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Horizon 2020 Societal challenge 5:
Climate action, environment, resource
efficiency and raw materials

VERIFY

Observation-based system for monitoring and verification of greenhouse gases

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Changes with respect to the DoA

The Future Earth international platform for global sustainability was developing a new Knowledge Assessment Platform (KAN) on decarbonisation. We proposed to dedicate effort and resources to support the elaboration of the KAN decarbonisation with the objective of providing the best possible scientific support to measure and assess progress in decarbonisation in Europe and elsewhere. However, Future Earth's development of the KAN ceased in 2018 and so our opportunity to support the platform disappeared.

Responding to this change of circumstance, we focussed our efforts on synthesis of the outstanding obstacles to verification of a change in the trajectory of atmospheric CO_2 concentrations, the ongoing and outstanding efforts to overcome those obstacles, reviewing the needs of decision makers for scientific insights.

Dissemination and uptake

(Who will/could use this deliverable, within the project or outside the project?)

This work serves two purposes. First it outlines to researchers working in diverse elements of carbon cycle science, the key known biases and uncertainties in the global carbon budget (GCB). It elaborates on activities that are required to resolve or alleviate those issues. It is hoped that targeted discussion of these issues might stimulate fresh ideas, draw in other perspectives and foster new breakthroughs that have hitherto been overlooked. This synthesis can serve as an agenda for future reduction of bias and uncertainty in the carbon cycle. Second it reflects on how the regular publication of updates on the carbon cycle can better serve the community of decision makers that use them.

Short Summary of results (<250 words)

Biases and spread in the estimates of each term of the global carbon budget challenge the robust detection of a trend in their central estimates, and moreover inhibit the attribution of a trend in atmospheric CO_2 to anthropogenic emissions. We outline the key sources of bias and spread in each term of the global carbon budget, highlight examples of progress made in recent years and opportunities for further progress in the coming decades. Overall, we suggest that the capacity to verify changes in atmospheric CO_2 on sub-decadal timescales will require concerted effort to incrementally address biases and uncertainties across all components of the budget.

Evidence of accomplishment
(report, manuscript, web-link, other)

The content of this report represents the accomplishment of the work.

Version	**Date**	**Description**	**Author (Organisation)**
V0	25/02/2021	Creation/Writing	Matthew Jones (UEA)
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1. Executive Summary

"Verification" refers to our capacity to detect a change in the trajectory of the atmospheric growth of CO_2 and attribute this to change in anthropogenic CO_2 emissions. For verification, we must first diagnose a change in the trend of atmospheric CO_2 and second attribute this to a change in anthropogenic CO_2 emissions. To inform and feed back to policy setting, it is desirable that verification is possible on timeframes relevant to political terms and to the evaluation and review of international agreements; ideally, less than 5 years.

Biases and spread in the estimates of each term of the global carbon budget challenge the robust detection of a trend in their central estimates, and moreover inhibit the attribution of a trend in atmospheric CO_2 to a specific driver. While it is not possible to completely remove bias and spread from reconstructions of the global carbon budget, our review of the current status of verification capacity allows us to identify some key examples of progress in resolving these issues in recent years as well as opportunities for the future.

We assess the requirements, progress and future outlook for reducing bias and spread as follows.

- First, it is critical to resolve known biases in each term of the budget. Known biases are present in all fluxes of the budget, and these contribute to imbalances between the reconstructed and observed growth rates of atmospheric CO_2. In the past, the systematic underestimation of fossil CO_2 emissions from Chinese coal has been addressed. On the other hand, the omission of the lost additional sink capacity from the carbon budget, caused by the combination of bookkeeping estimates for land use change emissions and process-based models for the land sink, has remained a persistent source of bias in the carbon budget. Additionally, the ensemble of process-based models systematically underestimate the response of the land sink to CO_2 fertilisation and overestimate the response of the tropical land sink to climate change. There are also mis-matches in the mean ocean CO_2 sink assessment between process models and data-based products, possibly due to uncertainties in the contribution of river input of carbon to the ocean. Emergent constraints are yet to be fully exploited through benchmarking or model weighting to reduce these biases in the land sink.
- Second, it is necessary to incrementally gather the observational evidence required to reduce uncertainty in model parameter values. Increasing the volume and specificity of observations of fossil fuel carbon content and emission factors is key to reducing spread in inventory estimates of fossil CO_2 emissions. Likewise, increasing the volume and specificity of vegetation carbon densities is key to reducing spread in inventory estimates of land use change emissions, and of ocean pCO_2 measurements to capture regional variability. Recent progress in the remote sensing of vegetation is likely to significantly aid with this goal in the near future. Improving records of historical land use change is also critical to reducing the spread of land use change emission estimates, however progress is hampered by poor or patchy historical records of land use and sluggish improvements in the availability of archaeological evidence. The slow convergence of

the assessment of ocean CO_2 variability between process models and data-based products shows the value of good observational coverage. Emergent constraints are likely to play a key role in the reduction of spread across models of the land and ocean sinks, as the values of parameters that are most uncertain and most challenging to observe are expected to converge across models as modellers strive for better alignment with those constraints.

Overall, the capacity to verify changes in atmospheric CO_2 on sub-decadal timescales will require concerted effort to incrementally address the biases and uncertainties across all components of the budget.

2. Introduction

2.1. Observing and Reconstructing the Global Carbon Budget

The Global Carbon Project (GCP) publishes an annual assessment of the global carbon budget, most recently in 2020 (Friedlingstein et al., 2020). As part of the budget, the atmospheric growth of CO_2 (G_{ATM}) is reconstructed as the residual of two source fluxes (fossil CO_2 emissions, E_F, and; land use change emissions, E_{LUC}) and two sink fluxes (the land sink, S_{LAND} and; the ocean sink, S_{OCEAN}):

$$(1) \qquad G_{ATM\_budget} = E_{FOS} + E_{LUC} - S_{LAND} - S_{OCEAN}$$

Where G_{ATM_recon} represents the reconstructed value of G_{ATM}. As E_{FOS} has continued to rise in the past half-century, around half of the emitted CO_2 has been sequestered by the land and ocean sinks. E_F, S_{LAND} and S_{OCEAN} have been rising on decadal timescales throughout the period of their robust estimation (since the 1960s). However, variability in the land and ocean sinks on interannual and quasi-decadal timescales means that G_{ATM} is far more variable than E_{FOS}.

As atmospheric growth can also be observed directly and with high accuracy (G_{ATM_obs}), it is also possible to redefine equation 1 to include the budget imbalance (B_{IM}) between G_{ATM_obs} and G_{ATM_budget}:

$$(2) \qquad G_{ATM\_m} = E_{FOS} + E_{LUC} - S_{LAND} - S_{OCEAN} + B_{IM}$$

Where the B_{IM} is the difference between reconstructed and measured values of G_{ATM}. The B_{IM} is small and rarely exceeds ~1 Gt CO_2 $year^{-1}$ (~0.3 Gt C $year^{-1}$) on decadal timescales, indicating that decadal trends in G_{ATM} can be estimated with reasonable accuracy through estimation of the sink and source fluxes. However, for individual years it frequently reaches ~2 Gt CO_2 $year^{-1}$ (~0.5 Gt C $year^{-1}$) or higher.

2.2. Defining Verification

"Verification" refers to our capacity to detect a change in the trajectory of the atmospheric growth of CO_2 and attribute this to change in anthropogenic CO_2 emissions. For verification, we must first diagnose a change in the trend of G_{ATM} and second attribute this to a change in global fossil CO_2 emissions – just one of the four accountable fluxes that impacts G_{ATM} (equation 1). To inform and feed back to policy setting, it is desirable that verification is possible on timeframes relevant to political terms and to the evaluation and review of international agreements such as the Paris Agreement; ideally, less than 5 years.

It is challenging to detect trends in G_{ATM} caused by a reduction in E_{FOS} for three reasons.

Type I: Variability of observed atmospheric growth

First, variability in G_{ATM}, driven largely by real (and not necessarily reconstructed) variation in the land and ocean sinks (see Figure 1), means that a change in the trend of G_{ATM} must be sustained for some time before it conclusively emerges beyond its own variability. Variability includes that occurring on interannual timescales as well as quasi-decadal timescales. This *Type I* issue inhibits our capacity to detect a long-term divergence of G_{ATM} from its own variability (the first requirement for verification).

Note that variability in E_{LUC} would also affect G_{ATM} (see equation 1) however E_{LUC} has a lesser magnitude and is more stable than the sink terms.

Type II: Biases affecting the central estimate of budget terms.

Second, the B_{IM} is typically non-zero on sub-decadal timescales indicating that G_{ATM} cannot be reconstructed without error ($G_{ATM\_recon} \neq G_{ATM\_obs}$). For example, when $G_{ATM\_recon} < G_{ATM\_obs}$ this indicates a central underestimation of sources or overestimation of sinks. This may highlight biases in the emission inventory estimates for E_{FOS}, biases in the bookkeeping models for E_{LUC}, or biases in the inventories or process representation of the land or ocean sinks. Biases are indicative of poor process representation across all models, or underlying biases in input data to these models (e.g. carbon density or emission factors).

Type III: Spread around the central estimates of budget terms.

Third, spread in estimates of E_{LUC} (~40%), S_{LAND} (~30%) and S_{OCEAN} (~25%) is large across different models and estimation approaches; indeed, larger than the variability in the central estimate. Uncertainties in E_{FOS} (5% globally) are smaller in relative terms but comparably large in absolute terms because E_{FOS} is the largest individual flux of the carbon budget. Spread relates to differences in the estimates of flux magnitude across methods and/or models which are considered equally possible.

Biases (*Type II*) and spread (*Type III*) in the estimates of each budget term challenge the robust detection of a trend in their central estimates, and moreover inhibit the attribution of a trend in G_{ATM} to a specific driver. Even if G_{ATM} has detectably reduced beyond its variability (see *Type I*), can we be confident that this is due to a reduction in E_{FOS}, and; can we rule out changes in the other terms of equation 1 (e.g. S_{LAND} or S_{OCEAN}) with confidence after accounting for the uncertainties of all terms?

2.3. Current Verification Capacity

Peters et al. (2017b) assessed the timeframe over which a change in the trend of G_{ATM} can be detected and attributed to a trend in E_{FOS}, considering *Type I*, *Type II* and *Type III* issues. They found that the verification of small changes in G_{ATM} is only feasible on decadal timescales (**Figure 1**), depending on the rate of change in E_{FOS}. At present, it would take around 10 years to detect the impact of flattening emissions (0% growth in E_{FOS}) for 68% confidence, and 20 years for 95% confidence. It might be possible to detect a reduction to E_{FOS} of -1% per year on shorter timescales (5 years for 68% confidence; 10 years for 95% confidence). The need to resolve these issues is growing. With stocktakes for the Paris agreement upcoming and with a growing number of countries strengthening their commitments on emissions reduction, frequent verification that policies are impactful may help to maintain momentum towards the stabilisation and reduction of fossil CO_2 emissions.

2.4. Scope of the Deliverable

Here, we consult and synthesise a number of recent publications that have outlined the key obstacles that limit verification with respect to E_{FOS}, E_{LUC}, S_{LAND} and S_{OCEAN}. We specifically highlight *Type II* (biases) and *Type III* (spread across estimates) issues related to each term and the progressive steps that have been taken, or could be taken in future, to alleviate these issues.

