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EDITORIAL

The growing role of methane in anthropogenic climate change

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Abstract

Unlike CO_2, atmospheric methane concentrations are rising faster than at any time in the past two decades and, since 2014, are now approaching the most greenhouse-gas-intensive scenarios. The reasons for this renewed growth are still unclear, primarily because of uncertainties in the global methane budget. New analysis suggests that the recent rapid rise in global methane concentrations is predominantly biogenic-most likely from agriculture-with smaller contributions from fossil fuel use and possibly wetlands. Additional attention is urgently needed to quantify and reduce methane emissions. Methane mitigation offers rapid climate benefits and economic, health and agricultural co-benefits that are highly complementary to CO_2 mitigation.

Introduction

Atmospheric methane (CH_4) has experienced puzzling dynamics over the past 15 years. After a period of relative stagnation in the early 2000 s ($+0.5 \pm 3.1$ ppb yr^{-1} increase on average for 2000–2006), atmospheric methane concentrations have increased rapidly since 2007 at more than ten times this rate ($+6.9 \pm 2.7$ ppb yr^{-1} for 2007–2015; figure 1 top left; Dlugokencky 2016). The atmospheric growth rate of methane accelerated to +12.5 ppb in 2014 and +9.9 ppb in 2015, reaching an annual average concentration of 1834 ppb in 2015 (Dlugokencky 2016). Because of this acceleration, the evolution of atmospheric methane over the last three years is inconsistent with the mitigation required in the Representative Concentration Pathways (RCP) of 2.5, 4 and 6 W m^{-2} and now most closely aligns with the RCP 8.5 W m^{-2} (figure 1 top left) (Fujino *et al* 2006, Clarke *et al* 2007, Riahi *et al* 2007, van Vuuren *et al* 2007). This emerging dynamic highlights methane's growing contribution to global warming relative to the observed slower growth rates of CO_2 over the past three years (Le Quéré *et al* 2016, ESSD; figure 1 top right, Jackson *et al* 2016) and a relatively constant growth rate of nitrous oxide (N_2O) (Hartmann *et al* 2013).

The global methane budget

The balance of surface sources and sinks determines the global methane budget. Surface sources include methane originating from biogenic (wetlands, lakes, agriculture, waste/landfill, permafrost), thermogenic (fossil fuel usage and natural seeps), pyrogenic (biomass and biofuel burning) or mixed (hydrates, geological) sources. Dominant sinks include methane oxidation by the hydroxyl radical (OH) and other radicals in the atmosphere as well as methanotrophy in soils. Based on a new ensemble of atmospheric studies, global emissions are estimated at 559 [540–568] Tg $CH_4.yr^{-1}$ for the 2003–2012 decade (Saunois *et al* 2016). Tropical sources, including both natural and anthropogenic sources represent two-thirds of total global emissions and are dominated by emissions from wetlands (figure 2). Approximately two-thirds of global emissions are also attributable to anthropogenic activities, including those from both mid-latitudes and the tropics (e.g., agriculture and waste, figure 2).

Changes in the methane budget since 2007

Despite substantial knowledge about the location, size and trends of methane sources and sinks, the relative

