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A. P. Ballantyne, P. Ciais, J. B. Miller

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Cautious Optimism and Incremental Goals Toward Stabilizing Atmospheric CO_2

A. P. Ballantyne[1,2], **P. Ciais**[2], **and J. B. Miller**[3]

[1]Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT, USA, [2]Laboratoire des Sciences du Climat et de l'Environnement, Gif Sur Yvette, France, [3]National Oceanographic and Atmospheric Administration, Boulder, CO, USA

Key Points:

- Emissions of fossil fuels to the atmosphere appear to have leveled off at 36 billion tons of CO_2 per year
- The atmospheric growth rate of CO_2 has reached record levels of ~3 ppm/year
- In order to ultimately stabilize the concentration of atmospheric CO_2, it is first necessary to stabilize the atmospheric CO_2 growth rate

Correspondence to:
A. P. Ballantyne,
apballantyne@gmail.com

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Abstract Fossil fuel emissions of CO_2 to the atmosphere appear to have leveled off in recent years; however, atmospheric CO_2 concentrations continue to rise. Our simple analysis shows that peaks in the growth rates of human population and fossil fuel emissions have been observed, but the growth rate of atmospheric CO_2 has reached record levels and shows no indication of peaking. Before atmospheric CO_2 concentrations can be stabilized at safe levels, a peak in the CO_2 growth rate must be achieved.

Plain Language Summary Stabilizing the concentration of CO_2 in Earth's atmosphere is one of the most daunting challenges to humanity. Despite recent evidence indicating that fossil fuel emissions of CO_2 have stabilized at approximately 35 billion tons a year, atmospheric growth rates of CO_2 have reached record levels of nearly 3 parts per million per year. Before we can ultimately stabilize the concentration of atmospheric CO_2, we must first stabilize its growth rate.

1. Introduction

One of the greatest challenges currently facing humanity is the stabilization of atmospheric CO_2. While we currently possess the technological know-how to stabilize and reduce CO_2 emissions (Pacala & Socolow, 2004), it remains a daunting task, due to significant social, political, and economic challenges to deploying this technology (Davis et al., 2013). Recent evidence suggests that we are making progress toward a peak in fossil fuel (Jackson et al., 2015) and land use (Houghton & Nassikas, 2017) emissions due to "irreversible momentum towards green energy" (Obama, 2017). However, ultimately Earth's radiative budget is controlled by atmospheric concentrations of greenhouse gases that are controlled by many processes. In order to stabilize atmospheric CO_2 concentrations, it is clearly necessary for anthropogenic CO_2 emissions to be reduced to 0 (Intergovernmental Panel on Climate Change, 2014). Just because emissions go to 0, however, does not necessarily mean that CO_2 concentrations will stabilize because atmospheric concentrations of CO_2 are controlled by many processes—not just emissions. Human beings have the capacity to directly regulate anthropogenic emissions, but Earth's natural carbon reservoirs cannot be directly regulated by humans. Thus, examining how the CO_2 atmospheric growth rate (AGR) has responded to recent changes in human population and fossil fuel emissions is a useful diagnostic for examining the state of Earth's carbon reservoirs.

Here we provide a simple analysis of human population, fossil fuel emissions, and atmospheric CO_2 concentrations. To diagnose how human population and anthropogenic emissions have interacted to affect the atmospheric CO_2 growth rate, we examine how their total quantities and their growth rates have changed over time. Lastly, based on the premise that a *peak* in any quantity is usually preceded by a peak in its growth rate (Deffeyes, 2008; Maggio & Cacciola, 2012), we search for peaks in these quantities and growth rates at global and regional scales. Lastly, we investigate the changing sensitivity of the atmospheric CO_2 growth rate to anthropogenic emissions and temperature and conclude with some policy implications (see section 4).

