How Should a Global Carbon Budget be Estimated?

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Research Article

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Abstract

The Intergovernmental Panel on Climate Change (IPCC), the authority for estimating a carbon budget for keeping to the Paris Agreement's 1.5–2°C target for limiting global warming, has indicated a budget of 580–1170 gigatons (Gt) of carbon dioxide (CO₂) from 2018. This budget is based largely on Earth system models using data from the instrumental record over the industrial period. During the prior 800,000 years, however, a range of 120 parts per million (ppm) in atmospheric CO₂ was associated with about a 6°C change in temperature, while temperature has only risen about 1°C with the 130 ppm increase in atmospheric CO₂ in the industrial period. The paleoclimate record indicates that the anthropogenic increase in CO₂ up to the present commits Earth to significant additional warming, such as from reduced albedo as Arctic sea ice melts and further CO₂ release from vegetative stores. Instrumental data and model updates also indicate greater warming from these sources than IPCC models predict. Additionally, reductions in CO₂ emissions to meet the Paris warming target will also reduce cooling from aerosols, which the IPCC may also have underestimated. Together, these factors indicate that CO₂ emissions consistent with the IPCC's carbon budget are likely to lead to at least 2–2.5°C global warming. I draw on the sustained critique of IPCC findings by Hansen and his colleagues, who have argued that the paleoclimate should be considered on par with Earth system models in climate analysis, and for more ambitious targets for reducing CO₂ emissions.

1. Introduction

In 2018, the Intergovernmental Panel on Climate Change (IPCC) estimated the global carbon budget for limiting global warming to the Paris Agreement target of 1.5–2°C at 580 to 1170 gigatons (Gt) of carbon dioxide (CO₂) from 2018 (Rogelj et al., 2018). Ever since the United Nations Framework Convention on Climate Change's (UNFCCC's) original 1992 commitment to “prevent dangerous anthropogenic interference with the climate system” (United Nations, 1992, 4), its central conflict has involved the division of responsibilities for reducing greenhouse gas (GHG) emissions among countries (Seo, 2017). The 2015 Paris Agreement target was an important accomplishment, but actual national commitments to reduce GHG emissions under this agreement would still lead to about 3°C warming according to IPCC calculations (Rogelj et al., 2016), and many governments are exceeding their Paris commitments (Climate Action Tracker, 2020). Since limiting global warming depends centrally on reducing and enforcing national limits to GHG emissions, the global carbon budget is the central science-based variable for climate change negotiations.

In this paper I argue that the IPCC carbon budget is too generous. I first lay out the overall argument, with details and citations to follow. The IPCC carbon budget is based mainly on models of interactions among elements of Earth's climate system and observations (measurements) mainly from the industrial period. Estimated uncertainties in these climate models, based on expert judgment as much as on statistical calculation, already exceed the low end of the IPCC carbon budget. Hansen and his colleagues have long argued, however, that Earth's paleoclimate record should be weighted on par with climate models in investigations of Earth's climate system. Over the last 800,000 years, an increase in atmospheric CO₂ on

the scale of the anthropogenic increase since 1800 has led to roughly 6°C global warming, but, so far, Earth's surface has only warmed about 1°C in the industrial period. The unprecedentedly rapid anthropogenic increase in atmospheric CO₂ has led to an energy imbalance at the top of Earth's atmosphere, with less energy leaving than entering the system, increasing to 0.87 Watts per square meter (W/m²) of Earth's surface in 2010 – 2018 (compared to a net increase of total radiative forcing of about 2.3 W/m² from 1750 to 2011). Earth's atmosphere must return to equilibrium – the Earth Energy Imbalance (EEI) must fall to zero – largely by release of heat stored in the ocean, implying that significant warming at Earth's surface remains “in the pipeline.” Together, the paleoclimate record of CO₂ and global warming and the EEI indicate that uncertainties in IPCC models are likely to be resolved in the direction of greater, not less, global warming.

In particular, evidence indicates that the IPCC carbon budget underestimates warming from (a) the reduction in Arctic sea ice, (b) the release of GHGs from melting permafrost and wetlands, and (c) large parts of the Amazon Rainforest potentially turning from a carbon sink into a carbon source, and possibly also from (d) changes in cloud dynamics. These factors are consistent with evidence from the paleoclimate period.

Considering evidence of rapid sea level rise preceding the last peak in global warming, about 115,000 years ago, and observations from recent decades, Hansen et al. (2016) argue that ice sheet melt from Antarctica and Greenland may be increasing at an exponential rather than the linear rate IPCC models have assumed. This would indicate that sea level could rise several meters in the present century, rather than a meter or less as the IPCC has it. If true, the increase in cold fresh water on the ocean surface would probably counteract global warming some time in the second half of this century. Rising seas, however, would hardly be less disastrous than increased warming, which, in any case, would merely be postponed.

The IPCC carbon budget for 2018 is based on a baseline temperature of 0.87°C warming in the industrial period averaged over 2006 to 2015, but temperatures since then have not only continued to rise—since 2016 the rise appears to have accelerated. An appropriate baseline for 2020 might be around 1.15°C, leaving only 0.35°C additional warming to reach the lower, 1.5°C end of the Paris target.

