CH_4 emissions may decrease. The balance of climate versus CO_2 as a driver of CH_4 emission is not well agreed, and modeling techniques differ widely. If this process is significant, it will operate on short timescales as CO_2 affects tundra ecosystem productivity. Therefore, we assess this uncertainty to (a) be small to moderate, (b) lead to a lower ZEC as reduced CO_2 reduces CH_4, and (c) operate on short timescales. Confidence in this assessment is low due to a limited literature base.

Potential release of N_2O from land

N_2O emissions from natural and semi-natural ecosystems are driven by climate and nitrogen cycle processes, which are directly or indirectly affected by the productivity response of plants to atmospheric CO_2 changes. The sign and magnitude of the response to changes in either driving factor are location-dependent, and there is no general understanding of the large-scale responses of terrestrial N_2O fluxes to either CO_2 or climate change. Models suggest that rising CO_2 decreases and climate change increases N_2O emissions (39, 141). We assess the uncertainty to (a) be moderate, (b) symmetrically impact ZEC, and (c) operate on a mid- to long-term timescale. The confidence in this assessment is low due to a limited observational and literature base.

Land-use change: legacy effects and continued change

Past land-use changes and land management have left the land out of equilibrium with regard to carbon storage and have reduced the additional sink capacity the land may have provided. The legacy effects of this disturbance could lead to either increased carbon accumulation (e.g., forest regrowth after abandonment) or carbon loss (e.g., following peatland drainage or drying) post zero emissions and hence could affect ZEC. As the land continues to adjust to past disturbances, the impact of these will decrease over time.

Continued land-use changes and changes in management are not directly related to ZEC but represent one of the dimensions in which a gross zero emissions world can differ from a net zero world. Given the large potential variations in net zero configurations (29, 142), they represent an additional source of uncertainty. This uncertainty is potentially large but either positive or negative in terms of carbon emissions depending on the balance of continued deforestation and any use of land for CO_2 removal. Both are very scenario-dependent.

Physical climate feedbacks: drivers of uncertainty

Inter-model differences in climate feedbacks are the dominant driver of the inter-model uncertainty in surface warming projections in CMIP6 projections (following a scenario of CO_2 concentrations increasing by 1% per year), as quantified by the proportionality between surface warming and cumulative carbon emissions (143). This inter-model uncertainty is primarily due to shortwave and longwave cloud effects, as well as changes in surface albedo. With regard to clouds, key uncertainties include the coupling of low clouds with surface temperature warming patterns, state dependence in the cloud response involving changes in the cloud water phase, and regime transitions in the coverage of cloud types. All of these changes in cloud distribution and cloud type alter the radiative energy balance and so will affect ZEC. Surface albedo changes involving snow and sea ice coverage also alter the physical climate feedback, and their distribution is coupled to the patterns of surface warming. On millennial timescales, there are potentially important changes in ice sheets, affecting surface albedo and the ocean overturning, with knock-on effects on the global energy balance. These sources of uncertainty from physical

FIGURE 3
The Zero Emissions Commitment (ZEC) can be thought of as a surface energy balance relation in a simplified "zero-dimensional" model. If, after carbon dioxide (CO_2) emissions cease and Earth's surface and lower atmosphere absorb more energy than they emit back to space or to the deep ocean, ZEC will be positive. On the other hand, if Earth's surface and lower atmosphere emit more energy than they absorb, ZEC will be negative. Under this simplified relationship, temperature stabilization is reached when energy out equals energy in. Abbreviation: GHG, greenhouse gas.

feedbacks affecting projections of future warming are likely to carry over to uncertainties in the warming projections when net zero is approached and may be sufficiently large to alter the sign of ZEC. In summary, key knowledge gaps remain in how physical climate feedbacks are likely to change over time with declining atmospheric CO_2, and the extent to which physical climate feedbacks affect the sign and magnitude of ZEC.

Expert assessment and future research

Expert assessment

Here we present an expert assessment by the article's co-authors, supported by available published evidence from the literature where possible, to quantify the plausible impact of these Earth system processes on the magnitude and sign of ZEC over decades, centuries, and millennia (Figure 4, Table 1). We propose this structure as a guide for future research into quantifying ZEC and reducing its uncertainties.

A key take-home message is the large proportion of low—and often only speculative—confidence assigned to the impact of many processes on ZEC. It is clear that uncertainty remains high in both ZEC's sign and magnitude over short- and long-term timeframes, owing to uncertainties in the impact of its constituent parts. Though it is known that some long-term changes to the Earth system, such as sea level rise, will continue beyond net zero, it is now clear that we must also consider the possibility of significant continued temperature rise even after anthropogenic emissions cease. This uncertainty should be factored into the risk assessment of global temperature limits, carbon budgets, and emissions reduction plans for countries and businesses.