2. Results: Trends and Peaks in Human Perturbation of the Global Carbon Cycle

Although human population, fossil fuel emissions, and atmospheric CO_2 continue to increase, some of their growth rates appear to have peaked within the last five decades (Figure 1). According to the most recent census data (United Nations [UN], 2013), total human population reached approximately 7.4 billion people in 2016 (Figure 1a), but the population growth rate appears to have peaked in 1988 at 93 million people per

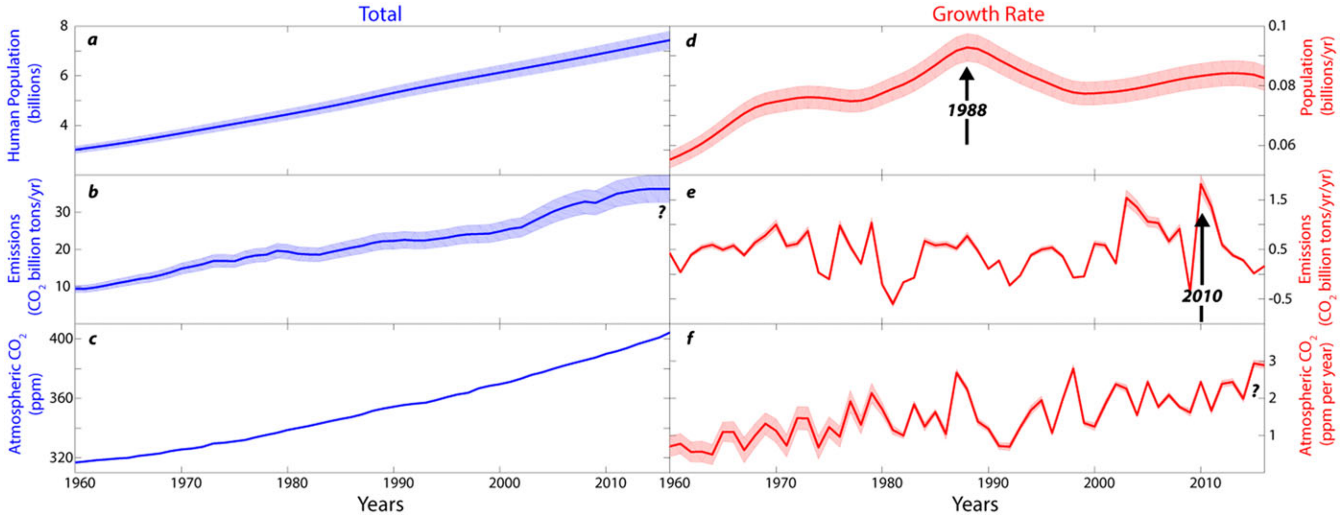

Figure 1. Comparison of human population, fossil fuel emissions, and atmospheric CO_2. The total amounts of human population (a), fossil fuel emissions (b), and atmospheric CO_2 (c) on left in blue, compared with their respective growth rates in red (d–f). Black arrows indicate apparent peaks in the human population growth rate in 1988 (d) and the emissions growth rate in 2010 (e) but with no evident peak in the growth rate of atmospheric CO_2 (f). Error envelopes on estimates represent 1σ error estimates for each quantity.

year (Figure 1d). While global emissions from fossil fuels have risen to 36.3 billion tons of CO_2 in 2016 (Figure 1b), the growth rate of fossil fuel emissions peaked in 2010 and has approached 0 in both 2015 and 2016 (Figure 1e). In contrast, atmospheric CO_2 concentrations reached an average of 404 ppm in 2016 (Figure 1c), and the AGR reached record levels with nearly 3 ppm of CO_2 added to the atmosphere in both 2015 (2.94 ppm/year) and 2016 (2.89 ppm/year; Figure 1f). Thus, we are cautiously optimistic that the growth rate of CO_2 emissions has reached its peak and that total emissions appear to be leveling off; however, there is no indication that AGR has yet to reach its peak.

While the long-term trend in CO_2 growth rate is best predicted by total emissions over the last 50 years (Betts et al., 2016), the sensitivity of interannual variability on decadal timescales can be sensitive to emissions (Peters et al., 2011) as well as temperature (Cox et al., 2013) and precipitation fluctuations (X. Wang et al., 2014). Indeed, if we examine the sensitivity of the interannual growth rate of CO_2 to temperature and emissions, we see notable decadal shifts in sensitivity (Figure 2). From 1960 to about 1985 the interannual AGR

