Towards real-time verification of CO_2 emissions

The Paris Agreement has increased the incentive to verify reported anthropogenic carbon dioxide emissions with independent Earth system observations. Reliable verification requires a step change in our understanding of carbon cycle variability.

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Emissions of CO_2 from fossil fuels and industry did not change from 2014 to 2016, yet there was a record increase in CO_2 concentration in the atmosphere[1]. This apparent inconsistency is explained by the response of the natural carbon cycle to the 2015–2016 El Niño event[2], but it raises important questions about our ability to detect a sustained change in emissions from the atmospheric record. High-accuracy calibrated atmospheric measurements, diverse satellite data, and integrative modelling approaches could, and ultimately must, provide independent evidence of the effectiveness of collective action to address climate change. This verification will only be possible if we can fully filter out the background variability in atmospheric CO_2 concentrations driven by natural processes, a challenge that still escapes us.

Recent changes in the carbon cycle

The atmospheric CO_2 increases of nearly 3 ppm in both 2015 and 2016 were record highs, raising the concentration to 402.8 ± 0.1 ppm in 2016 (ref. [1]). During the same period, CO_2 emissions from fossil fuel and industry remained approximately constant[3]. The much smaller but more variable CO_2 emissions from land-use change were higher than average in 2015, due to increased fires at some deforestation frontiers[4,5]. Total CO_2 emission[3] (fossil fuels, industry, and land-use change) grew 1.1% in 2015 to a record high of 41.5 ± 4.4 billion tonnes, and declined 2.1% in 2016 (Fig. 1). Despite the increase in total CO_2 emissions in 2015, the record high increase in the atmospheric CO_2 concentration in 2015 and 2016 occurred primarily due to a reduction in the uptake of carbon by terrestrial ecosystems in response to hotter and drier conditions associated with the 2015–2016 El Niño event[2], similar to past El Niño events[6].

We project global fossil fuel and industry emissions to increase by about 2.0% (0.8–3.0%) in 2017, based on increased emissions in China of 3.5% (0.7–5.4%), decreased emissions in the US of –0.4% (–2.7–1.9%), increased emissions in India of 2.0% (0.2–3.8%) and in the rest of the world of 1.9% (0.3%–3.4%) (ref. [3]). The increased fossil fuel and industry emissions technically bring an end to the three years of approximately constant emissions that persisted from 2014 to 2016. Land-use change emissions in 2017 should be similar to their 2016 level[5], based on fire observations using satellite data. When combining CO_2 emissions from fossil fuels, industry, and land-use change, we project 2017 global emissions to be 41.5 ± 4.4 billion tonnes of CO_2, similar to 2015 levels. Even though the projected 2017 emissions match those of the record year in 2015, they are not expected to increase atmospheric CO_2 concentration as much as in 2015 because of reinvigorated carbon uptake in natural reservoirs after the 2015–2016 El Niño event (Fig. 1).

Variability limits verification

CO_2 entering the atmosphere from combustion of fossil fuels, industrial processes, and land-use change is either absorbed by the carbon 'sinks', namely oceans (~25%) and land (~30%), or retained in the atmosphere (~45%). While measurements of atmospheric concentrations have low uncertainty, the attribution of concentration changes from year-to-year to specific sources and sinks is plagued by large uncertainties[3]. These uncertainties, combined with the inherent inter-annual to decadal variability in the land and ocean sinks, limit our ability to independently verify reported changes in fossil fuel and industrial emissions.

One indicator of our ability to verify global CO_2 emissions is the number of years required to detect a change in the trend of atmospheric concentration after a sustained change in global emissions takes place (Fig. 2). To quantify this detection delay, we use a well-established simple carbon-cycle model[7] to project future atmospheric concentrations for different emission trajectories without natural inter-annual variability (Fig. 2). We estimate atmospheric concentrations for three different emission trajectories: sustained growth of 1% per year, approximately consistent with the current pledges to the Paris Agreement[8], constant emissions as observed from 2014 to 2016, and an arbitrary sustained reduction of 1% per year.