The largest uncertainties registered in IPCC climate models are due to aerosols, a category including both natural and anthropogenic gasses, often localized, that on balance tend to cool rather than warm the atmosphere. Since the main source of anthropogenic aerosols is fossil fuels, Hansen has long argued that humanity faces a “Faustian bargain:” limiting warming by reducing CO₂ emissions also reduces cooling from aerosols. Recent studies indicate that the IPCC carbon budget underestimates warming from reduced aerosols that would accompany reduced burning of fossil fuels.

Altogether, the evidence indicates that the lower, 1.5°C end of the Paris climate target is no longer on the table. Another 580–1170 Gt CO₂ emissions from 2018 would probably lead, in the present century, and barring improbable advances in technology for CO₂ removal, either to at least 2–2.5°C warming or to

greatly increased sea level rise. It would be reassuring if potential harms could be estimated more precisely, but, unfortunately, current scientific knowledge allows no greater specificity.

2. The Ipcc Carbon Budget

The IPCC was established in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess the science of climate change, and by 2016 it had 195 member countries. It has published a series of assessment reports, with authors selected so that “the world major regions and member countries are all represented in a balanced way” (Seo, 2017, 123). The influence of increasing CO₂ and other GHGs on the climate system is extremely complex, as anthropogenic forcings are imposed on a natural climate system with considerable internal variability, and as most of the heat captured by higher atmospheric concentrations of GHGs is initially absorbed by the ocean, some of the increased CO₂ is also absorbed by ocean and land “sinks,” and increased heat causes a variety of feedbacks such as reductions in albedo (energy reflected back into the atmosphere mainly by snow and ice). All of these changes influence clouds, which, in turn, cause many, sometimes opposing influences on the climate system. In both anthropogenic climate change and in the paleoclimate, CO₂ is the dominant driver of changes in temperature, so standard models have been built around atmospheric concentrations of CO₂. As more and more scientists came to focus on climate change, the IPCC and the (preexisting) World Climate Research Programme have coordinated research programs around central metrics and ongoing assessments of high-priority questions.

By 2013, when its Fifth Assessment Report (AR5) was published, the IPCC had come to focus on two central metrics – equilibrium climate sensitivity (ECS) and the transient climate response (TCR) – and four main lines of evidence – observed 20th century warming, climate models, feedback analysis, and paleoclimate. Equilibrium climate sensitivity is the “equilibrium change in annual mean global surface temperature following a doubling of the atmospheric CO₂ concentration” (Collins et al., 2013, 1110-1111), while transient climate response is the “temperature change relative to the preindustrial state at the time of CO₂ doubling ... which occurs at 70 years after the start of the simulation” (Arora et al., 2020, 4195). The IPCC has used evidence from the paleoclimate to confirm broad ranges of ECS and TCR values, and it uses feedback analysis to confirm and extend system-wide models. The core analysis for the 2013 carbon budget, however, as is evident from the literature on factors contributing to this budget, is based on climate models informed by physical relationships among elements of the climate system and observations mainly from the 20th century (see especially Collins et al., 2013, 1110-1111). The IPCC has relied particularly heavily on the World Climate Research Programme’s Coupled Model Intercomparison Project (CMIP), which has supported coordination among dozens of climate research groups around the world.

Based on 15 coupled atmosphere-ocean general circulation models (AOGCMs) from the fifth phase of the CMIP (CMIP5) that use its core experimental method, which in turn informed AR5, Andrews et al. (2012) estimate ECS at 2.1–4.7°C with a 95% confidence interval. From a (different) set of 15 CMIP5 Earth System Models (ESMs), Gillett et al. (2013) estimate TCR at 0.8–2.4°C, also at 95% confidence. An

AOGCM models atmospheric interactions involving atmosphere, land surface, sea ice, and ocean, while an ESM builds on an AOGCM with additional biogeochemical land and ocean components that model the carbon cycle, that is, transfer of carbon between atmosphere, ocean, soil, and other sinks (Demeris, 2018). Although these ECS and TCR results are not expected to directly predict Earth's actual environment, it is instructive to estimate their applications. The ECS results suggest that if atmospheric CO₂ were to double from its 1800 level of 281 parts per million (ppm), at the dawn of the industrial era, to 562 ppm, we would expect about 2.1–4.7°C of global warming at equilibrium, after a couple of thousand years (assuming fixed ice sheets, vegetative distribution, and other GHGs). In 2019 atmospheric CO₂ was at 411 ppm (co2.earth 2020), an increase of 46% from 1800. Assuming a linear relationship, therefore, this ECS suggests about 1–2.2°C warming at equilibrium from anthropogenic CO₂ emissions up to 2019. A standard climate model finds 60% of the warming response to a rise in CO₂ in the first 100 years (Hansen et al., 2011, 13424), which indicates roughly 0.6–1.4°C warming by 2100 from emissions up to 2019. TCR is modeled at the time of CO₂ doubling in 70 years, so the contemporary analog is less clear, but 46% of the modeled warming from doubled CO₂ is about 0.4–1.1°C, while actual warming since the preindustrial period is about 1.15°C (Hansen and Sato, 2020). Note that even this simplistic application suggests that the lower ends of the ECS and TCR estimates are unrealistic.