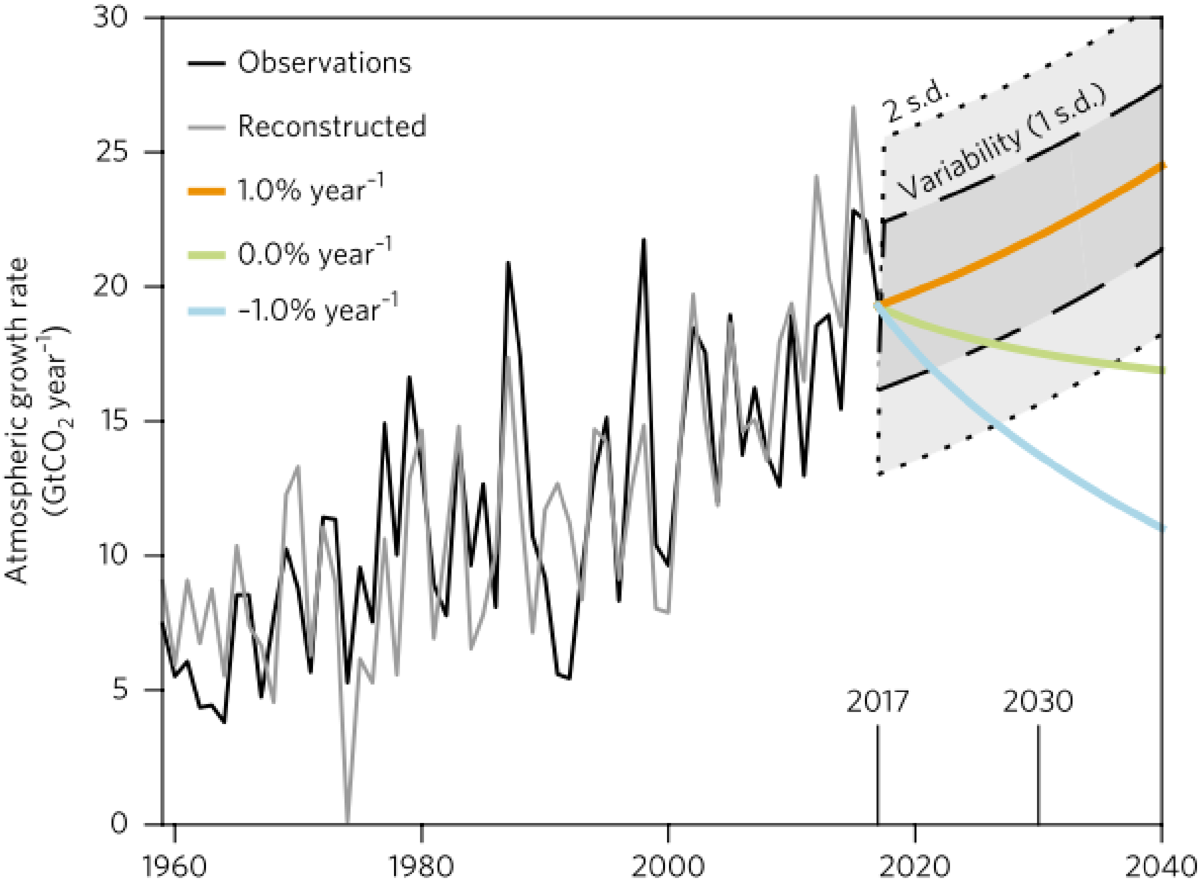

Figure 1: From Peters et al. (2017b). Our current ability to detect sustained changes in CO_2 emissions based on atmospheric CO_2 observations. Observations show a large inter-annual to decadal variability (black), which can be only partially reconstructed through the global carbon budget (grey; growth rate diagnosed by difference between estimated fossil fuel and industry emissions, and the simulated land and ocean sinks). Our limited ability to fully reproduce the observed variability is quantified through the budget imbalance (the difference between the black and

grey lines). The budget imbalance has zero mean over the 1959–2016 period, but the standard deviation (3 Gt CO_2 per year) is used here to illustrate variability and our current detection delay (grey bands). If CO_2 emissions stay flat for the next decades (green; 0% annual growth), then it may take 10 years before the estimated atmospheric concentrations would exceed the budget imbalance with a probability of 68% or more (and therefore could be detected) compared to a pathway of atmospheric concentrations consistent with growth in CO_2 emissions (orange, 1% per year similar to the emission pledges submitted to the Paris Agreement). This delay increases to 20 years for a 95% probability. If emissions declined faster than expected (blue, –1% per year), then a more marked change in atmospheric growth would be expected, and a much earlier detection.

3. Bias and Uncertainty Reduction: Progress towards Verification

Here we draw evidence from key recent publications on the current status of uncertainty in each term of the GCB (Equation 1). Peters et al. (2017b) provided succinct summaries of the major uncertainties in each term of the budget, with a specific focus on the uncertainties that principally drive limitations to verification. We present these summaries below. Since the publication of Peters et al. (2017b), the status of uncertainty and its reduction has been reviewed during annual iterations of the GCB assessment (Friedlingstein et al., 2020, 2019; Le Quéré et al., 2018b), and we include the latest perspectives below.

The study of Peters et al. (2017b) and subsequent reviews has driven action within the GCP research community and beyond, resulting in important breakthroughs in how we understand uncertainties in each term of the budget and inspiring some creative thinking on how to resolve those uncertainties. We draw on relevant information and recommendations from targeted studies of uncertainty in fossil CO_2 emissions, the ocean sink, land use change emissions and the land sink.

Table 1, reproduced from Friedlingstein et al. (2020), expressly summarises the key known uncertainties in the global carbon budget (GCB). Major known sources of uncertainties in each component of the Global Carbon Budget, defined as input data or processes that have a demonstrated effect of at least ±0.3 GtC yr-1.

Source of uncertainty	**Time scale (years)**	**Location**	**Evidence**
Fossil CO_2 emissions (E_{FOS}; Section 2.1)			
energy statistics	annual to decadal	global, but mainly China & major developing countries	(Korsbakken et al., 2016; Liu et al., 2015)
carbon content of coal	annual to decadal	global, but mainly China & major developing countries	(Liu et al., 2015)
system boundary	annual to decadal	all countries	
Net land-use change flux (E_{LUC}; section 2.2)			
land-cover and land-use change statistics	continuous	global; in particular tropics	(Gasser et al., 2020; Houghton et al., 2012)
sub-grid-scale transitions	annual to decadal	global	(Wilkenskjeld et al., 2014)
vegetation biomass	annual to decadal	global; in particular tropics	(Houghton et al., 2012)
wood and crop harvest	annual to decadal	global; SE Asia	(Arneth et al., 2017; Erb et al., 2018)
peat burning as result of interactions between land-use and climate	multi-decadal trend	global	(van der Werf et al., 2010)
loss of additional sink capacity	multi-decadal trend	global	(Gasser et al., 2020; Pongratz et al., 2014)
Ocean sink (S_{OCEAN}; section 2.4)			
variability in oceanic circulation (Could in part be due to uncertainties in atmospheric forcing)	semi-decadal to decadal	global	(DeVries et al., 2017, 2019; Swart et al., 2014)
internal variability	annual to decadal	high latitudes; Equatorial Pacific	(McKinley et al., 2016)
anthropogenic changes in nutrient supply	multi-decadal trend	global	(Duce et al., 2008)
Land sink (S_{LAND}; section 2.5)			
strength of CO2 fertilisation	multi-decadal trend	global	(Wenzel et al., 2016)
response to variability in temperature and rainfall	annual to decadal	global; in particular tropics	(Cox et al., 2013)
nutrient limitation and supply			
response to diffuse radiation	annual	global	(Mercado et al., 2009)

3.1. Fossil CO_2 Emissions (E_{FOS})

3.1.1.Summary

Summary from Peters et al. (2017b).

> Global fossil fuel and industry emissions are the sum of those countries with declining emissions (for example, US and Europe) and those countries with rising emissions (for example, China and India), indicating the importance of tracking country level changes (Peters et al., 2017a). They are also the sum of the declines in coal use, growth in oil and natural gas use, and the growth in renewables which displaces some fossil fuel use, indicating the importance of tracking changes in the energy system (Jackson et al., 2016; Peters et al., 2017a). Economic growth and new policies will play an important role in determining short-term emission pathways (Peters et al., 2017a). Emission uncertainty persists at the country level (Korsbakken et al., 2016) limiting our ability to accurately understand emission trends and drivers (Peters et al., 2017a). Considerable improvements are needed in estimating recent emission trends and their drivers, particularly in rapidly emerging economies and developing countries.

Updated perspective from (Friedlingstein et al., 2020):

> Estimates of global fossil CO_2 emissions from different data sets are in relatively good agreement when the different system boundaries of these data sets are taken into account (Andrew, 2020). But while estimates of E_{FOS} are derived from reported activity data requiring much less complex transformations than some other components of the budget, uncertainties remain, and one reason for the apparently low variation between data sets is precisely the reliance on the same underlying reported energy data.

3.1.2. Detail on Type II Issues (Biases)

Andrew (2020) described the alleviation of *Type II* issues through harmonization of system boundaries and isolated the key remaining biases that could not be resolved through harmonization:

> Since the first estimate of global CO_2 emissions was published in 1894, important progress has been made in the development of estimation methods while the number of available datasets has grown. The existence of parallel efforts should lead to improved accuracy and understanding of emissions estimates, but there remains significant deviation between estimates and relatively poor understanding of the reasons for this. Here I describe the most important global emissions datasets available today and – by way of global, large- emitter, and case examples – quantitatively compare their estimates, exploring the reasons for differences. In many cases differences in emissions come down to differences in system boundaries: which emissions sources are included and which are omitted.
>
> While “true” emissions cannot be known, by comparing different datasets methodically, differences that result from system boundaries and allocation approaches can be

highlighted and set aside to enable identification of true differences, and potential errors. This must be an important way forward in improving global datasets of CO_2 emissions.

Remaining biases:

At the global scale, a core reason for differing emissions estimates is simply the coverage of the dataset, whether geographic coverage or type of emitting activity. Some datasets do not include emissions from the decomposition of fossil carbonates, such as in the production of cement, while others include international bunker fuels in national estimates. The inclusion of emissions from non-energy uses of fossil fuels also varies across datasets.

Liu et al. (2015) highlight emissions that emissions from China can be estimates substantially by some inventories, including nationally reported figures, due in particular to poor constraints on the carbon content of Chinese coal.

> Nearly three-quarters of the growth in global carbon emissions from the burning of fossil fuels and cement production between 2010 and 2012 occurred in China. Yet estimates of Chinese emissions remain subject to large uncertainty; inventories of China’s total fossil fuel carbon emissions in 2008 differ by 0.3 gigatonnes of carbon, or 15 per cent. The primary sources of this uncertainty are conflicting estimates of energy consumption and emission factors, the latter being uncertain because of very few actual measurements representative of the mix of Chinese fuels. Here we re-evaluate China’s carbon emissions using updated and harmonized energy consumption and clinker production data and two new and comprehensive sets of measured emission factors for Chinese coal. We find that total energy consumption in China was 10 per cent higher in 2000–2012 than the value reported by China’s national statistics, that emission factors for Chinese coal are on average 40 per cent lower than the default values recommended by the Intergovernmental Panel on Climate Change, and that emissions from China’s cement production are 45 per cent less than recent estimates. Altogether, our revised estimate of China’s CO2 emissions from fossil fuel combustion and cement production is 2.49 gigatonnes of carbon (2 standard deviations ±7.3 per cent) in 2013, which is 14 per cent lower than the emissions reported by other prominent inventories. Over the full period 2000 to 2013, our revised estimates are 2.9 gigatonnes of carbon less than previous estimates of China’s cumulative carbon emissions. Our findings suggest that overestimation of China’s emissions in 2000–2013 may be larger than China’s estimated total forest sink in 1990–2007 (2.66 gigatonnes of carbon) or China’s land carbon sink in 2000–2009 (2.6 gigatonnes of carbon).