Future research

Ocean heat and biogeochemical cycles

One of the key properties of ZEC is that it emerges from the coupling of the climate and the carbon cycle. As such, improving ZEC in terms of sign and magnitude requires improving the couplings between Earth system components, including both physical and biogeochemical ocean components. Current models have evolved toward a more comprehensive treatment of biological boundary conditions (e.g., atmospheric deposition, riverine inputs, sediments, ice sheets, and geothermal sources) but the latter is currently largely represented using climatological data rather than dynamic connections (144). Progress toward more complete couplings between Earth system components such as rivers, ice sheet/iceberg calving, and ice shelves or atmospheric aerosols can help to better simulate interactions between marine biogeochemistry, biogeochemical cycles, and climate, and hence result in a more comprehensive assessment of ZEC. The representation of the coupling between ocean and ice sheets has been shown to be critical in simulating the decline in global ocean overturning circulation (145), with key implications for the ocean surface temperature affecting low cloud development (146), as well as for ocean heat and carbon uptake (147), though the quantification of the decline and its impact on ZEC remains to be clarified.

The emergence of high-resolution ocean models that include marine biogeochemical processes may be supported in a number of ways: (1) the availability of even greater computational resources; (2) the use of hybrid-resolution numerical schemes to decrease the cost of biogeochemical models (148); (3) reduced complexity models of marine biogeochemical processes [e.g., miniBLING (149)]; and (4) the use of machine learning to either accelerate marine biogeochemical models or to reduce the numerical cost necessary to improve their performance (i.e., via tuning). These (and potentially other) step-
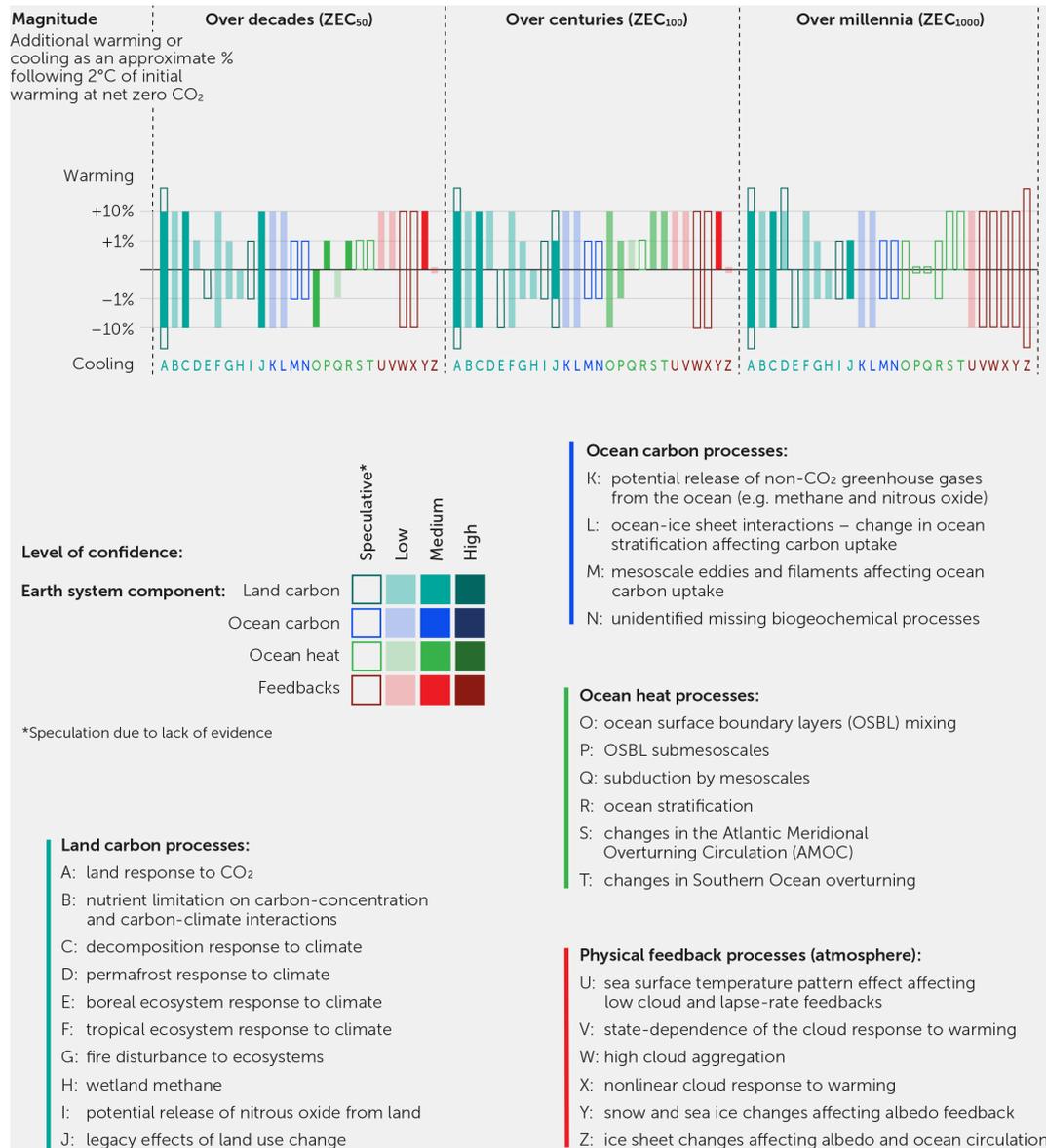
FIGURE 4
Expert assessment of the hypothesized impact of Earth system uncertainties on the magnitude of the Zero Emissions Commitment (ZEC) for futures initially aiming to limit global warming to 2°C.