All of these climate models are derived from multiple time series of observation data and equations that represent interactions among elements of the climate system. Variations among ESMs considered by Gillett et al. (2013), for example, are due in part to different estimates of

nitrogen available to promote CO₂ fertilization of plants, removing CO₂ from the atmosphere, and to different models of CO₂ flux between ocean and atmosphere (6850). An ESM from the contribution to CMIP6 from France's National Center for Meteorological Research "resolves the spatial distribution of 63 chemistry species [in Earth's atmosphere] but does not represent the low troposphere ozone non-methane hydrocarbon chemistry. Chemical evolution is computed down to the ad hoc level of 560 hPa [hectopascals, a unit of atmospheric pressure]" (Séférian et al., 2019, 4188). Models are routinely checked by how closely they approximate the historic record, but data quality for many variables declines markedly before the satellite era, typically beginning in the 1960s or 1970s. Many models share data streams and other modules, so errors may be correlated, but models also often vary in the specific components of the climate system they include, making comparisons more difficult. No model, of course, can capture the full complexity of Earth's present climate system, and anthropogenic forcings are driving many elements of the system far beyond recent historic ranges.

The wide range of results from climate models and variations in their designs has led to a renewed effort in CMIP6 to stratify analyses within focused model intercomparison projects in order to enhance comparisons within and across ensembles of models and to better understand factors responsible for differences in their projections (Séférian et al., 2019 4182-3). Recognizing the importance to policy of the carbon budget, Rogelj et al. (2019) propose a framework to track models' estimates of this budget and reconcile differences between budgets, thereby to reduce uncertainty in the range of future estimates. They point out that over the last decade, studies have clarified that "the rise in global average temperature

is roughly proportional to the total cumulative amount of CO₂ emissions produced by human activities since the industrial revolution” (335), with the resulting linear relationship between warming and cumulative CO₂ emissions defined as the transient climate response to cumulative emissions of CO₂ (TCRE). Whereas TCR is specific to CO₂ doubling in a 70 year simulation, TCRE refers to the warming associated with any level of cumulative emissions (within relevant ranges).

Rogelj et al. (2019, 336) note that the global carbon budget is a function of (1) the historical human-induced warming to date, (2) the non-CO₂ contribution to future temperature rise, (3) the zero-emissions commitment, defined as additional warming after net CO₂ emissions fall to zero, (4) the TCRE, and (5) an adjustment term for sources of unrepresented Earth system feedbacks. The factors identified in the Introduction that I argue are not adequately reflected in the IPCC’s carbon budget involve the first, second, fourth, and fifth of these terms. I should point out immediately, however, that although Rogelj et al. (2019) justify the use of TCRE, in part, on the basis of the roughly linear observed effect of anthropogenic CO₂ on global temperature, since anthropogenic aerosols are generally co-produced with CO₂ they do not disturb this linear relationship, but their cooling effect complicates the interpretation of the resulting warming.

The IPCC’s 2018 carbon budget uses this (Rogelj et al., 2019) methodology, with the TCRE based on Collins et al. (2013), prepared for AR5, and estimates of non-CO₂ contributions “based on published methods and integrated pathways” (Rogelj et al., 2018 105). For the lower, 1.5°C end of the 2018 carbon budget—580 Gt CO₂ for a 50% chance of keeping global warming below 1.5°C—key uncertainties and variations include (among others): plus or minus 250 Gt CO₂ for “Variations due to different scenario assumptions related to the future evolution of non-CO₂ emissions,” minus 400 to plus 200 Gt CO₂ for “Non-CO₂ forcing and response uncertainty,” and plus or minus 250 Gt CO₂ for “Historical temperature uncertainty” (Rogelj et al., 2018 108). With these uncertainties summing, on the negative side, to 900 Gt CO₂, compared to a carbon budget of 580 Gt CO₂, the indication is that Earth may already be committed to 1.5°C warming.

In 2019, Rogelj et al. revisit the uncertainty of the carbon budget. Without quantifying uncertainties, they find uncertainties in ranges including “Medium” (or above):

1. For the temperature limit, in “Choice of temperature metrics used to express global warming, choice of preindustrial reference period, and consistency [of temperature limit] with global climate goals;”
2. For historical human-induced warming, in “Choice of temperature metrics used to express global warming, choice of preindustrial reference period, consistency with global climate goals, incomplete coverage in observational data sets, and methods to estimate human-induced component;”
3. For non-CO₂ contribution to future global warming, in “The level of different non-CO₂ emissions that are consistent with global net-zero CO₂ emissions, which depends on policy choices but also on uncertain success in their implementation” and in “Climate response to non-CO₂ forcings, particularly in the level of aerosol recovery and temperature reduction from lower methane emissions;” and

4. For TCRE, in “When extended beyond peak warming ... uncertainty about linearity, value and distribution of TCRE for decreasing cumulative CO₂ emissions, and impact of temperature metrics on TCRE estimate” (339).

Collectively, these uncertainties indicate that limiting CO₂ emissions from 2018 to 580–1170 Gt CO₂ is quite uncertain to reach global climate goals.

The IPCC and World Climate Research Programme processes have focused great scientific attention on climate models. Given that these models integrate many series of data, however, to produce results that describe broad relationships in Earth’s climate system, they may obscure the importance to the climate system of individually significant elements, such as Arctic sea ice, the Amazon Rainforest, and anthropogenic aerosols, that the models represent imperfectly. Attending to climate models offers an attunement to long term relationships among system components, but the paleoclimate record offers a distinct perspective on these relationships, and this attunement can be complemented by a topographical sensitivity from attending to individual elements both in the paleoclimate record and in Earth’s contemporary environment. Given the imminence of 1.5°C warming with respect to climate model timeframes, it would only take a few marginal errors to undermine the plausibility of the global climate goals.