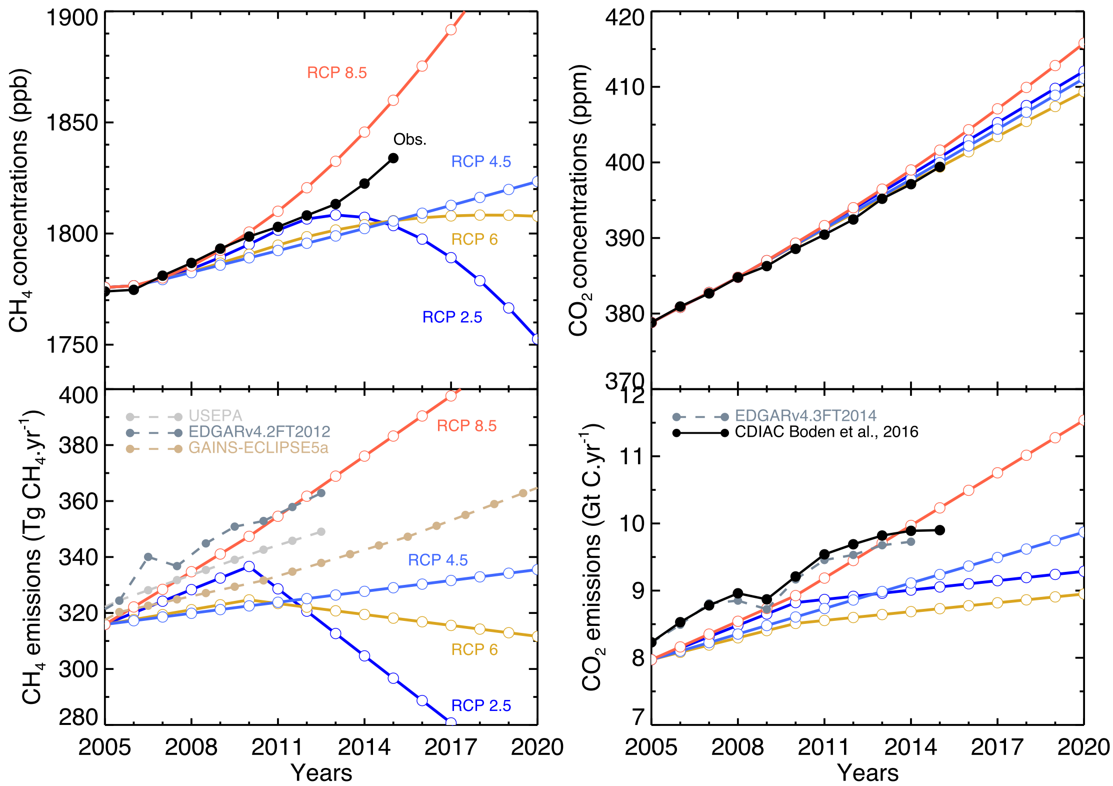

Figure 1. Top: projections of atmospheric methane concentrations (left, ppb) and carbon dioxide concentrations (right, ppm) for the four Representative Concentration Pathway (RCP) scenarios and observed globally averaged atmospheric abundance at marine boundary layer sites from the NOAA network (black, Dlugockenky 2016). Tropospheric concentrations from RCP models have been scaled to fit surface observations. Bottom: emissions of methane (left) and carbon dioxide (right) from anthropogenic sources. For methane, four harmonized RCP scenarios are plotted together with the EDGARv4.2FT2012, USEPA and GAINS-ECLIPSE5a inventories. For carbon dioxide, four harmonized RCP scenarios are plotted together with the recent EDGARv4.3FT2014, and CDIAC estimates for fossil and cement-production emissions. RCP concentration data are from Meinshausen *et al* (2011). Concentrations and emissions from RCP4.5 are above those of RCP6 before 2030.

contributions explaining the recent atmospheric increase remain uncertain (e.g. Nisbet *et al* 2014, 2016). Based on activity data and emission factors from various anthropogenic sectors, bottom-up inventories of anthropogenic emissions estimate an increase of fossil-related emissions of 3–4 Tg each year since 2007 (EPA 2012; EDGAR 2014). Using ethane measurements and methane-to-ethane ratios, Hausmann *et al* (2016) also suggest a substantial contribution of fossil-related emissions (18%–73% of the total increase in atmospheric methane). $^{13}CH_4$ isotopic observations show a significant depletion of ^{13}C in the atmosphere (∼−0.12‰ in seven years), suggesting that increases in methane emissions after 2006 are primarily biogenic and are more consistent with sources from agriculture than natural wetlands (Nisbet *et al* 2016; Schaefer *et al* 2016). Recent bottom-up inventories estimate an increase in agricultural annual emissions of 3–5 Tg between 2006 and 2012, mostly from Africa and Asia, whereas wetland emissions were estimated to be mostly unchanged between 2006 and 2012 (Poulter *et al* 2016). Meanwhile, biomass burning emissions decreased by 2–3 Tg yr^{-1} between 2007 and 2013 compared to 2000 and 2006, although the recent El Niño conditions have lead to abnormally large peat fires in Indonesia (Van der Werf *et al* 2016). Not accounting for this long-term decrease in the ^{13}C-heavy methane source from biomass burning, and based on ^{13}C atmospheric observations and on an enriched database for isotopic source signatures, Schwietzke *et al* (2016) even find decreasing fossil fuel emissions since 2000, a different conclusion than reached in most other recent studies.

Sinks may also be playing a role in the rapid rise in atmospheric methane over the last decade (figure 1). Using a chemistry-transport model run over 40 years, Dalsøren *et al* (2016) infer a stabilization of OH concentrations after 2006, in contrast to a total 3% increase since the late 1990s (8% since the 1970s). Stabilized OH concentrations can increase methane lifetimes and may help explain the atmospheric methane increase as well, as a decrease of 1% in atmospheric OH concentrations is roughly equivalent to ∼5 Tg yr^{-1} of increased methane emissions (e.g. Saunois *et al* 2016).

These various factors notwithstanding, there is no consensus scenario of methane sources and sinks that explains the atmospheric increase since 2007 (Kirschke *et al* 2013). Recent evidence from atmospheric observations suggests three main contributors for emission changes. The first element is an increase in biogenic emissions, mostly from agriculture (^{13}C compatible, Schaefer *et al* 2016). The second is an increase of fossil-