changes will help us to understand the extent to which mesoscale or submesoscale ocean physics might change the response of marine biogeochemistry to rising CO_2 and climate change—a missing factor in such models already highlighted about a decade ago (64).

Land carbon

Land carbon fluxes dominate the total uncertainty in assessments of changes in the natural carbon cycle on decadal timescales, with ocean processes dominating on longer timescales. Priorities for reducing uncertainty in ZEC are tightly related to priorities for modeling the land carbon cycle in general and its role in determining carbon cycle feedbacks, the transient response to cumulative CO_2 emissions (TCRE), and carbon budgets. Notably, the response of ecosystems to elevated CO_2 and the role of nutrient

limitation is considered the highest priority. Model data comparisons against site-level manipulation experiments [e.g., free-air CO_2 enrichment (FACE) experiments] or nutrient supply experiments [e.g., the Amazon Fertilisation Experiment (AFEX)] offer valuable ways forward. Forthcoming FACE experiments in a tropical forest in Brazil will prove extremely valuable. However, experiments must also capture the long-term response of ecosystems; it is well established that elevated CO_2 causes an initial increase in productivity, but less is known about the long-term impacts on ecosystem carbon storage. Similarly, ecosystem responses to environmental changes can be improved in models with valuable observational experiments, such as the Caxiuana throughfall exclusion site (150, 151) which intercepts rainfall to mimic drought conditions, or global syntheses of soil warming experiments (90, 152).

Representing missing processes is also increasingly important, including physical and carbon permafrost processes and vegetation dynamics. Some, but not all, models have improved in their representation of permafrost physics from CMIP5 to CMIP6 (153), but very few models represent loss of carbon from thawing permafrost.

Physical climate feedbacks

The role of time-varying physical feedbacks in determining the future climate response is under active investigation for increasing carbon emissions. There are key uncertainties in the representation of clouds over different parts of the atmosphere and in surface albedo changes linked to the presence of snow and sea ice. We are beginning to understand the physical mechanisms controlling the forced pattern of sea surface warming and its time evolution (154, 155), which is critical for the long-term evolution of climate feedbacks. Developments in high-resolution modeling are also elucidating possible state-dependence and regime transitions in cloud responses to warming (82). However, work so far has focused on cases of increasing or constant climate forcing; little attention has been given to the role of physical climate feedbacks in the climate response to the specific scenario of carbon emissions declining to net zero and the resulting effect on ZEC.

Simple climate models

Simple climate models (SCMs) provide tools for exploring how process interaction may lead to results that are not observed in the current ESM ensemble, which constitutes an "ensemble of opportunity" since the ESMs that have examined ZEC are a serendipitous selection of models from researchers interested in participating in the ZECMIP exercise. SCMs contain modules that represent many of the processes controlling ZEC, albeit in simplified ways. By tuning these modules to capture behaviors at different ends of the spectrum of scientific uncertainty, the link between ZEC and relevant processes can be examined in a simplified manner. This approach allows the exploration of results that would be expected if the behavior of multiple processes were at the extreme end of their potential range, recognizing that this simplified approach may miss couplings such as that between ocean carbon and heat uptake. Given the multiple feedbacks and non-linear processes involved, the high-end result could be much larger than a simple linear superposition would imply. The key to performing such investigations is a strong understanding of how simple climate model modules and behavior relate to the processes controlling ZEC. While the broad mappings are understood, research is needed to understand them in detail. With this detailed understanding, individual (partial) and combined (feedback) effects on ZEC can be isolated from variations in physical processes.