3. The Paleoclimate And Earth’s Temperature

In the last two decades Antarctic ice cores have provided reliable data on temperature and atmospheric CO₂ concentrations for the last 800,000 years (Figure 1). While the location in Antarctica amplifies changes in temperature, a change of 120 ppm CO₂ in this period is associated with roughly a 6°C change in average global temperature (Hansen et al., 2008, 219). Throughout the period’s several roughly 100,000-year glacial cycles, atmospheric CO₂ ranged between 180 and 300 ppm, while in the last 220 years it has increased from 280 to 410 ppm. Interglacial sea levels peaked up to nine meters above contemporary levels when temperatures cannot have been more than a degree above the 20th century average (Hansen et al., 2013). Hansen, who, with many colleagues, has offered perhaps the most sustained (if often implicit) scientific critique of the IPCC’s headline findings, has argued since 2008 that in light of paleoclimate evidence, limiting dangerous anthropogenic interference with the climate system requires atmospheric CO₂ to be reduced at least to 350 ppm (Hansen et al., 2008, 2011, 2013, 2016, 2017). The present paper’s argument, although consistent with Hansen’s critique, is much narrower, and it emphasizes some different lines of evidence.

The periodicity of glacial cycles over the last 800,000 years is due to variations in Earth’s orbit, the so-called Milankovitch cycles, with peaks at frequencies of roughly 20, 40, and 100 thousand years. These orbital variations, however, only slightly alter the total solar energy Earth receives. Temperature changes in this period are caused in roughly equal measure by changes in GHG concentrations (primarily CO₂) and changes in albedo, with variations in radiative forcing for each on the order of 3 W/m², while orbital variations only alter radiative forcing by about 0.1 W/m² (Hansen et al., 2016, 3787). CO₂, albedo, and

temperature are all highly congruent over the last 800,000 years, each boosting one another (Hansen et al., 2008, 219). In contrast to current warming, caused by release of carbon from organic remains stored underground over millions of years, glacial cycles in this period are associated with transfers of carbon mainly between the atmosphere and the ocean. A warming phase initiated by orbital variations increases circulation of ocean layers, particularly in the Southern Ocean, causing the ocean to vent CO₂. Warming from higher atmospheric CO₂ melts ice sheets from northern and southern poles, reducing albedo, which accelerates warming. This warming, in a grand cycle, causes further venting of ocean CO₂. Stores of carbon in vegetation and in soils, and other GHGs, respond to these variations in temperature and atmospheric CO₂, but with lower quantitative significance to the glacial cycle (Hansen et al., 2008).

Hansen's analysis of the paleoclimate record indicates greater warming from anthropogenic CO₂ than the IPCC's ECS and TCR. For both approaches, it is important to distinguish between "fast" and "slow" feedbacks. Fast feedbacks include water vapor, clouds, natural aerosols, snow cover, and sea ice. The principal slow feedbacks, "which may lag temperature change by decades, centuries, millennia, or longer time scales," are surface albedo and long-lived GHGs (Hansen and Sato, 2012, 25-26). Hansen and Sato argue that "Paleoclimate records yield, by far, our most accurate assessment of climate sensitivity and climate feedbacks," because we can never be sure that climate models "include all important processes" (2012, 25; see also 27). Hansen and Sato calculate Earth's sensitivity to fast feedbacks at 3°C for doubled CO₂ (95% confidence intervals between plus or minus 0.5 and 1.0°C), or 0.75°C per W/m² (28, 30). While temperature and CO₂ patterns over the last 800,000 years would indicate that slow feedbacks double this climate sensitivity, they point out that this period included greater variation in ice sheet coverage, increasing the contribution from albedo, than is possible in coming millennia. They argue that slow feedbacks relevant to anthropogenic climate change increase fast feedbacks by 30-50%, for doubled CO₂, to 3.9-4.5°C (34).

For a simple numeric comparison, applying climate sensitivities from Hansen and Sato to the 46% increase of CO₂ to 2019 in the industrial period gives about 1.4°C for fast feedbacks and 1.9°C for fast and slow, compared to a TCR of 0.4–1.1°C and ECS of 1–2.2°C. Note, however, that fast feedback "equilibrium" and TCR both refer to fast feedbacks, but in the paleoclimate context this has snow cover, sea ice, and other feedbacks responding to much more gradual temperature change than in the industrial period. This paleoclimatic fast feedback climate sensitivity indicates that Earth can expect perhaps another 0.25°C, beyond the 1.15°C warming that occurred by 2019, from CO₂ emissions up to 2019.

Hansen and Sato's fast+slow feedback includes changes in surface albedo and long-lived GHGs that are held to zero in ECS experiments. We previously estimated 0.6–1.4°C warming by 2100 from ECS up to 2019, assuming 60% of warming response in 100 years. This 60% estimate comes from GISS climate model-ER based on the 2000 year control run E3 (Hansen et al, 2007), a standard climate model. Hansen et al. (2011, 13424) argue that evidence from the paleoclimate indicates that "global climate models are ... too sluggish in their response to a climate forcing," partly due to diffusing heat from shallower to deeper levels of the ocean too quickly. They estimate global surface temperature response at 75% after 100 years (13424-13426), which would increase the estimated ECS for 2019 to 0.75–1.65°C by 2100, a

range more consistent with Hansen and Sato's fast feedback response of 1.4°. Hansen and Sato also argue, however, that some "slow" feedbacks, particularly ice sheet disintegration, in the paleoclimate, may take place faster with the much more rapidly increasing forcings of the industrial period (2011, 43-44). This would increase both the reduction in albedo and sea level rise. Since sea level rise would have more immediately disastrous consequences for humans, that is where they focus their analysis.