3.1.3. Detail on Type III Issues (Spread across estimates)

After alleviating *Type II* issues (see above), Andrew (2020) quantified spread amongst emission inventory estimates and isolated its two leading sources:

Magnitude:

With minimal work in harmonising these system boundaries across datasets, the range of estimates of global emissions drops to 5 %, and further work on harmonisation would likely result in an even lower range, without changing the data. Some potential errors were found, and some discrepancies remain unexplained, but it is shown to be inappropriate to conclude that uncertainty in emissions is high simply because estimates exhibit a wide range.

Key sources:

All emissions datasets build from data on energy and other activities, such as cement production, but it is emissions from fossil fuels and therefore energy data that are most important. There are several major energy datasets with global coverage. While some differences in emissions datasets are due to the use of different energy datasets, different processing methods can result in different emissions estimates even when emissions datasets rely on the same underlying energy data. Fundamentally, energy datasets are not independent, with all relying on the same underlying energy data in physical units reported by national agencies, with few exceptions. However, differences in interpreting these data, converting to the energy units required for estimating CO_2 emissions, emissions factors used, and of course errors, all result in different emissions estimates.

Of the three large emitters investigated here (USA, EU, China), estimates of the European Union’s emissions varied the least, after known differences in coverage were accounted for. It is expected that this results from the considerable effort put into energy and emissions statistics in the EU, combined with close collaboration both between countries and with the EEA and IEA. The EU’s Emissions Trading System also acts as a valuable data source.

That said, some discrepancies were found, such as the EIA’s apparent overestimate of China’s consumption of coal energy, and the sizable differences between estimates of US emissions could not be fully explained. Emissions and energy datasets are complex, and errors are bound to occur, requiring careful checks and comparison with other datasets. For China there was relatively good agreement between datasets for emissions from fossil fuels, apart from the EIA, mentioned earlier. While there is good agreement, revisions have previously led to substantial changes in all datasets.

The large discrepancies in estimates of emissions from liquid fuels in the USA warrant further investigation beyond what was possible in this article. The reporting of energy in physical units and use of gross calorific values rather than net calorific values, among other things, hamper a quantitative comparison between datasets.

3.2. Land Use Change Emissions (E_{LUC})

3.2.1. Summary

Summary from Peters et al. (2017b):

> Whereas emissions from land-use change are only about 10% of the global anthropogenic total, land-use change emissions are highly uncertain (Le Quéré et al., 2018a). The two dominant fluxes that make up the net flux from land-use change are emissions from land clearing and sinks from regrowth, such as afforestation, reforestation, land abandonment and shifting cultivation practices (Arneth et al., 2017). Major improvements in emission estimates will come from better estimates of standing biomass carbon and changes in carbon density across landscapes that include land degradation and disturbances currently poorly understood or not captured, and from better quantification of emissions associated with land management such as harvesting, afforestation, and shifting cultivation (Arneth et al., 2017; Baccini et al., 2017).

Updated perspective from Friedlingstein et al. (2020)

> Estimates of E_{LUC} suffer from a range of intertwined issues, including the poor quality of historical land-cover and land-use change maps, the rudimentary representation of management processes in most models, and the confusion in methodologies and boundary conditions used across methods (e.g. (Arneth et al., 2017; Pongratz et al., 2014)). Uncertainties in current and historical carbon stocks in soils and vegetation also add uncertainty in the LUC flux estimates. Unless a major effort to resolve these issues is made, little progress is expected in the resolution of E_{LUC}. This is particularly concerning given the growing importance of E_{LUC} for climate mitigation strategies, and the large issues in the quantification of the cumulative emissions over the historical period that arise from large uncertainties in E_{LUC}.

3.2.2. Detail on Type II Issues (Biases)

Pongratz et al. (2014) discuss issues relating to terminology and boundary conditions that introduce *Type II* issues to estimates of E_{LUC} from both bookkeeping models and DGVMs.

> Reasons for the large uncertainty in land use and land cover change emissions (E_{LUC}) go beyond recognized issues related to the available data on land cover change and the fact that model simulations rely on a simplified and incomplete description of the complexity of biological and E_{LUC} processes.
>
> The large range across published E_{LUC} emission estimates is also fundamentally driven by the fact that the net E_{LUC} flux is defined and calculated in different ways across models.
>
> We introduce a conceptual framework that allows us to compare the different types of models and simulation setups used to derive land use fluxes. We find that published studies are based on at least nine different definitions of the net E_{LUC} flux. Many multi-model syntheses lack a clear agreement on definition.
>
> Our analysis reveals two key processes that are accounted for in different ways:

(1) ***The inclusion or exclusion of indirect effects of E_{LUC} – the "land use feedback"***. The inclusion of the land use feedback (the effect of emissions from E_{LUC} on subsequent land carbon storage via higher concentrations of atmospheric CO_2 and other environmental changes). The land use feedback reflects changes in atmospheric CO_2 concentration as a result of human activity on the land, and as such should be quantified for full carbon accounting. The largest discrepancy occurs on natural land, which includes highly productive vegetation. The question becomes whether the land use feedback should be accounted as part of the net E_{LUC} flux. Alternatively, the net E_{LUC} flux can be defined so as to include only the feedback on managed land, while the feedback on unmanaged lands is counted as part of the land sink, or the net E_{LUC} flux can be defined to account only for fluxes associated with direct effects of human activity and to account for feedbacks as the residual terrestrial flux.

(2) ***The loss of additional sink capacity (LASC).*** Forests have large amounts of woody biomass and typically have a slower average turnover rate than managed land cover types with which they may be replaced, e.g. pastureland and cropland. An increase in biomass due to CO_2 fertilization would therefore be expected to lead to larger carbon stores and longer-term storage in forest than in non-woody managed vegetation. Thus, upon deforestation this possibility of surplus storage following an increase in atmospheric CO_2 is lost and leads to a "loss of additional sink capacity" (LASC) and a higher calculated E_{LUC}. To quantify the LASC, changes in productivity due to environmental changes have to be compared for managed land with a hypothetical situation where that particular land had not been converted, i.e. when it would be covered with "potential natural vegetation".

Note that the bookkeeping models exclude the land use feedback and the LASC, whereas the DGVMs account for the LASC but include the land use feedback with S_{LAND}.

Friedlingstein et al. (2020) further describe the loss of additional sink capacity due to historical land use change. They describe how ignoring the LASC introduces negative bias to DGVM-based estimates of E_{LUC}.

> Historical land-cover change was dominated by transitions from vegetation types that can provide a large carbon sink per area unit (typically, forests) to others less efficient in removing CO_2 from the atmosphere (typically, croplands). The resultant decrease in land sink, called the "loss of additional sink capacity", can be calculated as the difference between the actual land sink under changing land cover and the counterfactual land sink under pre-industrial land cover. This term is not accounted for in our GCB estimate.
>
> Here, we provide a quantitative estimate of this term to be used in the discussion. Seven of the DGVMs used in Friedlingstein et al. (2019) performed additional simulations with and without land-use change under cycled pre-industrial environmental conditions. The resulting loss of additional sink capacity amounts to 0.9±0.3 GtC yr^{-1} on average over

> 2009–2018 and 42±16 GtC accumulated between 1850 and 2018. OSCAR, emulating the behaviour of 11 DGVMs, finds values of the loss of additional sink capacity of 0.7±0.6 GtC yr−1 and 31±23 GtC for the same time period (Gasser et al., 2020).

Arneth et al. (2017) describe key processes that are excluded by DGVMs, resulting in biases in DGVM-based estimates of E_{LUC}.

> Until recently, most processes related to land management and the sub-grid-scale dynamics of land-use change have been ignored in large-scale assessments of the terrestrial carbon balance. We argue that including these missing processes – shifting cultivation (SC), wood harvesting (WH), grazing and crop harvesting (GH) and more realistic cropland management processes (MC) – might systematically increase the magnitude of E_{LUC}.
>
> When ignoring the additional land-use processes investigated here, average E_{LUC} is 119 ± 50 PgC. Adding effects of SC, wood harvesting WH, grazing and crop harvesting GH and more realistic cropland management processes MC enhance land-use-change emissions by, on average, 20–30% each, with individually large uncertainties.
>
> The combined effects of SC, WH, GH, and MC on E_{LUC} are difficult to judge as DGVMs do not yet account for all of these factors. For instance, SC and WH effects are expected to enhance E_{LUC} additively as there is little overlap in the input dataset used by DGVMs regarding the areas that are assumed to be under SC, and areas where other types of forest harvesting occur7. But in the case of accounting for harvesting and other management on arable lands and pastures, carbon cycle interactions with SC and WH cannot be excluded because subsequent transitions could occur in a grid location, between primary vegetation and cropland, pastures or secondary forests. The overall enhancement of E_{LUC} therefore, will need to be explored with model frameworks that include all dynamic land-use-change processes.
>
> DGVMs currently contributing to the annual update of the GCB account for some of the processes examined here, but as of yet not at all comprehensively, and we thus expect DGVM-based E_{LUC} to increase substantially compared to results reported therein (Le Quéré et al., 2015).

Wilkenskjeld et al. (2014) had earlier evaluated the bias resulting form exclusion of sub-grid scale land cover transitions, including shifting cultivation, in DGVMs.

> Using the land carbon model of MPI-ESM, CBALANCE, this study demonstrates that ignoring subgrid-scale LULCC conversions like shifting cultivation leads to much lower E_{LUC} than when such conversions are included (gross LULCC). In the four studied scenarios (historical, RCP2.6, RCP4.5 and RCP8.5), the cumulated E_{LUC} estimates are lowered by 85, 40, 2.4 and 30 Pg C (Table 2), corresponding to ignoring emissions of 0.54, 0.32, 0.02 and 0.42 Pg C yr−1, respectively on average.

Gross transitions need more input data. Accurate historical information on LULCC is scarce and thus Hurtt et al. (2011) applied a rather coarse and static map of the location of shifting cultivation (mostly in the tropics) and assumed a fixed period for which agricultural land is cultivated before it is again abandoned (15 years). In reality the extent and cycle period of shifting cultivation is strongly dependent on location and time. Hurtt et al. (2011) assesses the uncertainty of the LULCC data by testing a large ensemble of different assumptions, resulting in a large range of converted areas (both net and gross). Despite the uncertainties associated with existing data sets of LULCC and their assumptions on subgrid-scale conversions, it is known that shifting cultivation plays a role in global agriculture and therefore the estimates of E_{LUC} from the net transitions are highly likely to be underestimated.

Gasser et al. (2020) evaluated the bias in bookkeeping estimates of E_{LUC} due to ignoring the LASC.

Our experimental setup allows for the investigation of several factors within OSCAR that affect the spread in our global results: Over the last decade, the difference between including and excluding the LASC corresponds to a debiased 1σ range of ±0.43 PgC yr−1 and a coefficient of variation (CV) of ±25%. This rather substantial value is in line with previous studies that quantified this discrepancy (Gasser and Ciais, 2013; Stocker and Joos, 2015). Because the LASC only became non-negligible in the recent past, the effect of its inclusion or exclusion on cumulative LULCC emissions is smaller than for recent annual emissions: we estimate that it is only ±20 PgC (±9 %) over the 1750–2018 period. However, it is crucial to understand that the intensity of this discrepancy will keep increasing and accumulating as long as changes in environmental conditions do not stabilize (Gasser and Ciais, 2013).