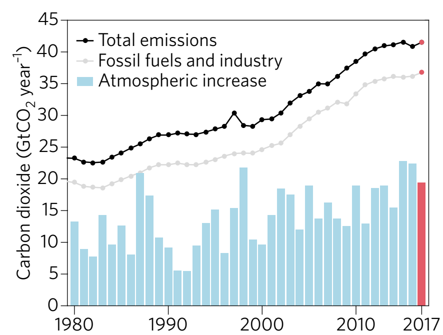

Fig. 1 | Trends in CO_2 emissions and atmospheric CO_2 concentrations. Even though CO_2 emissions from fossil fuel and industry, and total emissions including land-use change, have been relatively flat from 2014 to 2016, atmospheric concentrations saw a record increase in 2015 and 2016 (bars) due to El Niño conditions. We expect CO_2 emissions to grow in 2017 (red dots), but we expect the growth in atmospheric concentrations (red bar) to be lower in 2017 compared to 2015 and 2016, in the absence of an El Niño event.

Our current capability to detect a change in emissions trajectory is captured by the difference between observed and reconstructed historical atmospheric concentration changes (Fig. 2). The reconstructed atmospheric growth is the difference between the reported emissions from fossil fuels, industry, and land-use change, and the estimated land and carbon sinks from models[3]. Over the observational period, the difference between observed and reconstructed concentrations changes, which we call the carbon budget imbalance[3], has zero mean over the 1959–2016 period, but has large variability of ±3 billion tonnes CO_2 per year (one standard deviation). With sustained changes in emission trajectories from 1% per year to 0% per year, it may take 10 years to distinguish the different emission trajectories using atmospheric observations

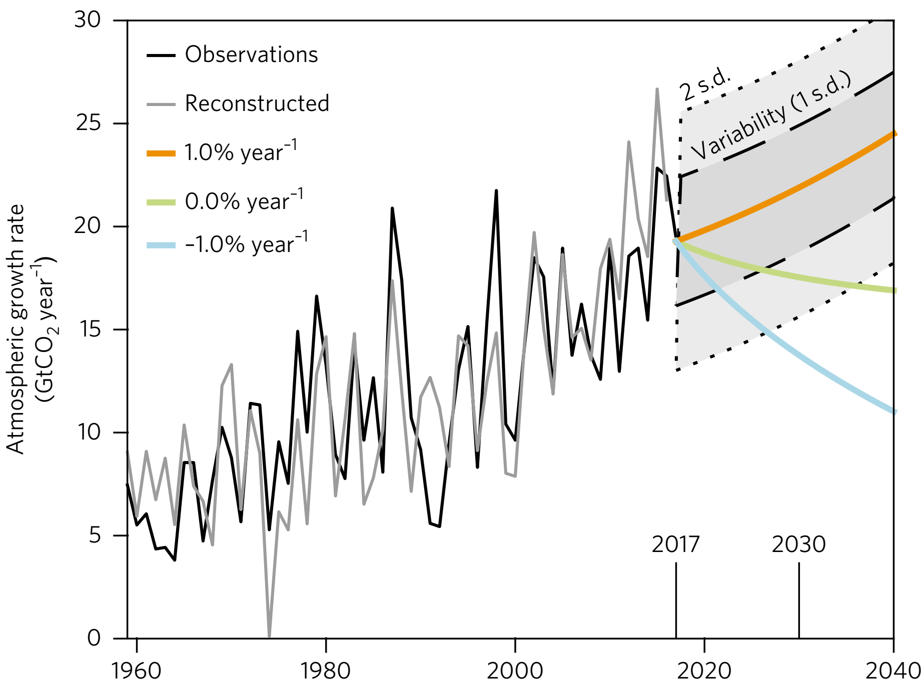

Fig. 2 | Our current ability to detect sustained changes in CO_2 emissions based on atmospheric CO_2 observations. Observations show a large inter-annual to decadal variability (black), which can be only partially reconstructed through the global carbon budget (grey; growth rate diagnosed by difference between estimated fossil fuel and industry emissions, and the simulated land and ocean sinks[3]). Our limited ability to fully reproduce the observed variability is quantified through the budget imbalance[3] (the difference between the black and grey lines). The budget imbalance has zero mean over the 1959–2016 period, but the standard deviation (3 $GtCO_2$ 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.

and carbon cycle models with a probability of 68% (Fig. 2). This detection delay is too long to inform the stocktake of the Paris Agreement, which occurs every five years.