Of course, fast and fast+slow warming estimates for emissions to 2019 derived from Hansen and Sato, 1.4°C and 1.9°C (plus or minus about 25%) respectively, refer to atmospheric processes from the paleoclimate period. They would not capture effects of anthropogenic aerosols or of a possible die-off of the Amazon Rainforest, driven by anthropogenic deforestation and exceptionally rapid climate change, that I argue further undermine the validity of the IPCC's carbon budget.

4. Earth's Energy Imbalance (Eei) And Zero Emissions Commitment Models

Expectations from the paleoclimate period of significant unrealized warming from CO₂ emissions to date are reinforced by the increasing energy imbalance at the top of Earth's atmosphere. Von Schuckmann et al. (2020) report from a comprehensive Global Climate Observing System study that the EEI, the excess in energy Earth is absorbing from the Sun over energy emitted to space, has increased from 0.47 W/m² over 1971–2018 to 0.87 W/m² during 2010–2018. Physics requires Earth to return to energy equilibrium; the planet must continue gaining energy until EEI returns to approximately zero. They argue that the EEI "is the most fundamental metric that the scientific community and public must be aware of as the measure of how well the world is doing in the task of bringing climate change under control," and that atmospheric CO₂ "would need to be reduced from 410 to 353 ppm to increase heat radiation to space" by this amount (2014). Their analysis reinforces and updates Hansen et al's (2005 and 2011) finding that about 90% of this positive EEI is stored in the ocean (2015).

Hansen et al (2005, 1431) calculate that an EEI of 0.85 W/m² implies "additional global warming of about 0.6°C without further change of atmospheric composition." MacDougall et al (2020) find, however, based on 18 Earth system models in the Zero Emissions Commitment Model Intercomparison Project, that when net CO₂ emissions fall to zero, the medium term (50 year) change in global mean temperature is close to zero. In their analysis, additional warming from the ocean's thermal inertia after net-zero emissions is offset by absorption of CO₂ by ocean and land sinks. Their experimental protocol has CO₂ concentrations increasing exponentially until emissions reach 1000 PgC (billion tons of carbon) and then falling to zero, with land use change and non-CO₂ forcings held at pre-industrial levels (2988-2990). Among MacDougall et al's 18 models, the change in temperature 50 years later ranges from -0.36 to 0.29°C (2993), with variations depending largely on the efficiency of land and ocean carbon uptake, of which the latter is more uncertain (2998). The 18 models vary in the components of the carbon cycle they include, with only three, for example, including carbon released from permafrost (3004-3007). They make no reference, however, to EEI or to Hansen's analyses, and von Schuckmann et al. make no reference to

Zero Emission Commitment models. Hansen et al (2011) find 40% of the temperature response to a climate forcing in the first five years (13424). In the context of a 1.5°C warming target with feedbacks that may not be well represented, a short-term overshoot could have significant consequences, and concerns about climate models discussed elsewhere in this paper apply similarly to this set. Differences between the two approaches in expectations for global temperature immediately following net zero CO2 emissions remain to be reconciled by the scientific community.

5. The Paleoclimate And Sea Level Rise

Hansen et al. have long argued that the paleoclimate record indicates much faster potential sea level rise due to anthropogenic climate change than indicated in IPCC reports (2005, 2007a, 2007b, 2008, 2012, 2016, 2017). This issue is explored most thoroughly in Hansen et al. (2016), focusing on parallels between rapid sea level rise near the end of Earth's last interglacial period, about 120,000 years ago, and the present period. Late in this interglacial period, Earth's temperature was probably only a few tenths of a degree warmer than today, but sea level rose rapidly, about 6-9 meters in a few hundred years at most, including a 2-3 meter jump within several decades (3781). Hansen et al. attribute these sea level rises to the collapse of Antarctic and Greenland ice sheets due to relatively extreme orbital variations that warmed the Southern Ocean (3786), with a slowdown of the Atlantic Meridional Overturning Circulation (AMOC, sometimes referred to as the Gulf Stream) as a secondary factor. Rapid warming of the Southern Ocean strengthened currents that increased release of CO2 from the deep ocean, raising global temperature. This in turn increased ice melt from ice sheets at both poles. The resulting layer of cold, less salty water stayed mainly at the ocean surface, and heavier warm salty water moved to lower levels. Since ice sheets (such as in Antarctica and Greenland) melt from the bottom, this accelerated glacier collapse and ice melt. The colder surface water, however, temporarily slowed atmospheric warming, while increasing ocean warming.

Hansen et al. identify a similar pattern of ice melt and ocean warming due to the anthropogenic increase in CO2, with dynamics not found in IPCC models (3778). They hypothesize that measurements from recent decades, heuristic factors, and the paleoclimate record collectively indicate that Antarctic and Greenland ice sheets are likely to collapse more quickly than IPCC models indicate, leading to an exponential rate of sea level rise, up to several meters in the present century, if CO2 emissions are not radically curtailed, although they emphasize that empirical data are too brief to confirm this hypothesis (3792-3795). Colder water on the ocean surface from increased ice melt counteracts global warming, potentially leading to global surface air temperature below preindustrial levels in the second half of this century (3768). Sooner or later, however, heat initially kept at lower ocean levels diffuses upward, and the avoided surface warming is realized.