Implications of ZEC for climate policy

The identified uncertainties in ZEC come with implications for climate policy, both in the near and the long term. Over the coming decades, the potential variation in ZEC on timescales of decades to centuries is most relevant. To understand the implications for climate policy, ZEC insights need to be translated from model studies to the real world. ZEC is studied with idealized model experiments, often assuming a sudden stop in global emissions (4, 28). The real-world evolution of global emissions will be different with a presumably more gradual decline to net zero over multiple decades. In such a scenario, ZEC over decadal timescales will already be partially realized at the time of reaching global net zero CO_2 emissions (4, 156). This suggests that for practical applications, ZEC can be usefully defined as the committed warming relative to the expected linear TCRE relationship, instead of as the warming still to occur after reaching net zero (156). The potential additional increase or decrease in warming implied by ZEC should be folded into assessments of the remaining carbon budget (17, 64, 141). If the decadal ZEC is positive, the remaining carbon budget until net zero CO_2 emissions are reached will be smaller. If it is negative, there could be a bit more leeway, or alternatively, more stringent climate targets could be achieved. Our current assessment of ZEC uncertainties, however, shows more uncertainties pointing toward a potentially higher ZEC (Figure 4) and thus a further tightening of the already very small remaining carbon budget.

Because ZEC already partially materializes before total global CO_2 emissions reach zero (4, 156), the sign and magnitude of ZEC to some degree also inform the timing of peak warming relative to reaching net zero CO_2 emissions. The evolution of non-CO_2 emissions further modulates this relative timing. Understanding and communicating clearly on these issues can be important, as the general public might expect temperatures to peak once net zero CO_2 emissions are reached.

Over the long term, the uncertainty in ZEC comes with further implications for policy. In case of a negative ZEC over centuries to millennia, future societies will have fewer challenges to reverse some of the global warming. This would be good news. However, the assessed uncertainties on these timescales indicate a positive rather than a negative ZEC (Figure 4). Over millennia, some Earth system feedbacks could result in significant additional amounts of warming. Such additional warming would frustrate achieving a peak and decline in global warming, as is assumed in many global mitigation scenarios (29, 30) and potentially even the Paris Agreement (157, 158).

To counteract potential continued gradual warming over centuries to millennia, our global society will most likely have to prepare for continued active management of the global carbon cycle by drawing CO_2 out of the atmosphere, while taking issues related to land use and biodiversity into account. The long-term consequences of the CO_2 already emitted, and that which will be emitted until global net zero is reached, imply that net zero CO_2 remains an important milestone but that it might not be enough. The uncertainties in ZEC point toward further long-term warming risks and the imperative to develop sustainable, safe, and reliable options for long-term CO_2 removal to keep Earth's climate stable. Importantly, the assessment of ZEC uncertainties also emphasizes that to limit risks it is essential to keep the initial disturbance of the Earth system as low as possible. This can be achieved first and foremost by reducing global CO_2 emissions to net zero swiftly in this decade and over the coming decades, and by continuing to pursue limiting global warming to as close to 1.5°C as possible.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsci.2023.1170744/full#supplementary-material

SUPPLEMENTARY DATA SHEET 1
Expert assessment supporting Figure 4. Hypothesised impact of individual processes on the uncertainty in ZEC over decades, centuries and millennia.

Statements

Author contributions

SPC: Investigation, Project administration, Visualization, Writing – original draft, Writing – review & editing. MS: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. PC: Investigation, Writing – original draft, Writing – review & editing. BF-K: Investigation, Writing – original draft, Writing – review & editing. TF: Investigation, Writing – original draft, Writing – review & editing. AG-S: Investigation, Writing – original draft, Writing – review & editing. JH: Investigation, Writing – original draft, Writing – review & editing. GH: Investigation, Writing – original draft, Writing – review & editing. CJ: Investigation, Writing – original draft, Writing – review & editing. RK: Investigation, Writing – original draft, Writing – review & editing. CK: Investigation, Writing – original draft, Writing – review & editing. AM: Investigation, Writing – original draft, Writing – review & editing. MM: Investigation, Writing – original draft, Writing – review & editing. ZN: Investigation, Writing – original draft, Writing – review & editing. JS: Investigation, Writing – original draft, Writing – review & editing. BS: Investigation, Writing – original draft, Writing – review & editing. RS: Investigation, Writing – original draft, Writing – review & editing. MT: Investigation, Writing – original draft, Writing – review & editing. RW: Investigation, Writing – original draft, Writing – review & editing. SZ: Investigation, Writing – original draft, Writing – review & editing. JR: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

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