Towards real-time verification of carbon dioxide emissions

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The Paris Agreement has raised 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.

Emissions of carbon dioxide (CO_2) from fossil fuels and industry were flat from 2014 to 2016, yet there was a record increase in CO_2 concentrations in the atmosphere[1]. This apparent inconsistency is explained by the response of the natural carbon cycle to the 2015/2016 El Niño[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 modeling 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 increase of nearly 3 parts per million in both 2015 and 2016 were record highs, raising the concentration to a level of 402.8±0.1ppm in 2016[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 in some deforestation frontiers[4,5]. Total CO_2 emission[3] (fossil fuels, industry, land-use change) grew 1.1% in 2015 to a record high of 41.5±4.4 billion tonnes CO_2, and declined 2.1% in 2016 (Figure 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], as seen in past El Niño events[6].

We project fossil fuel and industry emissions to increase by about 1.8% [0.9% to 2.9%] in 2017, based on increased emissions in China of 3.5% [0.7% to 5.4%], decreased emissions in the US of -0.3% [-2.8% to +2.2%], and increased emissions in India of 1.4% [-0.9% to +3.7%] and in the rest of the world of 1.6% [-0.9% to +3.7%][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. Fire observations using satellite data suggest land-use change emissions in 2017 should be similar to their 2016 level[5]. 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 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 (Figure 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 ocean (about 25%) and land (about 30%), or retained in the atmosphere (about 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 interannual 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 (Figure 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 interannual variability (Figure 2). We estimate atmospheric concentrations for three different emission trajectories: sustained growth of 1%/yr, approximately consistent with the pledges to the Paris Agreement[8], constant emissions as observed from 2014 to 2016, and an arbitrary sustained reduction of 1%/yr.

Our current capability to detect a change in emissions trajectory is captured by in the difference between observed and reconstructed historical atmospheric concentration changes (Figure 2). The reconstructed atmospheric growth is the difference between the reported emissions from fossil fuel, 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 but is large at ±3 billion tonnes CO_2 per year (1 standard deviation). With sustained changes in emission trajectories from 1%/yr to 0%/yr, it may take 10 years to distinguish the different emission trajectories using atmospheric observations and carbon cycle models with a probabililty of 68% (Figure 2). This detection delay is too long to inform the five yearly stocktake of the Paris Agreement.

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 summed over countries with declining emissions (e.g., US and Europe) and those with rising emissions (e.g., China and India), also between declines in coal and growth in renewables, partially offset by growth in oil and natural gas[9]. 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: The variability in the land sink is estimated from terrestrial ecosystem models driven by observed changes in environmental conditions. However, the 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 (e.g., biomass, productivity, 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 interannual 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: (1) an optimized system of long-term, sustained observations to directly monitor the ocean carbon sink, and (2) targeted field studies that elucidate critical processes driving interannual 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 2000's, independent verification of global emissions takes on a new imperative. Providing independent verification in the context of the Paris Agreement, with its five-yearly stocktake cycle, 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 policy makers and society.

Acknowledgements

This work was possible thanks to substantial contributions by many scientists and funding agencies that supported the Global Carbon Budget 2017 compiled by the Global Carbon Project. G.P.P., R.M.A., J.I.K. acknowledge the support of the Norwegian Research Council (project number 209701). J.G.C. acknowledges the support of the NESP-Earth Systems and Climate Change Hub. F.J. acknowledges support from the Swiss National Science Foundation (#200020_172476). P.F. acknowledges support from the European Commission Horizon 2020 project CRESCENDO (grant no. 641816).

Author contributions

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

Additional information

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Competing financial interests

The authors declare no competing financial interests.