In light of the devastating consequences it could have for humanity, their analysis focuses on a potentially rapid acceleration of sea level rise. If confirmed, however, their analysis also implies greater committed warming of Earth's atmosphere after some delay. It also indicates that the warming trend will be more geographically diverse, with possible cooling southeast of Greenland and around Antarctica

(3775), so average global temperature more significantly underestimates warming in most populated areas. Greater temperature gradients also increase the power of storms. It is notable that while Hansen et al. point out differences in their analysis and conclusions from those of the IPCC, the chapter on sea level rise in the IPCC special report on the Ocean and Cryosphere (2019) makes no reference to Hansen.

6. Adjustments To The Ippc Carbon Budget

Fast feedbacks of 1.4°C from CO₂ emissions up to 2019 derived from Hansen and Sato (2012) and an EEI of 0.87 W/m² indicate that high uncertainties in the IPCC analysis are likely to be resolved in the direction of greater warming and a lower carbon budget. Earth may escape greater warming in this century with faster sea level rise, but this would be little consolation.

6.1 Human-induced warming to date

The first term in Rogelj et al.'s (2019) formula for a global carbon budget is historical human-induced warming to date. Here the IPCC estimate is 0.87°C plus or minus 0.12°C based on “a weighted average of near-surface air temperature (SAT) changes over land and sea surface temperature (SST) changes over the oceans” from 1850–1900 to 2006–2015. “[W]arming at a given point in time is defined as the global average of combined land surface air and sea surface temperatures for a 30-year period centred on that time” (Allen et al., 2018, 56); the figure for 2006–2015 “comprises an estimate of the 30-year average centred on this decade, or 1996–2025” (Allen et al., 2018, 58). (The IPCC finds the change in global SAT, however, without SST, to be 0.97°C to 2006–2015, and this is the unit the IPCC uses to estimate future warming when it calculates the carbon budget; Rogelj et al., 2018, 108).

Warming has, of course, continued to increase since 2006–2015. Hansen and Sato (2020) report acceleration of warming since 2013 “too large to be unforced noise,” which they attribute by elimination to a relative reduction in unmeasured cooling aerosols. This could result from cleaner burning of fossil fuels aimed at reducing local pollution. Writing in mid-December 2020, they expect 2020 to be the warmest year on record based on GISTEMP data, despite the start of a strong (cooling) La Niña. GISTEMP has warming to 2006–2015 at 0.89°C (Allen et al., 2018, 58), only 0.02°C above the IPCC estimate. Hansen and Sato (2020) report a 60-month running global temperature average above 1.15°C in 2018, the most recent year for which it can be calculated, and the 12-month trend line indicates continued rising. It does not seem unreasonable, then, to estimate historical human-induced warming to date at 1.15°C in 2020.

6.2 Non-CO₂ contribution to future temperature rise

“Aerosol uncertainty is the principle barrier to quantitative understanding of ongoing climate change,” and their indirect climate forcing, due to effects on clouds, may exceed their direct forcing (Hansen et al., 2011, 13442, 13445). The most significant anthropogenic aerosol, sulfur dioxide, mainly from “burning of fossil fuels by power plants and other industrial facilities” (EPA 2020), is also directly harmful to human health. Although AR5 finds “increasing evidence that the aerosol RF [radiative forcing] of the 20th century

is not strongly negative, which makes it unlikely that the observed warming was caused by a very large ECS in response to a very small net forcing” (Collins et al., 2013, 1111), Bellouin et al. (2019, 1) find aerosol radiative forcing of $-2.0 - -0.4 \text{ W/m}^2$ (90% likelihood) or $-1.6 - -0.6 \text{ W/m}^2$ (68% likelihood) based on multiple lines of evidence for the industrial period, compared to a net increase in radiative forcing of about 2.3 W/m^2 from 1750 to 2011 (Myhre et al., 2013, 661). Consistent with Hansen and Lacis’s early analysis (1990, 716), this implies that roughly 1.2 W/m^2 additional forcing, or about a 50% increase in warming, was masked by the cooling effects of aerosols.

It is not surprising, therefore, that Samset et al. (2018, 1020) find that removing anthropogenic aerosol emissions would increase global mean surface heating by $0.5-1.1^\circ\text{C}$. Rogerj et al. (2019, 337) note that for the second term in the formula for a carbon budget, non-CO₂ contribution to future warming, “Future non-CO₂ warming might be considerable, given that reducing emissions of cooling sulphur dioxide causes warming and the knowledge that no obvious mitigation options have been identified that can completely eliminate several important sources of non- CO₂ greenhouse gasses.” The rapid reduction in CO₂ emissions required by a 580–1170 Gt budget would bring about a similarly rapid reduction in anthropogenic aerosols, increasing net warming by perhaps 0.4°C .

6.3 The transient climate response to cumulative emissions (TCRE)

The TCRE expresses the linear relationship between warming and cumulative CO₂ emissions, as noted above, in units of $^\circ\text{C}$ per Gt of CO₂. Although it is “Arguably the most central term to estimating the remaining carbon budget,” Rogerj et al. (2019, 336) note that it is highly uncertain. “In its latest assessment, the IPCC reported the TCRE to fall within the range of $0.2-0.7^\circ\text{C}$ per 1,000 Gt CO₂ with a probability of at least 66%.” With about 2,308 Gt CO₂ emitted over 1870-2018 (Jones and Friedlingstein, 2020, 2), the TCRE falls between $0.46-1.62^\circ\text{C}$, a range that includes the lower, 1.5°C end of the Paris target. Rogerj et al. (2019 336) note that “The TCRE can be estimated from several lines of evidence, including the observational record, CO₂-only simulations and multi-gas simulations with Earth system models of varying complexity.” All these lines of evidence make use of the observational record, so uncertainty in how much warming in the industrial period has been masked by aerosol cooling contributes to the uncertainty in the TCRE.