3.2.3. Detail on Type III Issues (Spread across estimates)

Gasser et al. (2020) used a bookkeeping model to estimate the leading causes of spread in bookkeeping estimates of E_{LUC} forced by different datasets for land cover change. Bookkeeping models using different land cover change input datasets give considerably different estimates of E_{LUC}.

We find that the annual emissions from the two data sets are in particularly good agreement on average over the last decade (Table 3), although this is purely fortuitous as the discrepancy is ±0.30 PgC yr−1 (±24 %) over the 1995–2004 period and even peaks at ±0.39 PgC yr−1 (±34 %) in 1999. More worrying, perhaps, is the two data sets' disagreement on the trend in emissions after 1990.

Additionally, there is visible uncertainty among different versions of each of the two main data sets. We find that the difference among several versions of the same data set is of the same order of magnitude as the difference between our two main data sets. For the LUH data set, this is explained by several factors, from the simple update of the historical land cover data used as input to the complete overhaul of how shifting cultivation is estimated.

An additional important factor of uncertainty is the parameterization of carbon densities in different bookkeeping models. Using our Monte Carlo ensemble, we find a weighted standard deviation of ±0.40 PgC yr−1 (±29 %) for annual emissions averaged over the 2009–2018 period and of ±55 PgC (±27 %) for emissions cumulated over the 1750–2018 period. Carbon densities (and the parameters determining them) are the key modeling factors explaining this spread. The variation caused by the parameters that relate to harvest wood products is found to be one order of magnitude smaller than the total uncertainty caused by all parameters, confirming that biogeochemical parameters explain most of the uncertainty.

Bastos et al. (2020) further investigated the impact of differences in carbon stocks and allocation used in two bookkeeping models on the spread of E_{LUC} estimates from those models.

The rules for allocation of displaced carbon to different pools have the strongest effect on average E_{LUC}, as well as their variability, but they appear to affect mainly recovery fluxes. That global E_{LUC} curves 1850-2015 of BLUE and HN2017 show better agreement is a consequence not of making temporal dynamics in highly dynamic regions more similar, but of the fact that the C density and allocation parameterizations of HN2017 dampen the effect of land-use change dynamics. In particular, differences between BLUE and HN2017 arise from the higher allocation of cleared and harvested material to quickly decomposing pools in BLUE, compared to HN2017, combined with higher emissions in BLUE due to often larger differences in soil and vegetation C densities between natural and managed vegetation or primary and secondary vegetation. It should be noted however that specific transitions and prevalence of specific PFTs in certain regions prohibits generalizing this statement. Together with the larger land-use dynamics which stem from BLUE representing gross transitions and its usage of LUH2v2.1 as LUC forcing, these changes lead to overall higher carbon losses that have a faster decay.

The parameterization of C densities of vegetation and soil pools is the second most relevant parameter, but one that affects all flux components. Even though both models were parameterized based on observation-based C densities, these parameters are highly uncertain, as they are derived from sparse plot-level data with high variance across datasets. The large contribution of the C densities to the differences between the E_{LUC} estimates of the two BK models found in our results highlights the importance to derive spatially explicit maps of vegetation and soil C densities discriminated per vegetation type would be required. Producing such maps is challenging, especially for the estimates of C densities in undisturbed land, as most of the land surface has been directly or indirectly impacted by human activity. However, observation-based maps of vegetation and soil C densities in both disturbed and undisturbed land would be highly valuable, as they could be used in BK models to reduce uncertainties in E_{LUC}.

Similarly, improvements in allocation can be performed. Bookkeeping models, and many DGVMs, follow very simple assumptions of the fate of cleared or harvested material, which distinguishes only three product pools (fast, medium, slow) with timescales defined rather ad-hoc as 1, 10, 100 years. The fractions going into these and into slash are compiled from individual studies for specific regions, but are hard to quantify on the global level throughout several centuries. Such long timescales are needed, however, to capture the slow dynamics of decay and regrowth and thus to capture legacy fluxes accurately. For the last decades, however, more detailed data has become available than that currently used in the models of the Global Carbon Budgets, such as global sets of dynamic carbon-storage factors that define a larger number of product pools and time-varying fractions of allocation.

3.3. Land Sink (S_{LAND})

3.3.1. Summary

Summary from (Peters et al., 2017b):

Variability in the land sink is estimated from terrestrial ecosystem models driven by observed changes in environmental conditions. However, understanding of the land sink is limited by the lack of spatially explicit observations of changes in carbon in vegetation and soils (Arneth et al., 2017). Major improvements can come from systematic benchmarking of these models against the increasing availability of observations of key components of the biosphere (for example, biomass, productivity, and leaf area), and also taking advantage of emergent constraints from atmospheric CO2 data to reduce uncertainties in the sensitivity of fluxes to climate variability, CO2, and nutrients (Anav et al., 2013; Wenzel et al., 2016).

Updated perspective from (Friedlingstein et al., 2020):

The assessment of the net land–atmosphere exchange derived from land sinks and net land-use change flux with atmospheric inversions shows a substantial discrepancy, particularly for the estimate of the total land flux over the northern extra-tropics in the past decade. This discrepancy highlights the difficulty to quantify complex processes (CO_2 fertilization, nitrogen deposition, N fertilizers, climate change and variability, land management, etc.) that collectively determine the net land CO_2 flux. Resolving the differences in the Northern Hemisphere land sink will require the consideration and inclusion of larger volumes of observations.

3.3.2. Detail on Type II (Biases) and Type III Issues (Spread)

Wenzel et al. (2016) advanced knowledge of the CO_2 fertilisation effect – the change in S_{LAND} caused by a doubling of atmospheric CO_2 – estimated by coupled DGVMs, by following an emergent constraints approach. This emergent constraint can be used in future to understand

if DGVMs are producing sensible estimates of increase in S_{LAND} under an increasing atmospheric concentration of CO_2. The DGVMs show a range of CO_2 fertilisation effects which appear also in the GCB as spread amongst the DGVM estimates of S_{LAND} (a *Type III issue*). However, the DGVMs also show a collective bias towards underestimation of the CO_2 fertilisation effect under enhanced CO_2 (a *Type II issue*).

> Uncertainties in the response of vegetation to rising atmospheric CO_2 concentrations contribute to the large spread in projections of future climate change. Climate–carbon cycle models generally agree that elevated atmospheric CO_2 concentrations will enhance terrestrial gross primary productivity (GPP). However, the magnitude of this CO_2 fertilization effect varies from a 20 per cent to a 60 per cent increase in GPP for a doubling of atmospheric CO_2 concentrations in model studies.
>
> Here we demonstrate emergent constraints on large-scale CO_2 fertilization using observed changes in the amplitude of the atmospheric CO_2 seasonal cycle that are thought to be the result of increasing terrestrial GPP.
>
> Our comparison of atmospheric CO_2 measurements from Point Barrow in Alaska and Cape Kumukahi in Hawaii with historical simulations of the latest climate–carbon cycle models demonstrates that the increase in the amplitude of the CO_2 seasonal cycle at both measurement sites is consistent with increasing annual mean GPP, driven in part by climate warming, but with differences in CO_2 fertilization controlling the spread among the model trends.
>
> As a result, the relationship between the amplitude of the CO_2 seasonal cycle and the magnitude of CO_2 fertilization of GPP is almost linear across the entire ensemble of models. When combined with the observed trends in the seasonal CO_2 amplitude, these relationships lead to consistent emergent constraints on the CO_2 fertilization of GPP.
>
> Overall, we estimate a GPP increase of 37 ± 9 per cent for high-latitude ecosystems and 32 ± 9 per cent for extratropical ecosystems under a doubling of atmospheric CO_2 concentrations on the basis of the Point Barrow and Cape Kumukahi records, respectively. These emergent constraints therefore give a consistent picture of a substantial CO_2 fertilization effect and point to the need for further improvements in the treatment of nutrient limitations in ESMs.
>
> *In this study, four of the seven models gave CO_2 fertilisation estimates of less than 25%, indicating a bias towards the low end of the full range of estimates for CO_2 fertilisation amongst current DGVMs. In addition, the same four models all included nitrogen limitations and appear to underestimate CO_2 fertilization (<25%), especially for the extratropical domain.*

Cox et al. (2013) advanced knowledge of the sensitivity of tropical S_{LAND} to climate as simulated by coupled DGVMs, by following an emergent constraints approach. The new emergent constraint can be used in future to understand if DGVMs are producing sensible estimates of

S_{LAND} under changing temperatures. Tropical S_{LAND} shows a range of sensitivities to climate across the DGVMs, which appear also in the GCB as spread amongst the DGVM estimates of S_{LAND} (a *Type III issue*). However, the DGVMs also show a bias whereby tropical S_{LAND} is excessively sensitive to warming (a *Type II issue*).

The release of carbon from tropical forests may exacerbate future climate change, but the magnitude of the effect in climate models remains uncertain. Coupled climate–carbon-cycle models generally agree that carbon storage on land will increase as a result of the simultaneous enhancement of plant photosynthesis and water use efficiency under higher atmospheric CO_2 concentrations, but will decrease owing to higher soil and plant respiration rates associated with warming temperatures.

At present, the balance between these effects varies markedly among coupled climate–carbon-cycle models, leading to a range of 330 gigatonnes in the projected change in the amount of carbon stored on tropical land by 2100. Explanations for this large uncertainty include differences in the predicted change in rainfall in Amazonia and variations in the responses of alternative vegetation models to warming.

Here we identify an emergent linear relationship, across an ensemble of models, between the sensitivity of tropical land carbon storage to warming and the sensitivity of the annual growth rate of atmospheric CO_2 to tropical temperature anomalies.

The observed IAV in the growth rate of global atmospheric CO_2 was compared with the IAV in the annual mean tropical temperature. Aside from the years immediately after the volcanic eruptions of Mount Agung, El Chichon and Mount Pinatubo, the IAV in the growth rate of atmospheric CO_2 is linearly correlated with the IAV in the tropical temperature (r = 0.65 (correlation coefficient), P,0.0001; Fig. 2b), with a best-fit 'IAV sensitivity' of 5.1±0.9 GtC yr-1 K-1.

Combined with contemporary observations of atmospheric CO_2 concentration and tropical temperature, this relationship provides a tight constraint on the sensitivity of tropical land carbon to climate change. We estimate that over tropical land from latitude 30 north to 30 south, warming alone will release 53±17 gigatonnes of carbon per kelvin.

A similar calculation is made for each of the coupled climate–carbon-cycle models, to derive the sensitivity of the CO_2 growth rate to tropical temperature for the period 1960–2010. Compared with the observational data, models tend to overestimate the IAV in the tropical temperature by a factor of up to two, and to overestimate the IAV in the CO_2 growth rate by a factor of up to three. The correlation between these variables is underestimated in some models (F, B and D) and overestimated in others. Hence, IAV sensitivity varies across the C4MIP model ensemble, from 2.9±1.4 GtC yr-1 K-1 (model F) to 9.7±0.7 GtC yr-1 K-1, with most of this range resulting from differences in the sensitivity of heterotrophic respiration to climate. The application of the IAV constraint reduces the estimated probability of loss of >100 GtC K-1 from tropical land stocks, typically associated with models that project CO_2-induced tropical forest dieback, by almost two orders of magnitude from 21% to 0.24%.

Compared with the unconstrained ensemble of climate–carbon-cycle projections, this indicates a much lower risk of Amazon forest dieback under CO_2-induced climate change if CO_2 fertilization effects are as large as suggested by current models.

Mercado et al. (2009) identified diffuse radiation as a missing factor that should be considered by DGVMs. Changes in cloud cover and atmospheric aerosol can influence the quality of the light available for plant photosynthesis.