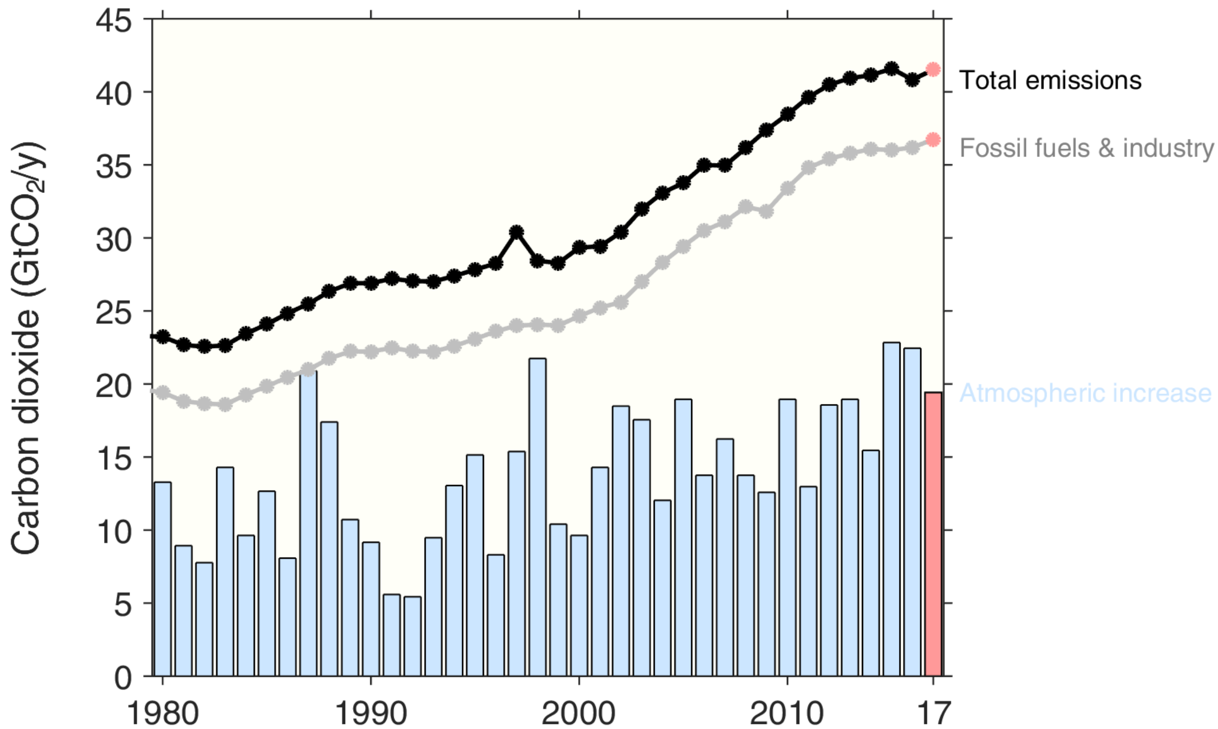

Figure 1: Even though CO_2 emissions from fossil fuel and industry, and total emissions including land-use change, have been relatively flat from 2014 to 2016, atmospheric concentrations saw a record increase in 2015 and 2016 (bars) due to El Niño conditions. We expect CO_2 emissions to grow in 2017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

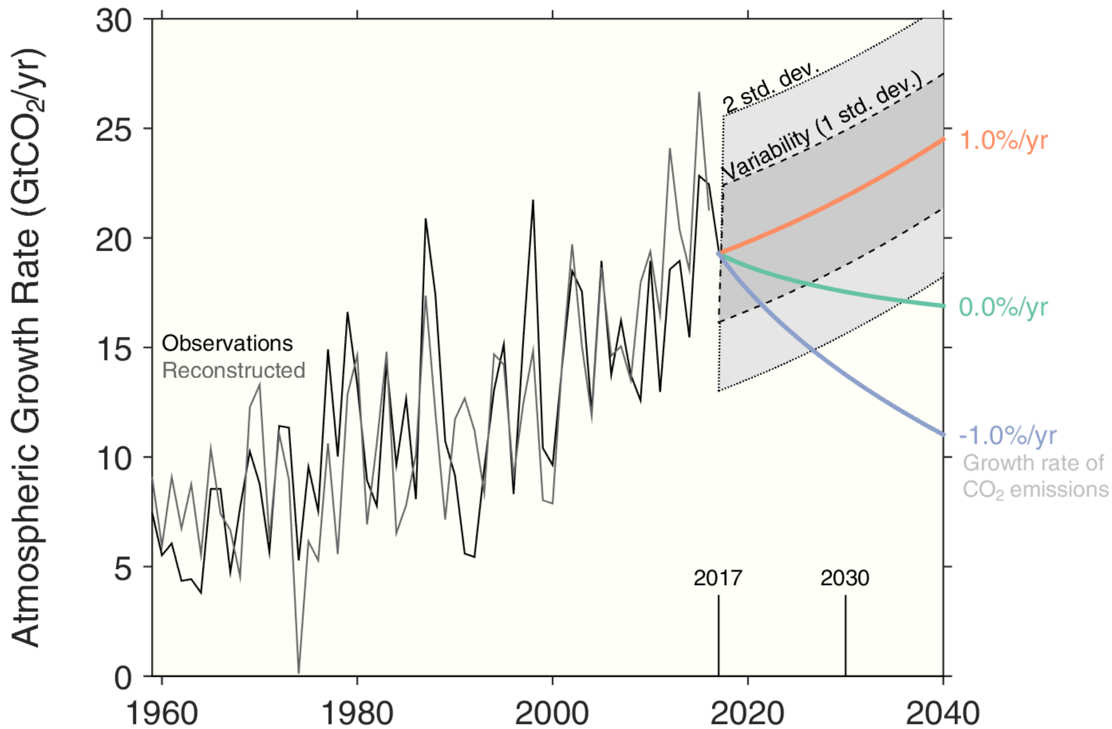

Figure 2: The observed atmospheric CO_2 growth rate compared to reconstructions. Observations show a large interannual to decadal variability (black), which can be only partially reconstructed through the global carbon budget (grey, growth rate diagnosed by difference between estimated fossil fuel and 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, but the standard deviation (3$GtCO_2$/yr) is used here to illustrate our current detection delay (grey bands). If CO_2 emissions stay flat for the next decades (green, 0%/yr growth), then it may take take 10 years before the estimated atmospheric concentrations would exceed the budget imbalance with a probability of 68% or more (and therefore it could be detected) compared to a pathway of atmospheric concentrations consistent with growth in CO_2 emissions (orange, 1%/yr 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%/yr), then a more marked change in atmospheric growth would be expected, and a much earlier detection.

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