Jones and Friedlingstein (2020, 3) argue that the large uncertainty in the TCRE can be divided between uncertainty in the carbon cycle response – how Earth’s carbon reservoirs respond to increasing atmospheric CO₂ – and the climate response – how warming affects these carbon sinks. Among factors that I argue are not adequately represented in the IPCC carbon budget, permafrost and wetlands and the Amazon Rainforest are part of the carbon cycle response. Arctic sea ice and cloud dynamics arguably fall under Rogerj et al.’s fifth term, unrepresented (or inadequately represented) Earth system feedbacks.

6.3.1 Permafrost

Seventeen percent of Earth's exposed land surface is underlain by permafrost (Biskaborn et al., 2019, 2), and the IPCC's SR15 acknowledges that its carbon budget for 1.5°C "could be reduced by 100 gigatons due to thawing permafrost and methane released from wetlands" (2018, 14). The earlier AR5 excludes permafrost from its carbon balance due to "insufficient understanding" (Collins et al., 2013, 1116), and MacDougall and Knutti (2016, 2123) note that studies published in 2014 "are the first to formally quantify the uncertainty of permafrost carbon pool metrics based on field measurements and laboratory experiments." While some CMIP6 models include permafrost modules, the level of understanding of carbon feedback from permafrost and wetlands is "very low" (Rogerj et al. 2019, 335, 339). Gasser et al. (2018) find, unsurprisingly, that the potential feasibility of large-scale CO₂ removal from the atmosphere makes the carbon budget path dependent, as a greater temporary overshoot of a warming target increases carbon emissions from permafrost. "For the 1.5°C target, reductions [due to permafrost] in the median remaining budget range from -10% to more than 100%" (Gasser et al., 2018, 830). Biskaborn et al (2019, 1), as they report the first globally consistent assessment of permafrost temperature change, note that "permafrost change is not yet adequately represented in most Earth System Models," and release of CO₂ and methane from melting permafrost "is expected to augment global warming by 0.13–0.27°C by 2100 and by up to 0.42°C by 2300."

6.3.2 The Amazon Rainforest

AR5 finds with medium confidence "that climate change alone ... will not drive large scale [Amazon] forest loss by 2100," but also notes "new evidence of critical ecological thresholds and positive feedbacks between climate change and land use activities that could drive a fire-mediated, self-reinforcing dieback in the next few decades" (IPCC, 2014, 309). Forests currently remove about 27% of anthropogenic carbon emissions, but during the 2015-2016 El Niño-related drought, tropical forests overall switched from a net carbon sink to net carbon emitters (Brando et al., 2019). The Amazon Rainforest sequesters about 1.8 Gt CO₂ in a normal year (May, 2013, 9), and in the Amazon's hydrological cycle, moisture is recycled five to six times as, after rainfall, "at least 75% of the moisture is returned to the westward-moving air mass" (Lovejoy and Nobre, 2019, 1). It has long been recognized that deforestation and drought could lead to a tipping point, beyond which more than half of the Amazon Rainforest converts to tropical savannah.

Whereas independent early estimates indicated 40% deforestation or 4°C global heating as likely tipping points, more recent estimates accounting for "synergies between deforestation, climate change, and widespread use of fire indicate a tipping point for the Amazon system to flip to non-forest ecosystems in eastern, southern and central Amazonia at 20-25% deforestation" (Lovejoy and Nobre, 2018, 1). With deforestation of the Amazon Rainforest at 17% and rising (Lovejoy and Nobre, 2019, 1), and no recent decline in rates of forest fires (Numata et al., 2017, 135), about 20% of the forest area has already become a carbon source, rather than sink (Gatehouse, 2020; Hubau et al., 2020). While the Amazon tipping point theory is contested, crossing such a point would probably lead to a net reduction of around a gigaton of CO₂ per year in Earth's carbon budget, or perhaps 50 Gt by 2100.

6.4 Unrepresented Earth system feedbacks: sea ice and clouds

It is widely recognized that IPCC models have underestimated the loss of Arctic sea ice (Johnson, et al., 2020, 7; Notz and Stroeve, 2016; SIMIP community, 2020). Pistone, Eisenman and Ramanathan note that:

“[An] open ocean surface typically absorbs approximately 6 times more solar radiation than a surface covered with sea ice and snow. ... The observed Arctic sea ice retreat per degree of global warming is 2.1 times larger than the [IPCC’s] CMIP5 ensemble-mean result, with no model ... simulating a value as extreme as the observations” (2019, 7474-7475).