Plant photosynthesis tends to increase with irradiance. However, recent theoretical and observational studies have demonstrated that photosynthesis is also more efficient under diffuse light conditions. Changes in cloud cover or atmospheric aerosol loadings, arising from either volcanic or anthropogenic emissions, alter both the total photosynthetically active radiation reaching the surface and the fraction of this radiation that is diffuse, with uncertain overall effects on global plant productivity and the land carbon sink. Here we estimate the impact of variations in diffuse fraction on the land carbon sink using a global model modified to account for the effects of variations in both direct and diffuse radiation on canopy photosynthesis. We estimate that variations in diffuse fraction, associated largely with the ‘global dimming’ period, enhanced the land carbon sink by approximately one-quarter between 1960 and 1999. However, under a climate mitigation scenario for the twenty-first century in which sulphate aerosols decline before atmospheric CO2 is stabilized, this ‘diffuse-radiation’ fertilization effect declines rapidly to near zero by the end of the twenty-first century.

3.3.3. Detail on Type III Issues (Spread)

Zaehle et al. (2005) systematically analysed the sensitivity of a DGVM to its parameterization and evaluate the resulting uncertainty in model outcomes. They evaluated the relative importance of different parameters for determining model estimates of net primary production (NPP).

This study focuses on the uncertainty in process-based terrestrial biosphere models due to imperfect knowledge (or implicit uncertainty) of the “correct” parameter values used in scaled representations of ecosystem processes, and aims at providing quantitative information about the confidence that can be placed in model results.

Of the 36 parameters included in the survey only few have an overriding influence on the modeled terrestrial biosphere dynamics. In particular, LPJ-DGVM shows little sensitivity to many of those parameters whose “correct” values, in the absence of suitable measurements, are particularly uncertain, for example, several parameters describing allometry, stand structure, and fire dynamics. Parameters that contribute most to overall model uncertainty are those controlling net assimilation rate and water exchange.

The most important parameters controlling NPP are the intrinsic quantum efficiency for C3 plants, which influences the amount of energy available for GPP, and the parameter αa, which primarily accounts for photosynthetically active radiation (PAR) absorbed by non-photosynthetic structures (e.g., branches) and thus lost to canopy photosynthesis. Of secondary importance are the shape parameter θ, controlling the degree of co-limitation by light and Rubisco activity in the Farquhar photosynthesis scheme, and the canopy light extinction coefficient, kbeer, which determines the shape of the relationship between canopy leaf area index (LAI) and the fraction of incoming PAR absorbed by the canopy. Parameters governing autotrophic respiration (Ra) have also notable, though less pronounced, effects on annual NPP.

The uncertainty range of NPP is of a similar magnitude to the range among models reported from model inter-comparison studies. This suggests that these differences might to a large extent be associated with parameter-based uncertainty. Since NPP is the major driving force for plant performance and vegetation dynamics, parameters that influence NPP have a strong influence on the overall ecosystem dynamics simulated by the model. NPP plays the dominant role in determining the sizes of the various C pools in equilibrium.

3.4. Ocean Sink (S_{OCEAN})

3.4.1. Summary

Summary from (Peters et al., 2017b):

> Our understanding of the ocean sink is limited primarily by the insufficiency of physical, chemical and biological observations that would allow for quantitative understanding of the causes of inter-annual to decadal variability (DeVries et al., 2017; Fay and McKinley, 2014; Landschützer et al., 2015). To reduce the uncertainty in the ocean sink and quantify its variability sufficiently so as to make a material contribution to the five-year-or-less detection goal, two types of observations are critical: an optimized system of long-term, sustained observations to directly monitor the ocean carbon sink, and targeted field studies that elucidate critical processes driving inter-annual to decadal variability. These observations will allow both for direct estimation of the sink and support improvements in model-based estimates.

Updated perspective from (Friedlingstein et al., 2020):

The assessment of the Global Ocean Biogeochemistry Models (GOBMs) used for S_{OCEAN} with flux products based on observations highlights a substantial discrepancy in the Southern Ocean (Hauck et al., 2020). The long-standing sparse data coverage of pCO_2 observations in the Southern compared to the Northern Hemisphere (e.g. (Takahashi et al., 2009)) continues to exist (Bakker et al., 2020) and to lead to substantially higher uncertainty in the S_{OCEAN} estimate for the Southern Hemisphere (Watson et al., 2020). This discrepancy points to the need for increased high-quality pCO_2 observations, especially in the Southern Ocean. Further uncertainty stems from the regional distribution of the river flux adjustment term being based on one model study yielding the largest riverine outgassing flux south of 20◦ S (Aumont et al., 2001), with a recent study questioning this distribution (Lacroix et al., 2020). The data products suggest an underestimation of variability in the GOBMs globally and, consequently, the variability in S_{OCEAN} appears to be underestimated.

Further updated perspective from (Hauck et al., 2020):

There is growing evidence and consistency among methods with regard to the patterns of the multi-year variability of the ocean carbon sink, with a global stagnation in the 1990s and an extra-tropical strengthening in the 2000s. GOBMs and data-products point consistently to a shift from a tropical CO_2 source to a CO_2 sink in recent years. On average, the GOBMs reveal less variations in the sink than the data-based products. Here we evaluate the GOBM simulations by comparing the simulated surface ocean pCO_2 to observations. Based on this comparison, the simulations are well-suited for quantifying the global ocean carbon sink on the timescale of the annual mean and its multi-decadal trend, as well as on the time-scale of multi-year variability, despite the large model-data mismatch on the seasonal time-scale.

Biases in GOBMs have a small effect on the global mean ocean sink, but need to be addressed to improve the regional budgets and model-data comparison. Accounting for non-mapped areas in the data-products reduces their spread (as measured by the standard deviation) by a third.

3.4.2. Detail on Type II Issues (Biases)

Watson et al. (2020) challenged the assessment of the mean ocean CO_2 sink based on data products, which they argue does not take into account the temperature at the point of measurement. When adding a correction for this, they calculate a net flux into the oceans by 0.8–0.9 PgC yr^{-1} larger than without the correction. Such a correction can reconcile surface uptake with independent estimates of the increase in ocean CO_2 inventory, and suggest most ocean models underestimate uptake, provided the river flux of carbon to the ocean is smaller than previously thought. This topic is currently debated in the ocean carbon cycle research community.

3.4.3. Detail on Type III Issues (Spread across estimates)

Hauck et al. (2020) did a detailed comparison of ocean process models and data products. They assess that the process-based model simulations are well-suited for quantifying the global ocean carbon sink on various time-scale: the annual mean, the multi-decadal trend, and the multi-year variability, despite the large model-data mismatch on the seasonal time-scale. There highlight:

- a growing evidence and consistency among methods with regard to the patterns of the multi-year variability of the ocean carbon sink, with a global stagnation in the 1990s and an extra-tropical strengthening in the 2000s.
- A consistent shift from a tropical CO_2 source to a CO_2 sink in recent years.
- less variations in the sink in GOBM at high latitudes compared to data-based products.

Finally, this synthesis paper confirms the need for “a game-changing increase in high-quality pCO_2 observations” and a re-evaluation of the regional river flux adjustment.

4. Synthesis: Biases and Uncertainty in the Carbon Budget

Here, we synthesise the dominant sources of Type II and Type III issues for each component of the GCB based on the information explored in Section 2. **Table 2** provides an efficient summary.

Table 2: A synthesis of Type II (bias) and Type III (spread of in the estimate) issues based on section 2.

Flux	**Key Biases (Type II Issues)**	**Key Sources of Spread in the Estimate (Type III)**
E_{FOS}	● Inclusion/exclusion of bunker emissions. ● Inclusion/exclusion of carbonation. ● Inclusion/exclusion of non-energy usus of fossil fuels. ● Underestimation of carbon content of Chinese coal.	● Different inventories use different energy datasets ● Frequent revisions to Chinese energy statistics. ● Uncertainty in emission factors. ● Emissions from US liquid fuels vary between inventories for unknown reasons.
E_{LUC}	● Exclusion of lost additional sink capacity (LASC) from bookkeeping models. ● Missing processes, especially sub-grid scale processes (e.g. shifting cultivation), especially from DGVMs.	● Uncertainty in records of land cover change, represented by differences across input datasets to both bookkeeping models and DGVMs. ● Uncertainty in vegetation carbon density and its allocation, represented by differences across bookkeeping models.
S_{LAND}	● Bias towards underestimation of the strength of the CO_2 fertilisation in DGVMs, relative to the likeliest range from emergent constraints. (particularly in models with strong nutrient limitation). ● Bias towards overestimation of the reduction of tropical S_{LAND} by climate warming in DGVM ensembles, relative to the likeliest range from emergent constraints.	● Wide spread of estimates of the strength of the CO_2 fertilisation effect in DGVM ensembles, relative to the likeliest range from emergent constraints. ● Wide spread of reduction in the tropical S_{LAND} by climate warming in DGVM ensembles, relative to the likeliest range from emergent constraints. ● Uncertainty in the parameter choices, particularly those controlling net assimilation rates and water exchange.
S_{OCEAN}	● Potential bias in the mean CO_2 flux estimated by data-based products caused by uncertainties in the river flux of carbon.	● The uncertainties in the assessment of variability in the CO_2 sink at high latitudes, particularly in the Southern Ocean,

4.1. Fossil CO_2 Emissions (E_{FF})

There are number of sources of bias (*Type II* issues) in estimates of fossil CO_2 emissions and these are principally related to boundary conditions, particularly with respect to the inclusion/exclusion of bunker emissions, carbonation emissions and non-energy use of fossil fuels (Andrew, 2020). Variability in boundary conditions is seen across different fossil CO_2 emission inventories, and such biases can largely be accounted for through harmonisation of estimates (Andrew, 2020). The

GCB estimates of E_{FF} are based on only one inventory of emissions, however the method is designed to include emissions from sectors or processes that are often excluded by other datasets such that issues with boundary conditions are avoided. The GCB's emissions estimates also adopt the higher carbon content of coal as derived by Liu et al. (2015), which avoids underestimation of CO_2 emissions by coal as seen in other datasets. Hence, significant effort has already been made to alleviate *Type II* issues from GCB estimates of E_{FF}.

Nonetheless, the GCB estimates of E_{FF} carry uncertainty based on *Type III* issues. After harmonizing the boundary conditions of the inventories, spread amongst inventory estimates is assessed as 5% globally and this is the value applied in the GCB (Andrew, 2020). The key *Type III* issues are the availability of different national energy statistics and use of different datasets by different inventories, the use of different emission factors (CO_2 per unit energy) by different datasets due to uncertainty in the optimal values, frequent substantial revisions of Chinese energy statistics and unattributed variability in emissions from US liquid fuels across datasets.

Moving forward, increasing the amount of data available with respect to the carbon content and emission factors for different fuels would be helpful, particularly if those data can be derived within increasing specificity within fuel groups (e.g. for different classes of coal). Prioritisation should be given to sub-classes of fuel that contribute most towards global emissions, in particular to support the weighting of emission factors by the sub-fuel mix used in China and other leading emitters (e.g. US, EU27 and India) would be particularly valuable. Eliminating other sources of spread in E_{FF} would likely require collaboration with national energy agencies and international providers of energy statistics to understand the reasons for discrepancy across datasets, rank conformity to existing best practice measures and identify best practice measures where necessary.

While proportional uncertainties in E_{FF} are smaller than in other components of the budget, absolute uncertainties remain large owing to the large magnitude of E_{FF}. Hence, taking action to reduce spurious spread of the estimates would provide real benefits to verification capacity.