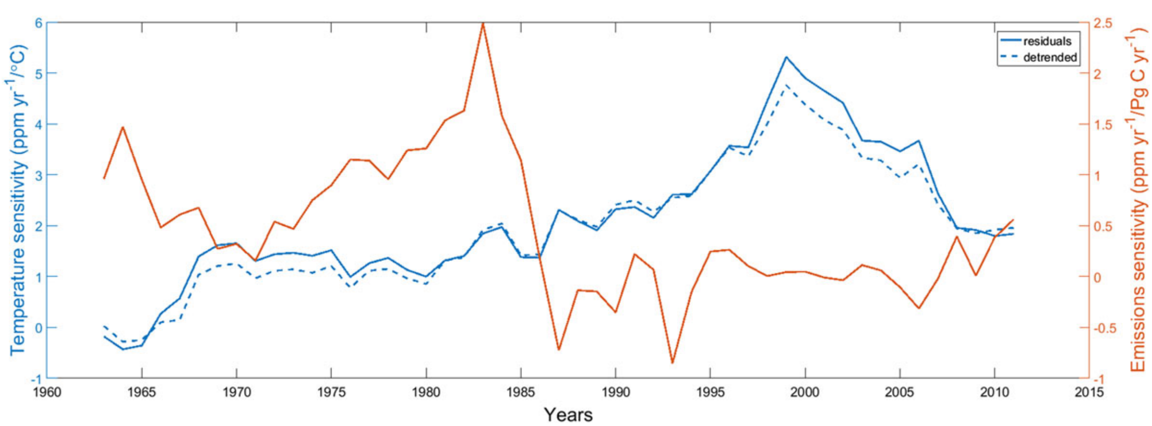

Figure 2. The sensitivities of the interannual growth rate of atmospheric CO_2 to temperature and emissions, where the interannual atmospheric growth rate of CO_2 has been obtained either as the residual of a linear fit (X. Wang et al., 2014; blue dashed) or as the residual from a linear regression with total emissions from fossil fuels and land use as a dependent variable (Le Quéré et al., 2015; blue solid). Total emissions have been detrended for calculating interannual CO_2 growth rate sensitivities (red line). Sensitivities of the interannual CO_2 growth rate to detrended land surface temperatures (Schmidt et al., 2009) and total emissions are calculated using a 10-year moving window, illustrating the greater sensitivity of CO_2 growth rate to total emissions in the first half of the record and greater sensitivity to temperature in the second half of the record.

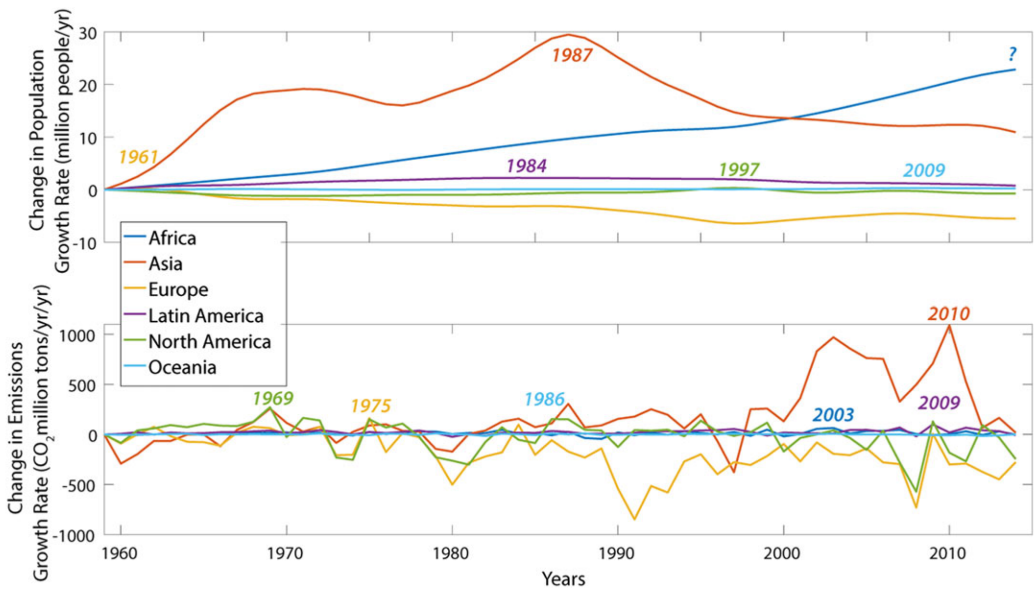

Figure 3. Changes in the growth rates of human population and fossil fuel emissions by region. Apparent peaks in the regional growth rate of human population (top) and fossil fuel emissions (bottom) normalized to 1959 are indicated by colored years in italics corresponding to regions (see legend).