Even the most current Earth system model reported by Séférian et al. (2019, 7474-5) still substantially underestimates recent declines in sea ice. Pistone, Eisenman and Ramanathan find, in what they call a “worst-case” scenario where Arctic sea ice disappears completely in the sunlit part of the year much earlier than currently projected, that additional heat absorption would be equivalent to that of 1000 Gt CO₂ (7474), almost as much as the IPCC’s carbon budget for 2°C. Reviewing evidence from a variety of sources, Meleshko et al. (2019 406) report time horizons for summer Arctic sea ice loss of “roughly 2020, 2030 and 2040.” In their synthesis of observational trends and projections Overland et al. (2019, 8) find that an extrapolation of recent trends could lead to a seasonally ice-free Arctic Ocean within the next few decades. Niederdrenk and Notz (2019, 1963), combining observations and simulations, “find that Arctic September sea ice is lost with low probability ($P \approx 10\%$) for global warming of +1.5°C above preindustrial levels and with very high probability ($P > 99\%$) for global warming of +2°C above preindustrial levels.”

As the IPCC’s 2018 carbon budget is based on CMIP5 models, its underestimation of the reduction in albedo due to loss of Arctic sea ice loss is significant. Considering also the additional warming expected due to reductions in aerosols, it seems reasonable to estimate that reductions in Arctic sea ice will add perhaps 0.2-0.3°C warming in coming decades beyond CMIP5 estimates, reducing the carbon budget by perhaps 300 Gt.

Based on standard CO₂ quadrupling experiments, the newest, CMIP6 round of global climate models finds greater climate sensitivity to increasing CO₂ than earlier rounds due to decreasing low cloud coverage and albedo. Zelinka et al. (2020, 1) report values from 1.8–5.6°C from these experiments, compared to the recent consensus of 1.5–4.5°C. The newer models find greater reduction in “low cloud water content and coverage ... causing enhanced planetary absorption of sunlight.” While implications for the carbon budget from this development have not yet been quantified, it clearly can only reduce the budget.

7. Summary And Conclusion

I have argued that the IPCC’s carbon budget of 580–1170 Gt CO₂ from 2018 to limit global warming to the Paris target of 1.5–2°C is too generous. The IPCC’s SR15 acknowledges that this budget has (in effect) a very wide confidence interval. Estimates of 1.4°C likely warming due to fast feedbacks from CO₂ emissions to date, based on the paleoclimate record, and of a current Earth Energy Imbalance of about

0.87 W/m², together suggest that the many sources of uncertainty in calculations leading to the carbon budget are likely to be resolved in the direction of greater warming (and a lower budget). This interpretation of the EEI, however, is in tension with findings from the Zero Emissions Commitment Model Intercomparison Project, which estimate global mean temperature change close to zero fifty years after net CO₂ emissions fall to zero.

Taking the anthropogenic temperature rise from 1850–1900 to 2020 to be 1.15°C, I have argued that the IPCC budget underestimates warming in several ways. It underestimates the warming effect of the reduction in aerosols that is likely to accompany the required reduction in CO₂ by perhaps 0.4°C. SR15 acknowledges that its budget is likely to underestimate carbon emissions from permafrost and wetlands by perhaps 100 Gt CO₂, which could itself be an underestimation. Anthropogenic and climate factors not represented in IPCC models that cause parts of the Amazon Rainforest to turn from a sink to a source of carbon may reduce the budget by a further 50 Gt. Underestimated warming from the reduction of albedo due to Arctic sea ice melting faster than modeled may increase warming by 0.2–0.3°C, reducing the carbon budget by perhaps 300 Gt. While the CMIP6 round of global climate models indicates that earlier rounds have underestimated warming from reduced albedo from clouds, the effect of such a reduction on the carbon budget is yet to be quantified.

Collectively these adjustments indicate that Earth is already committed to at least 1.5°C due to anthropogenic emissions to date, and the IPCC carbon budget is more likely to lead to global warming from 2–2.5°C. This is, of course, a loose estimate, and probably still on the low side. The evidence we have considered also indicates that IPCC estimates of the probability of its warming estimates, based as much on expert judgement as on statistical calculations, tend also to be on the low side. The high ends of its expressed or implied probability distributions are often actually more likely than the low ends. Our knowledge of Earth's climate system is probably still too limited to allow reliable estimates of such probability distributions. Compared to Earth's history, the speed with which we are altering the climate system and the magnitude of the increase in GHGs indicate that Earth system responses are likely to exceed estimates from current models.

As a case in point, Hansen et al. (2016) make a plausible case, based on the paleoclimate record and observations, that sea level is rising exponentially, implying a much greater rise this century (and beyond) than the IPCC has estimated. The ice melt that would cause this sea level rise, as it spreads across the surface of the ocean, would probably reverse the increase in Earth's surface level temperature at some point in this century, but harms from rising sea levels would be devastating.

The international community has put great stock in IPCC climate change projections, and the most strategically important of these is the global climate budget. From the start of international climate change negotiations, the division of responsibilities for reducing carbon emissions among countries has been the main sticking point. Despite the landmark Paris Agreement, according to IPCC calculations national commitments to reduce GHG emissions would still lead to about 3°C warming, and many countries are not keeping to their Paris commitments. The evidence we have discussed also indicates

greater harms than indicated by IPCC estimates in the 2100s and beyond. It is imperative that international climate change negotiations should be based on the most reasonable estimates of likely harms from GHG emissions.

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Figures

Temperature Change and Atmospheric Carbon Dioxide Change measured from the EPICA Dome C ice core in Antarctica Temperature change (light blue) and carbon dioxide change (dark blue). Source: NOAA

[National Oceanic and Atmospheric Administration] National Centers for Environmental Information (2020) (Jouzel et al. 2007; Lüthi et al. 2008). Used with permission.