4.2. Land Use Change Emissions (E_{LUC})

At present, land use change emissions are subject to the highest relative uncertainties of any term in the budget and this relates to a wide range of known biases and causes of spread amongst the estimates. Moreover, estimates of E_{LUC} can be derived from either bookkeeping models or DGVMs, which have different boundary conditions in terms of the processes they include. From the perspective of the GCB, the most important bias (*Type II* issue) relates to the exclusion of lost additional sink capacity (LASC) from bookkeeping models, since it is the central estimates from bookkeeping models that is used to construct the GCB (estimates from the DGVMs inform the uncertainty analysis only). The LASC refers to the additional sink that would have occurred on intact land if it had not been subject to land use change; the historical conversion of forest to agriculture means that the growth of S_{LAND} on intact land is lower than it would have been otherwise. Unlike the bookkeeping models, DGVMs estimates of E_{LUC} include the LASC

(Friedlingstein et al., 2020). The combination of bookkeeping estimates for E_{LUC} with DGVM estimates for S_{LAND} as part of the budget thus leads to a bias in carbon accounting, whereby the LASC is not included in either term (Friedlingstein et al., 2020).

Other key biases (*Type II*) affect DGVM-based estimates of E_{LUC}. In particular, the representation of sub-grid scale processes, including shifting cultivation, wood harvesting, grazing and crop harvesting and more realistic cropland management processes, strongly affects DGVM estimates of CO_2 because model resolution is coarse. These sub-grid processes drive large gross sources and sink of CO_2 that are not captured by most DGVMs. Sub-grid processes can be included in DGVMs based on uncertain assumptions tied to population and development, and this has been shown to increase estimates of E_{LUC} and increase the uncertainty of the flux estimate (Arneth et al., 2017). DGVMs contributing to the annual GCB increasingly include these additional processes, such that biases are being reduced incrementally through time.

A range of uncertainties in input data cause spread in both bookkeeping models and DGVM estimates of E_{LUC}. Both approaches are driven by gridded estimates of population and land cover change from historical records, and from satellite observations since the 1990s. A number of historical land use change records have been collated, and they differ strongly from each other in magnitude and trend. Bastos et al. (2020) have recently shown that differences between different versions of the same datasets can be equally as large as those between records. It is difficult to envisage the major reduction of uncertainties in past land use change in regions without major progress in methods for detecting and tracing historical land use change (e.g. isotopic analysis of soil or advances in archaeology).

Another important uncertainty that spans bookkeeping models is the carbon stock density applied to different land covers, as well as the allocation of that carbon stock across different vegetation pools with different rates of turnover. Moving forward, this uncertainty is more straightforward to address through increasing the number of observations of C stock densities and assessing spatio-temporal variability and its relationship with bioclimatic variables and human management practices. New lidar imagery is increasingly being used to quantify vegetation carbon stocks, dramatically increasing the volume of C stock density observations. Hence, there are positive signs that spread amongst bookkeeping estimates of E_{LUC} associated with uncertainty in carbon stock density will reduce in future.

The known biases and spread in the bookkeeping estimates of ELUC are quantified as part of the uncertainty assessment of the global carbon budget. ELUC has the largest absolute uncertainty of any flux, and presents serious challenges to the detection of trends in ELUC.

4.3. Land Sink (S_{LAND})

The land sink estimate derives from DGVMs capturing biological responses of ecosystems to increases in CO_2 concentration, increases in nitrogen availability, and changes in climate. *Type II* issues (biases) in the land sink relate to a collective tendency of DGVMs to underestimate the strength of CO_2 fertilisation and overestimate the sensitivity of tropical vegetation to climate warming. The underestimation of CO_2 fertilisation also tends to be strongest in those models with strong nutrient limitations. Consistent relationships between the amplitude of the CO_2 seasonal cycle and the magnitude of CO_2 fertilization of gross primary production (GPP) across models provide an emergent constraint on the impact of doubling CO_2 on plant productivity (+37 ± 9%), however the majority of models indicate a value below 25% (Wenzel et al., 2016). Meanwhile, relationships between the sensitivity of tropical land carbon storage to warming and the sensitivity of the annual growth rate of atmospheric CO_2 to tropical temperature anomalies are also seen across models. These relationships provide an emergent constraint on the sensitivity of tropical land carbon storage to warming of 5.1±0.9 GtC yr-1 K-1 (Cox et al., 2013). The DGVMs show a bias whereby tropical S_{LAND} is excessively sensitive to warming. The emergent constraints on CO_2 fertilisation and sensitivity of tropical land carbon storage to warming provide new resources for model benchmarking.

In future, there is an option to rank models according to their conformity to emergent constraints and use ranks to generate appropriate weightings across the ensemble. At present, the GCB benchmarks DGVMs against observable vegetation properties but does not include these key metrics of model dynamic performance. Moreover, weighting is not currently applied based on benchmarking and this additional step may improve the consistency of the GCB S_{LAND} estimate with observational constraints.

Spread in the DGVM estimates of S_{LAND} (*Type III* issues) derives from spread in the CO_2 fertilisation effect and the sensitivity of the tropical S_{LAND} to climate. Different models arrive at different estimates of CO_2 fertilisation effect and the sensitivity of the tropical S_{LAND} to climate because each uses a different set of parameter values that influence the biological response of vegetation responses to rising CO_2 concentrations and climate. Many parameter values in DGVMs are informed by field and experimental data, although some processes are less observable than others and carry large uncertainties. Zaehle et al. (2005) found that the parameters contributing most to overall parameter uncertainty in DGVM estimates of S_{LAND} are those controlling net assimilation rate and water exchange. Moving forward, a focus on modifying the parameter values of these parameters within their large uncertainty ranges might shift the modelled vegetation responses to CO_2 concentrations and climate responses to within the emergent constraints. Such efforts across the ensemble of DGVMs would be expected to reduce model spread in S_{LAND} and boost the compliance of models with emergent constraints.

4.4. Ocean Sink (S_{OCEAN})

The key limitations for the assessment of the ocean CO_2 sink were summarised in Friedlingstein et al. (2020) and are replicated here: the GOBMs used for estimating the ocean sink with flux products based on observations highlights substantial discrepancy in the Southern Ocean (both *Type II* and *Type III* issues). The long-standing sparse data coverage of pCO_2 observations in the Southern compared to the Northern Hemisphere continues to exist and to lead to substantially higher uncertainty in the assessment of the ocean sink estimate for the Southern Hemisphere. This discrepancy points to the need for increased high-quality pCO_2 observations especially in the

Southern Ocean. Further uncertainty stems from the regional distribution of the river flux adjustment term (*Type II* issues) being based on one model study yielding the largest riverine outgassing flux south of 20°S, with a recent study questioning this distribution. The data-products suggest an underestimation of variability in the GOBMs globally and consequently, the variability in ocean sink appears to be underestimated (*Type III* issues). The size of the underestimation of the amplitude of interannual variability (order of <0.1 GtC yr^{-1}) could account for some of the budget imbalance, but not all.

5. Discussion

Here we have reviewed the current capacity to detect a significant trend in atmospheric stock of CO_2 and attribute this trend to specific components of the global carbon budget on sub-decadal timescales. These two tasks are critical to verifying that a trend in atmospheric CO_2 is due to a specific element of the budget, such as a reduction in fossil CO_2 emissions. We summarise the current status in verification, recent progress and future outlook as follows.

5.1. Current Status of Verification

It is not currently possible to detect a significant trend in atmospheric stock of CO_2 and attribute this trend to specific components of the global carbon budget on sub-decadal timescales. The obstacles for verification fall under three categories.

First, interannual and quasi-decadal variability in the growth of atmospheric CO_2 is large due principally to real variability in the terrestrial and oceanic sinks for CO_2. Hence, a central trend in CO_2 must be either steep or maintained for some time before it can be detected through observations. We have not explored this at length here because it is not something that can be addressed through methodological change.

Second, known biases in the estimates of CO_2 sources and sinks contribute to imbalances between the observed and reconstructed growth rate of atmospheric CO_2. Reconstruction of the growth in atmospheric CO_2 stocks is dependent on independent estimation of four fluxes: emissions from fossil CO_2 and land use change, and sinks of CO_2 to land and ocean.

> The key biases affecting estimates of **fossil CO_2 emissions** relate to system boundaries as well as a potentially systematic underestimation of the carbon content of Chinese coal.
>
> The key known biases affecting estimates of **land use change emission** are the exclusion of thee lost additional sink capacity by bookkeeping approaches, while missing sub-grid scale processes introduce bias to estimates of land use change from process-based models.
>
> The key known biases in the **land sink** are a bias towards underestimation of the strength of the CO_2 fertilisation effect and towards overestimation of the sensitivity of tropical land sink to climate change.

The key known biases in the **ocean sink** are the underestimation of variability at high latitudes, particularly in the Southern Ocean.

Third, spread amongst different estimates of the same fluxes challenges the detection of trends in the central estimate. Reconstruction of each emission and sink flux relies on estimates from multiple models (or other estimation approaches), which are averaged to give a central estimate. The spread of these estimates introduces a margin of error around the multi-model mean. Spread results from variation in input data or model parameters used by each model, ultimately reflecting the uncertainty in the best value or parameter choices to be used in models that stems from variability in observations. Overall, spread in the estimate of all fluxes of the budget contributes to low confidence that a trend in GATM can be attributed to any particular sink or source.

Substantial variation in the magnitude of fossil CO_2 emission is seen across inventories due to differences in the energy statistics used by the inventories, as well as the carbon content of fuel and emission factors for fuel-technology combinations that each inventory adopts. Frequent revisions of energy statistics in China are a particularly large source of spread in emission estimates, both across inventories and between versions of the same inventory.

Spread in the estimate of land use change emissions is principally caused by poor constraints on the history of human land use during periods with limited regional land use records, and also by variability across different records even in periods that are well-covered by land use records. This affects both bookkeeping and process-based estimation of land use change emissions, as both use similar land cover datasets as a forcing. There is also variation in the carbon density of land covers that bookkeeping models adopt, which stems from observational uncertainty in carbon densities.

There is spread in process-based model estimates of the land sink as a result of parameter choices, particularly those controlling net assimilation of carbon and exchange of water by vegetation. Variable parameter selection likely contributes to the spread in the strength of the CO_2 fertilisation effect across process-based models, as well as the highly variable responses of tropical vegetation to climate across models.

There is spread in process-based ocean models that result from both the parameterisation of the physical processes and the resolution of the models, and of the way the ocean physical and biogeochemical processes respond to climate variability and other stressors. A step change in observations of pCO_2 in remote locations could help resolve some of the known issues. The response of marine ecosystems becomes more uncertain with a higher level of climate change and ocean acidification.

5.2. Progress and Outlook

There has been notable progress in resolving some of the sources of bias and spread that persist in components of the global carbon budget.

Notably, the forensic examination of system boundary issues related to fossil CO_2 emissions has allowed biases to be minimised and spread amongst the available inventories to be isolated (Andrew, 2020). Biases due to the known absence of processes have largely been incrementally removed in recent iterations of the global carbon budget. The uncertainty relating to input data alone is known robustly. Increasing the number of observations of the carbon content of fuel, with increasing specificity to fuel sub-classes, and of emission factors, with increasing specificity to fuel-technology combinations, would improve the information available to inventories and likely contribute to a narrowing of spread across the inventories.