was most sensitive to changes in emissions (Figure 2; red) and since then the AGR appears to be much more sensitive to temperature changes (Figure 2; blue). Thus, the apparent recent decoupling between the leveling off of emissions and continued rise in atmospheric CO_2 is most likely due to the sensitivity of terrestrial ecosystems to recent temperature and precipitation anomalies in 2015 and 2016 (Anderegg et al., 2015; Liu et al., 2017). Thus, long-term objectives of stabilizing atmospheric CO_2 concentrations below *dangerous levels* of atmospheric CO_2 (Hansen et al., 2008) can only be achieved by first reaching the short-term goal of stabilizing the growth rate of atmospheric CO_2, which shows no indication of peaking.

While peaks in the growth rates of human population and emissions have occurred at the global scale (UN, 2012), there is considerable variability in the relative peaks of growth rates at regional scales (Figure 3). In Africa, there is no indication that a peak in population growth rate has been observed; however, it is remarkable to note that a peak in the emissions growth rate occurred in 2003 (Figure 3; blue). In Asia, a peak in the population growth rate occurred in 1987 and a peak in emissions growth rate happened in 2010 (Figure 3; orange), but a peak in total emissions has yet to occur (Table 1). In Latin America, a peak in the population growth rate occurred in 1984 followed by a peak in the emissions growth rate in 2009 (Figure 3; purple), with absolute emissions appearing to have peaked in 2014 (Table 1). In North America (Figure 3; green), a peak in population growth rate occurred in 1997 and a peak in emissions growth rate happened in 1969, but nearly four decades passed before total emissions peaked in 2007. In Oceania (Figure 3; cyan) the population growth rate peaked in 2009 and the emissions growth rate peaked in 1986, with peak emissions occurring in 2009. In Europe peaks in population growth rate were observed in 1961 and followed by peaks in emission growth rates in 1975. It is also noteworthy that Europe is the only region in which peaks in both total human population have been observed in 1996 and total emissions in 1990 (Table 1). It is evident that the lag between peaks in the growth rate of emissions and peaks in absolute emissions have varied widely by region, from just 5 years in Latin America to almost 40 years in North America. While it is clear that at the global scale we have not reached peak emissions within 5 years of the peak in emissions growth rate that

Table 1
Peaks in Growth Rate and Quantity for Human Population, Fossil Fuel Emissions, and the Atmospheric Growth Rate at Regional and Global Scales

Region	Year PPGR	Year PP	Year PFGR	Year PF
Africa	?	?	2003	?
Asia	1987	?	2010	?
Europe	1961	1996	1975	1990
Latin America	1984	?	2009	2014
North America	1997	?	1969	2007
Oceania	2008	?	1986	2009
Global	1987	?	2010	?

Note. Human population data from United Nations world census data and emissions data are from Global Carbon Budget (GCB) and Carbon Dioxide Information Analysis Center (CDIAC) (Le Quéré et al., 2015). Years of peak in human population growth rate (PPGR), and peak population (PP), as well as peak fossil fuel emissions growth rate (PFGR), and peak emissions (PF) are shown regionally and globally.

occurred in 2010, it is also clear that we cannot afford to wait four decades to reach peak fossil fuel emissions in order to prevent 2 °C of warming (Rogelj et al., 2016).

3. Conclusions: Policy Implications

We propose that a multipronged targeted policy is required to reduce future emissions and ultimately stabilize atmospheric CO_2. Based on population and emission data, we have identified nations in three tiers: Tier 1 (countries that have already reached peak emissions and peak population; mainly European nations), Tier 2 (countries that have reached peak emissions but not peak population; mainly nations in the Americas and Oceania), and Tier 3 (countries that have not reached peaks in emissions or population; mainly Asian and African nations). We have also devised specific policy recommendations for nations by tier:

- Tier 1 nations: intellectual and resource investment in negative emission technologies (NETS), including active carbon dioxide removal (CDR) strategies, and greater efficiency and deployment of renewable energy technologies (RETs) for Tiers 2 and 3 countries.
- Tier 2 nations: continued deployment of RETs and increasing investment in NETS, while investing in greater efficiency and deployment of RETs in Tier 3 countries.
- Tier 3 nations: investment in RETs to reduce future emissions and improve human well-being.