Steps to reduce key uncertainties

A step-change in our ability to understand and quantify the inter-annual to decadal variability in emissions and sinks of CO_2 is needed before reported emissions can be challenged by Earth system observations. On top of continuous atmospheric measurements essential for verification, we propose several ways to better constrain each component of the global carbon budget.

Emissions from fossil fuels and industry. 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[10]. 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[9,10]. Economic growth and new policies will play an important role in determining short-term emission pathways[10]. Emission uncertainty persists at the country level[11], limiting our ability to accurately understand emission trends and drivers[10]. Considerable improvements are needed in estimating recent emission trends and their drivers, particularly in rapidly emerging economies and developing countries. High-precision measurements of $^{14}CO_2$ could quantify, objectively and transparently, the contribution of fossil and biogenic CO_2 sources[12].

Emissions from land-use change. Whereas emissions from land-use change are only about 10% of the global anthropogenic total, land-use change emissions are highly uncertain[3]. 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[13]. 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[13,14].

Land sink. 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[13]. 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 emerging constraints from atmospheric CO_2 data to reduce uncertainties in the sensitivity of fluxes to climate variability, CO_2, and nutrients[15,16].

Ocean sink. 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[17–19]. 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.

Now that we see signs of a sustained change in emission trajectory away from the high growth rates of the first decade of this millennium, independent verification of global emissions takes on a new imperative. Providing independent verification in the context of the Paris Agreement, with its global stocktake every five years, leads to a new urgency for the scientific community to focus on reducing key uncertainties and quantifying natural variability in all components of the carbon cycle so that it can collectively meet the demands of policymakers and society. ❐

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Author contributions

G.P.P., C.L.Q., and J.G.C. designed the research; G.P.P. made Fig. 1; G.P.P., C.L., P.F., F.J. made Fig. 2. All authors analysed the data, figures, and contributed to the text.

Competing interests

The authors declare no competing financial interests.

Reassessing emotion in climate change communication

Debate over effective climate change communication must be grounded in rigorous affective science. Rather than treating emotions as simple levers to be pulled to promote desired outcomes, emotions should be viewed as one integral component of a cognitive feedback system guiding responses to challenging decision-making problems.

Daniel A. Chapman, Brian Lickel and Ezra M. Markowitz

David Wallace-Wells' *New York Magazine* article describing the possible devastating impacts of climate change has reignited an increasingly heated debate among researchers, advocates, and commentators over the pros and cons of 'doom and gloom' messaging in climate change communications[1]. Some prominent scientists have pushed back against the article in part arguing that such pessimistic coverage depresses and demoralizes the public into further inaction[2]. Others have praised the piece for its honest portrayal of the challenges we face while highlighting the potential for such writing to induce strong emotional responses in readers, such as fear, anger and resolve[3].

Both camps in this debate refer to affective science to support their conclusions and recommendations. Yet, both positions reflect misuse and misunderstanding of what the evidence does and does not tell us about the effects of targeting specific emotions — especially fear and hope — in motivating or inhibiting public engagement with climate change. The bifurcation between 'go positive' and 'go negative' simultaneously oversimplifies the rich base of research on emotion while overcomplicating the very real communications challenge advocates face by demanding that each message have the right 'emotional recipe' to maximize effectiveness.

Rather than treat emotion as a lever or switch to be directly calibrated and pulled for a desired effect, the climate change communication community should adopt a more nuanced, evidence-based understanding of the multiple and sometimes counterintuitive ways that emotion, communication and issue engagement are intertwined. Emotions should be viewed as one element of a broader, authentic communication strategy rather than as a magic bullet designed to trigger one response or another.

Emotions are not simple levers

In the on-going debate over the effectiveness of emotional climate change appeals, emotions have largely been treated as simple levers communicators can pull to obtain specific goals. For example, some