Also, the application of an emergent constraints framework to process-based models of the land sink has provided a new lens through which to evaluate the feasibility of estimates by individual models (Cox et al., 2013; Wenzel et al., 2016). While the land sink shows a structurally similar response to atmospheric CO_2 concentrations and climate across models, the magnitude of the response varies considerably across models. By combining information across models and observations, emergent constraints have been used to identify a tighter range of the most feasible response of the land sink to atmospheric CO_2 concentrations and climate. This facilitates enhanced model benchmarking, encourages revision of parameters to improve conformity of model estimates with emergent constraints, and is ultimately expected to narrow the spread of estimates of the land sink. For the ocean, the availability of data-based estimates of the global ocean CO_2 sink since about five years means that we have a far better grasp on the variability of the ocean and on the remaining uncertainties. It becomes apparent that high-latitude regions are more variable than previously thought, and this could be a focus for future research.

In contrast, some sources of bias and uncertainty in the carbon budget are persistent and challenging to address. For example, process-based models of land use change emissions can be configured to include sub-grid scale processes that are known to be omitted and reduce negative bias; however, this occurs at the expense of additional uncertainty because information on sub-grid scale processes require assumptions that are poorly constrained by observations. Hence, there is a trade-off between including further processes and introducing spread to estimates from an ensemble of models taking different approaches to resolve the same process (Arneth et al., 2017).

Also with respect to land use change emissions, the increasing availability of vegetation carbon densities based on remote sensing is likely to improve the robustness and specificity of observational values and increase the volume of information available to bookkeeping models. This is expected to reduce some of the spread amongst models. On the other hand, it is difficult to envisage that major uncertainties in the historical reconstruction of land use during periods with patchy records will be alleviated without critical improvements in archaeological techniques and a major expansion of evidence stemming from those techniques. Such evidence will be required on sub-grid scales if observations are to support the wider employment of sub-grid processes in models while minimising additional spread across models.

6. Conclusions

While it is not possible to completely remove bias and spread from reconstructions of the global carbon budget, our review of the current status of verification capacity allows us to identify some key examples of progress in resolving these issues in recent years as well as opportunities for the future. We summarise the requirements, progress and future outlook for reducing bias and spread as follows.

First, it is critical to resolve known biases in each term of the budget. Known biases are present in all fluxes of the budget, and these contribute to imbalances between the reconstructed and observed growth rates of atmospheric CO_2. In the past, the systematic underestimation of fossil CO_2 emissions from Chinese coal has been addressed. On the other hand, the omission of the lost additional sink capacity from the carbon budget, caused by the combination of bookkeeping estimates for land use change emissions and process-based models for the land sink, has remained a persistent source of bias in the carbon budget. Additionally, the ensemble of process-based models systematically underestimate the response of the land sink to CO_2 fertilisation and overestimate the response of the tropical land sink to climate change. Emergent constraints are yet to be fully exploited through benchmarking or model weighting to reduce these biases in the land sink.

Second, it is necessary to incrementally gather the observational evidence required to reduce uncertainty in model parameter values. Increasing the volume and specificity of observations of fossil fuel carbon content and emission factors is key to reducing spread in inventory estimates of fossil CO_2 emissions. Likewise, increasing the volume and specificity of vegetation carbon densities is key to reducing spread in inventory estimates of land use change emissions. Recent progress in the remote sensing of vegetation is likely to significantly aid with this goal in the near future. Improving records of historical land use change is also critical to reducing the spread of land use change emission estimates, however progress is hampered by poor or patchy historical records of land use and sluggish improvements in the availability of archaeological evidence. Emergent constraints are likely to play a key role in the reduction of spread across models of the land sink, as the values of parameters that are most uncertain and most challenging to observe are expected to converge across models as modellers strive for better alignment with those constraints.

Overall, the capacity to verify changes in atmospheric CO_2 on sub-decadal timescales will require concerted effort to incrementally address the biases and uncertainties across all components of the budget.

7. Role of annual updates of the Global Carbon Budget in meeting the needs of the Stakeholder community

According to a commissioned report by strategic communications experts Young and Mengel (Appendix A) the annual update of the global carbon budget by GCP is in a unique position to support science to improve understanding of the carbon cycle and support the process of verification by communicating and networking with scientists, policymakers and the media. The GCP has a strong reputation as an authoritative voice amongst scientists and policymakers and can thus set the agenda of priorities for scientific investigation and the advocate funding of research in line with these priorities. The report proposes three avenues of science delivery:

- One is to stay in the purely scientific lane, making only incremental adjustments to what kind of data the project provides and how it communicates.
- A “middle ground” option would be about aligning GCB products with the needs of specific target audiences, including ones that are not the traditional core users of the project.
- The third option is a policy-impact-oriented approach that seeks to develop products focused on policy goals such as holding governments to account in their progress to decrease emissions.

The insights from the strategic communications report are providing a basis for discussions through the GCP community on how the scientific community should engage. This is particularly timely in the post-COVID period, where the very relationship between science and decision-making is shifting, with science playing an increasing central role in the specific design of national policies, and in the scrutiny of outcomes.

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9. Appendix A: The Global Carbon Budget in the decarbonization decade

This appendix is an external assessment by Young and Mengel strategic communications.

9.1. The policy and narrative context at a turning point

Since its launch in 2001, the Global Carbon Budget has succeeded in standardizing carbon budget reporting and becoming the go-to resource for up-to-date emissions figures used by both global media and relevant actors in the climate space.

Now, the policy context in which the GCB is operating is shifting significantly. Since 2018, the release of the 1.5C report, the Fridays for Future youth movement, a series of extreme weather events such as bushfires in Australia, California and Brazil, have moved the climate issue from being a niche technical concern to a mainstream political and societal issue. This is a major historic shift, which many sectors are still trying to catch up with in terms of literacies, governance, and strategy.

In the past two years, many countries have also embraced ambitious, long-term climate coals. Furthermore, with peak emissions expected to arrive soon, the world is entering a new narrative arc where the GCB’s key messages will move from urgency about increasing emissions to charting and validating progress on emissions reductions.

Similar thoughts echo in a recent article by David-Wallace Wells. He writes that the Biden victory “signals an effective end to the age of denial and the probable beginning of a new era of climate realism”. Journalist Akshat Rathi (one of the survey respondents) also wrote that the Biden victory sends “a strong sign that climate action is starting to be ‘institutionalized’, meaning that it is getting deeply embedded into how the world works.

An additional question to consider is the relationship between the annual COP meetings and the GCB. It is likely that the COPs will become less political and more technical in nature, and this means news organizations will be less inclined to send high profile reporters to cover them. The Montréal Protocol is an example of how after the conclusion of the political process the “media moment” was over and implementation has been a relatively low-key, technical affair.

This is a timely moment to ask questions about the role, relevance, and the future of the GCB. The high credibility and legitimacy of the GCB as a go-to resource creates potential to build on this reputation with new products and services.

Based on our analysis of the GCB’s current and future policy context as well as our stakeholder survey, we believe that the GCB has three options available:

- One is to stay in the purely scientific lane, making only incremental adjustments to what kind of data the project provides and how it communicates.

- A “middle ground” option would be about aligning GCB products with the needs of specific target audiences, including ones that are not the traditional core users of the project.
- The third option is a policy-impact-oriented approach that seeks to develop products focused on policy goals such as holding governments to account in their progress to decrease emissions.

9.2. Option 1: the Scientific Lane

9.2.1. Products

Introduction

This direction builds on the success of the past 15 years and takes into account the likelihood that there won’t be significant injections of new funding or resources. It adjusts the data production and communications products to the new policy context and the latest technological developments.

It remains true to the original purpose of the GCP which is to increase knowledge and communicate that knowledge, via the media for the most part, without differentiating clearly among different user groups, or customizing to their needs.

There is an opportunity to meet an increasing demand for new datasets, by:

- making data more accessible to audiences,
- increasing transparency around uncertainties and models,
- setting a regular schedule for the release of a methane budget,
- providing more information on sinks and sources.

The risk in this approach is that media coverage and interest will decline over time as emissions decline and the sense of urgency around global emissions erodes.

Be a data provider to news websites

The GCB could partner with news organizations to be the trusted data provider for climate dashboards and build an API to automate the process of updating these. Many media have started adding climate dashboards to their websites (e.g. Bloomberg Green , Süddeutsche Zeitung , Der Spiegel).

Being the data provider for news websites’ climate dashboards will bring additional exposure especially to the general public but will bring with it the challenge to update the budget more frequently and to maintain the technical platform.

Create a real-time climate data dashboard

A key communication challenge for the GCB is that there is actually no “safe” budget for remaining below 1.5°C or below any target. The uncertainties around how the climate will react to any given number of emissions is just too high. At the same time, the 1.5°C target is of high political value to some communities and in the NGO space.

Interactive data visualization could be key to communicating these uncertainties. The GCB could develop a new dashboard — for example an updated Global Carbon Atlas — that better communicates uncertainties and probabilities. For example, such a product could allow users to explore uncertainties by adjusting a slider with a desired goal of e.g. limiting climate change to 1.5°C, with a 25% chance of success, and see the remaining carbon budget? It could also create opportunities to improve understanding of carbon sinks.

Examples of such live dashboards have emerged during the Covid-19-pandemic. One of these is the German vaccination dashboard, http://impfdashboard.de . This updates daily to provide key numbers and visualizations on how the vaccination campaign is progressing.

A dashboard for the GCB could include messages like "at current rate of emissions, we lock in 0.1°C of warming every X years"; "we'll hit GHG neutrality in the year X"; "by that time, sea level will have risen by x cm".

In the medium term, the dashboard and the GCB website should merge to become one, as running both in parallel creates potentially confusing user journeys and stretches resources.

Refresh the GCP website

The current website is suffering from organic growth over the timeline of the project, with projects and information added over time with little attention dedicated to the overall structure and information hierarchy. This results in difficult navigation and the need to invest additional resources to make users aware of existing content. Taking a more user-centric approach would help create a shift over time towards building new channels of real time engagement, that are also searchable as an archive.

Themed quarterly updates

One way to sustain media interest might be to publish themed quarterly updates. These could cover topics such as:

- Methane
- Land use change
- Sinks and sources

9.2.2. Metrics

In this approach, the metrics used to measure success will be largely similar to what is already in place: Media reach, social media reach, etc.

9.3. Option 2: The user-centric lane

9.3.1. Introduction

This approach would, while staying mostly in the realm of data provision, create custom products for specific stakeholder groups ranging from policy to business and finance.

In a way, this already happens naturally. For example, on Twitter, Glen often shares emerging data trends and his followers frequently ask for more analysis, interpretation of the data, they want the policy implications of that data. Another example is Corinne’s appearance in the Carbon Brief webinar on the first COVID emissions data and policy implications.

There is an opportunity to develop a more user-centric approach, one that is contextually adjusted to a changing policy environment and narrative.

The risk in this approach is that:

- This would stretch the resources of the GCB or would require additional funding and/or humans.

- It requires going beyond “business as usual” to engage deeply with stakeholder groups to understand their needs and design products that are fit for their purposes.

9.3.2. Products

Launch an open repository where users can log requests for data or analysis

This is an idea that emerged from our survey of GCB users and stakeholders. One of the respondents suggested creating an online open-source repository on a platform like Github or a similar online repository. Users could then open issues and suggest ideas for visualizations or log data needs. Depending on the platform used, other users could vote for the suggestions that seem most pertinent.

A PI would then accept a project and respond with a publication.

Verbatim quote from the survey respondent:

"Crazy idea: have an open-source github repository (or other shared online repo), and allow people to open issues and suggest ideas (e.g. Analysis or visualisation, directly in the code).

Instead of having a limited number of authors, be open to more. Of course, a PI will still have to accept each suggestion."

Embrace more channels for dissemination of GCB messages

An important first step in moving to a more user-centric approach is to embrace the ongoing shift away from websites to more direct, tailored forms of communication with users. Overall, fewer and fewer users satisfy their information needs by visiting websites, rather, they tailor their information flows by subscribing to specialist newsletters, podcasts or Youtube channels. In the last few years, podcasts and newsletters have become popular formats because they help cut through information overload yet help people get smarter about a topic they are passionate about.