Therefore, it is evident that the most effective strategy for quickly stabilizing atmospheric CO_2 is to stabilize emissions and stabilize human population. For instance, per capita emissions have stabilized in Africa due to a decrease in energy emission intensity, despite a continued increase in population. Thus, peak absolute emissions in Africa can be achieved most quickly by further decreases in emission intensity combined with population stabilization. This can be accomplished by deployment of renewable energy technologies in lieu of fossil-based energy technologies and providing equal gender access to education (Bongaarts, 2016). In fact the most expeditious way to stabilize atmospheric CO_2 may be through the investment of Tier 1 nations into the deployment of existing RETs in Tier 3 nations. It is also clear, that in order to meet emission reduction targets to avoid 2 °C warming by 2100 (Rogelj et al., 2016), we must develop active CDR technologies to complement existing passive CDR services currently provided by terrestrial and marine ecosystems (Field & Mach, 2017). Society should also be prepared for a scenario in which fossil fuel emissions peak in the coming years, but the growth rate of atmospheric CO_2 continues to rise. Such a *negative-emission positive-growth* scenario is not only possible but also predictable as negative fertilization feedbacks disengage and positive climate feedbacks engage (Jones et al., 2016). It is critical that under such a scenario, society remains steadfast in its commitment to renewable energy and redouble its investment in NETS. Lastly, incremental goals should make the ultimate objective of stabilizing atmospheric CO_2 at a safe level less daunting by first stabilizing the atmospheric CO_2 growth rate.

4. Supplementary Methods

For global and regional population estimates we relied on recently compiled data from the UN (2012). Errors in national census data vary by an order of magnitude; however, based on previous analyses we assumed a 10% 2σ error for global population estimates (Bongaarts, 2016). These errors were propagated to our growth rate estimates at the global scale (Figure 1) but not at the regional scale (Figure 3) because the errors for certain regions were considered to be unreliable.

Fossil fuel emission estimates included coal, oil, and gas, as well as cement production and gas flaring (Boden et al., 2013). We did not include potential emissions from land use change in our analysis because these emissions are highly uncertain (Houghton & Nassikas, 2017) and have shown no significant change over the last 50 years (Ballantyne et al., 2015). Because fossil fuel emissions are based on well-constrained estimates of consumption by fuel type, the main source of error is due to emission factors (Liu et al., 2015). However, fossil fuel CO_2 emissions 2σ errors from developed nations are approximately 5% compared to the 2σ errors from developing nations that are approximately 10% leading to relatively small errors in global fossil fuel emission inventories. Furthermore there are errors based on different fossil fuel inventories. The total 2σ error on global fossil fuel emissions is approximately 13% as of 2015 (Ballantyne et al., 2015). Nonetheless, resolving fossil fuel emissions at regional to continental scales can be challenging and verifying apparent changes in emissions from atmospheric measurements is difficult due to temporal autocorrelation of errors and sparse sampling networks (Y. Wang et al., 2017).

The major source of error in estimating the annual AGR of atmospheric CO_2 (e.g., AGR) is mainly due to biases and incompleteness of the surface sampling network (Masarie & Tans, 1995). To estimate how sampling error contributes to our estimate of AGR, we used a bootstrap method to simulate different configurations of the global sampling network. For each bootstrap simulation different sites were randomly selected with geographic distribution from approximately 40 sites located within the marine boundary layer. AGRs were calculated by subtracting mean December and January values from the previous year from mean December and January values from the current year. The overall, 1σ error for the entire AGR time series is 15%; however, these errors have gone down considerably since 1980 when the global sampling network was greatly expanded.

For statistical analyses we used the *findpeak* function in MatLab to locate local maxima in time series of emissions and population growth rates. We also used a 10-year moving window to test the slope of the sensitivity between the AGR and emissions and AGR and temperature data from NASA Goddard Institute for Space Studies (Schmidt et al., 2009).

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