The GCB could channel its rapidly expanding knowledge base by building custom products that enable users to add the GCB's messages to their regular information diet by subscribing to e.g. a podcast, newsletter or video channel.

Such products would raise the users' level of knowledge about climate change and climate data and, when done right, can also help increase understanding of the user base through feedback received from the distribution channels.

Example 1: Develop a climate data newsletter, for a generalist audience

One example of a product in this vein would be a climate data explainer product that builds on the existing GCB resources and also on Glen's heavy Twitter activity, however that is focused on an audience with less prior knowledge of climate, modeling and data. For example, the finance and business communities have an increasing need for evidence to support shifts to greener activities and supply chains.

Such a product could take the form of a weekly newsletter written in an accessible style for policy and business audiences - explaining trends in climate change that are emerging from the latest data. A popular platform for all kinds of newsletters right now is Substack - see the Sinocism and Volts newsletters for examples that dive deeply into a particular subject.

Example 2: Run a climate data explainer Youtube channel

An advantage of a video channel rather than e.g. a podcast, would be that it allows users to look at the charts being discussed in real time. There are great examples of data explainer videos, especially the ones created by the late Hans Rosling.

There is an opportunity here for one of the project's PIs to be the host of such a channel, and co-host with younger scientists as a way to build outreach capacity for the next generation.

Become an agenda-setter on underreported data

In the coming decade, there will be increasing demand for all different types of climate data. For example, as "disclosing climate risk" eventually becomes standardized financial reporting, the business and finance communities will have increased data needs.

While the GCB may not have any interest in aligning with these heavy corporate processes, it will inevitably have an agenda-setting function by signalling new areas and data sets that are important scientifically but may not yet be on the radar of the corporate worldview.

For example, a regular Methane budget release will send a signal that they need to consider how to report on this.

9.3.3.Metrics

Measuring usefulness to stakeholder groups will require a combination of quantitative and qualitative metrics. It will also involve a more complex process of setting targets and of developing ways of meaningfully measuring progress towards these, for example by conducting surveys in target groups, but also collecting qualitative and even anecdotal evidence.

Quantitative metrics - for example on usage of particular products - would complement the qualitative metrics but should not be regarded in isolation.

This combination of metrics will enable a deeper understanding of the GCB’s role in the climate change space than just simple quantitative metrics like media reach or website usage statistics.

9.4. Option 3: The advocacy lane

9.4.1. Introduction

With very little effort, the Global Carbon Atlas could be changed to show a “scorecard” of how well each country progresses towards its declared emissions reduction goals, thus naming and shaming the laggards. This would change completely how the Global Carbon Budget is used and perceived.

There is an opportunity to become a much more active partner in the policy process to:

- Hold governments to account and be a data source to monitor whether or not national policies are on track.
- Have a bigger impact on the actual reduction of emissions.

The risk in this approach is that:

- perceptions of the GCB could shift towards it being perceived as somewhat activist.

This is echoed in the survey responses, with some respondents supporting the idea of providing more policy analyses quite strongly, and others feeling equally strongly that this would fall outside of the GCB’s remit.

9.4.2. Products

A Global Carbon Atlas refocused on policy impact

The Global Carbon Atlas could be refocused to support specific goals for change. For example, if the goal of GCB communications becomes to push governments to increase their ambition in emissions reduction, the Global Carbon Atlas could show the above mentioned scorecard where the difference between stated ambitions, actual reductions and global climate goals is made evident.

9.4.3. Metrics

This approach would require thinking backward from a specific target - e.g. getting government X to adjust their ambitions to Y - and thinking back from there, developing products that can help others to put pressure on said government.

9.5. Survey Findings

9.5.1. Our process

To inform our work on the GCB's potential for evolution, we designed an informal survey collaboration with the GCB leadership and Katharine Mansell of the GSSC. It invites respondents to provide input on four fundamental questions:

- How do you use the Global Carbon Budget in your work? For you, is it a data set, a scorecard, a source of a narrative, a source of policy analysis, or something else? What is unique about it?
- What would you like to see more of from the Global Carbon Budget?
- How satisfied are you with the yearly communication of the Global Carbon Budget? What could the Global Carbon Budget do to better communicate its work? Are there any specific products you would like to see?
- Should the Global Carbon Budget continue to publish on an annual basis, or should it evolve into a process of continuous policy advice and dialogue? If the latter, please elaborate how such a process could usefully work?

The survey also asked respondents to self-identify as belonging to a field of work such as media, academia, policy, NGO, etc. This survey was sent to mailing lists of the GSSC, GCB, to personal contacts, and was also shared on Twitter. A total of around 115 users responded to the survey.

Of the respondents, roughly 70% were from academia. In order to not have the results skewed uniquely towards this group, we provide separate analyses for the academia group and for other stakeholders such as media, civil society, and policy. We label these as 'scientists' for the former and 'users' for the latter.

9.6. Perceptions of the GCB

9.6.1. Users

An overwhelming majority of respondents emphasise that they come to the GCB for reliable and authoritative data. Its provenance from an independent, scientific network is what also sets it apart from some of the competing sources of emissions data.

Words used to describe the GCB were: authoritative, reference, trustworthy, reliable, yardstick.

However, there were also a few voices that said they see the GCB as a source of a narrative for moving towards zero emissions.

9.6.2.Scientists

Academia respondents mostly perceive the GCB as a reference data set. Many respondents use GCB materials for teaching or for public talks. This applies especially to the figures and the data, but some also say they use it as a source of a narrative.

One respondent said that they formulate research directions based on GCB data, another said that it helps placing their research in context. Another uses the data as a target for designing climate models.

Words used to describe the GCB were: credible, important, unique, comprehensive, reputable, useful.

9.7. Needs and demands

9.7.1. Users

Several respondents express a desire for more and more frequent and timely policy analysis from the GCB. One respondent suggested “policy analysis that can be used to explain the statistical findings.” Another affirmed that “we are in the decade for delivery and governments need to be held accountable.”

One responding journalist pointed out that the media are increasingly interested in emissions & carbon budget implications of political/energy/macro stories, and suggested more frequent analysis to aid reporters with this kind of work.

Further requests include quarterly updates for key emitters such as China or India.

9.7.2. Scientists

There is a clear frontrunner among scientists on what they want to see more of: data on carbon sinks. A key stated reason for this is that without a deeper understanding of how carbon sinks react to future emissions it will be difficult to estimate trajectories or to calculate the amount of negative emissions technology needed. Detailed data on carbon sinks would also help better understand countries’ net-zero policies that use carbon sinks.

There was some support for more policy analysis, but also dissenting voices cautioning that this would not play to the strengths of the GCB and stretch its resources too widely.

9.8. Communications

9.8.1. Users

Several respondents complimented the animated bucket GIF and suggested more output in a similar vein. Additional responses suggested a basic slide deck or video explaining the key findings in an accessible way, suggesting that the current 90+ page slide deck may be somewhat too complex for these users.

One respondent, who is working in China, points out that the political and economic reality there is quite different. More specific analysis and policy recommendations that's tailored for China would thus be needed for additional impact.

9.8.2. Scientists

Respondents from academia express a high level of satisfaction with GCB communications and are particularly enamored with the slide deck: "The slide deck you produce each year is terrific." They use figures from the slide talks for teaching and public talks.

One respondent however thinks that "the figures can be improved quite a lot, in presentation and also being more easily reproducible" and says that they would be happy to provide additional feedback on this. (gerbrand.koren@wur.nl).

Some respondents suggest improvements may be possible in making the communications of the GCB more accessible to a generalist audience by providing background information on models & terminology, putting more emphasis in communications products on parametric uncertainty in the models. This could also mean producing a different slide deck for a more generalist audience.

Another respondent proposes going beyond static 2D graphics towards web based visualisation, interactive use of datasets and models, suggesting that this would be more attractive to a generalist audience, and adds that "[o]pen-source, transparency and accessibility will be key for next generations of scientific collaboration and communication to politics and the public."

Other suggestions include: translating the GCB slides into other languages, doing an explainer video, communicating more at the national level, adding more data sources, explaining uncertainties.

9.9. Publication schedule and process

9.9.1. Users

Overall, respondents favour the annual publication schedule, or at least an emphasis on an annual event to drive media coverage. However, some see the value in supplementing this with a more continuous reporting and publication of data, one respondent even going so far as suggesting a long-term goal of providing real-time data.

More granular data was also cited as a need, especially on cities, sectors, companies .-and finding new ways of visualising this data.

9.9.2. Scientists

A majority of respondents favoured maintaining the annual publishing schedule, saying that publishing more frequently could dilute or lessen its importance, as well as its media impact: “I think your messaging would be diluted if you went into continuous policy advocacy.”

A few were in favour of mid-term reviews, citing the 2020 paper on impact of COVID-19 on emissions as an example. This was also suggested once as a model that would allow maintaining the current annual schedule while still reacting flexibly to opportunities to complement the annual publication with important data on emerging trends.

One responded suggested quarterly updates coordinated with a revamped IPCC process. Another pointed out that the annual publishing schedule is useful as it bridges the gaps between IPCC reports.

9.10. Anything else you would like to share?

9.10.1. Users

One respondent pointed out that the website is not very clear for those looking for the current data/estimates on the carbon budget. Design & navigation/architecture changes could improve this a lot.

9.10.2. Scientists

There were two suggestions that the GCP/TRENDY should become more inclusive and open. The first suggested that the scientists involved in creating the models used in the creation of the GCB do not receive enough credit in the publication and suggests taking a cue from the fields of genetics or field ecology to develop more inclusive authorship strategies. The second suggests the GCB should support the shift to more open and reproducible science by publishing data proactively, for example the underlying model output of the GCB’s annual estimate of the global terrestrial sink.

9.11. Outlook: Developing a new narrative

As we described in our introduction, the shifting policy and narrative context for the GCB makes the year 2021 the perfect moment to be the first to move in defining a new narrative about global emissions that preempts the already emerging efforts (in the media, within the GSSC) to craft new messages beyond 1.5°C. This requires examining the overall messaging and framing of the GCB’s communications, including the publication of a “budget”.

As we understand from conversations with GCB researchers, the budget framing is popular with journalists but is difficult from both a scientific and a communications perspective. On the one hand, the uncertainties around the remaining budget for any given target are extremely high. On the other, publishing a fixed budget for emissions that are "safe" to emit risks locking in those emissions, when in reality, every fraction of a degree of global warming is one too many.

One respondent to our survey, Sabine Fuss, made a similar comment on the importance of policy analysis supporting decarbonisation efforts:

"Comparison of emissions trends only will not be enough in the future, different decarbonisation pathways will have different implications for sinks and it is in my opinion time to move away from a focus on science-based targets (like temperature goals), which can be a real distraction from the needed transformation. I had an argument with a journalist about the SR1.5 budget being too high, as AR6 is expected to come out somewhat lower again. But whether we have 2-3 years more or less to reach net zero does not make the big difference. You still have to do all the same things like coal exit, preparing for at least some CDR, etc. This is where we have to concentrate more efforts in my opinion."

Our recommendation is that the GCB convene a workshop to develop a new narrative in a systematic and user-centric way, taking into account the high political sensitivity of the question. It is important to consider how to frame such a new narrative so it does not sound like the scientific community is "giving up" on saving small island states, or handing a "get out of jail free" card to politicians who can now decarbonize at their own pace. The output of the workshop could then be developed into a commentary in Nature or Science, a policy statement or a white paper outlining the GCB's vision for the future.