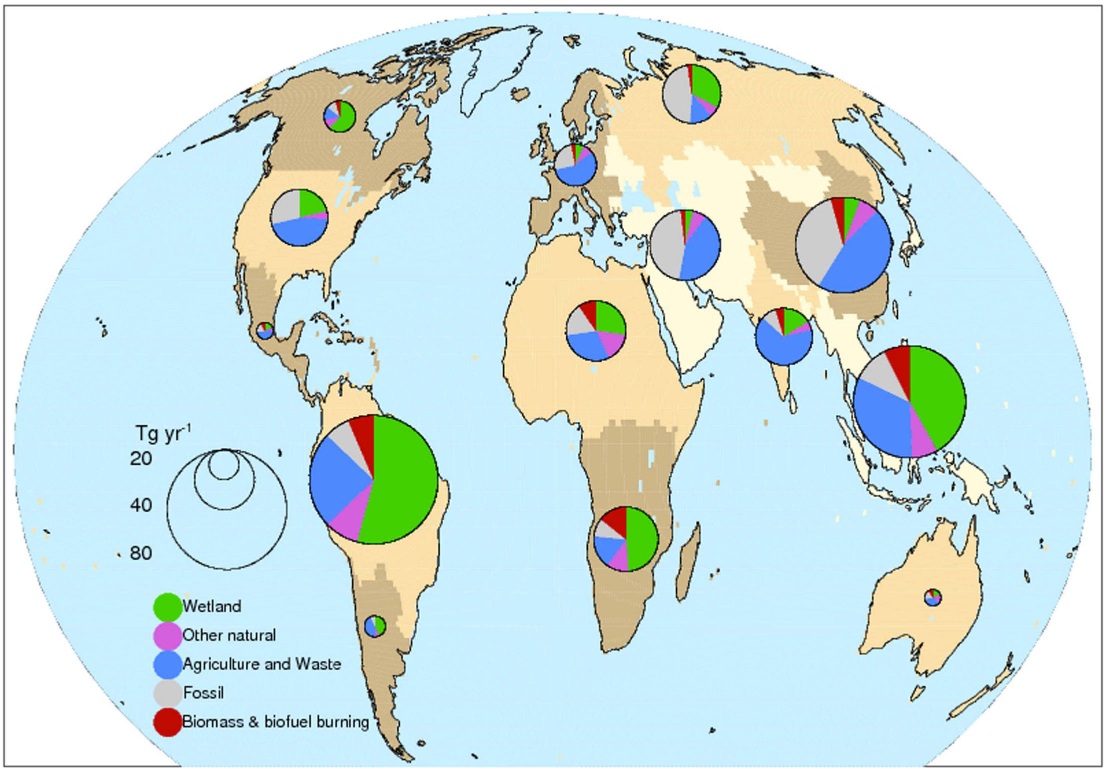

Figure 2. Annual methane emissions (in Tg yr^{-1} for the 2003–2012 decade) for fourteen continental regions and five emission categories. Estimations are the average of an ensemble of top-down inversion models described in Saunois *et al* (2016).

related emissions (ethane-compatible, Haussman *et al* 2016). The third is a decrease of biomass burning emissions (^{13}C compatible and cancelling a fossil fuel increase, Van der Werf *et al* 2016). The necessity of an anthropogenic emission increase can still be reduced by a possible stagnation of OH concentrations or by regional contributions from wetland emissions, such as emissions fluctuations resulting from drought conditions in South America (e.g., in 2010–2011; Basso *et al* 2016).

At the regional scale, methane emissions contributing to the observed atmospheric increase since 2006 are most likely tropical, although some mid-latitude regions, such as China, also appear to contribute to the increase (e.g. Bergamaschi *et al* 2013). To date, no significant contribution to the atmospheric increase from Arctic regions has been found, except in 2007 and attributable then to a relatively warm and late summer (Dlugokencky *et al* 2011). Contrary to a recent estimate based on three different atmospheric inversions (Turner *et al* 2016), no trend in US methane emissions is found in the ensemble of inversions gathered in Saunois *et al* (2016), and thus a substantial contribution of US shale gas industry to the recent methane atmospheric increase seems unlikely (Bruhwiler *et al* 2016).

Strategies to reduce uncertainties on the methane budget

Scientific breakthroughs are needed to predict methane emissions today and in the future, particularly with a changing climate. First, annual to decadal CH_4 emissions from natural wetlands and other inland water systems are highly uncertain. The sum of all natural methane sources as inferred by process-based bottom-up modelling is too large by about 30% compared to the constraint provided by methane atmospheric mixing ratios. The strategy to address this issue requires developing and synthesizing (i) direct methane flux measurements in the field to constrain the parametrizations of land surface models similarly to Fluxnet-CO_2, (ii) process-based models for lakes, rivers, and permafrost methane emissions (e.g., Tan and Zhuang 2015 for lakes), and (iii) dynamic global high resolution maps (50–100 m) with all inland water surfaces consistently categorized to avoid double counting emitting surfaces (Yamazaki *et al* 2015).

Second, the partitioning of CH_4 emissions and sinks by region and process needs to be better constrained by atmospheric observations and process-based models. Beyond the recurring need for a broader network of methane observations, it is essential (i) to extend observations of tracers more specific to individual methane sources and sinks such as methane isotope concentrations and emission signatures (Röckmann *et al* 2011; Schaefer *et al* 2016) and ethane (Haussmann *et al* 2016), and (ii) to improve the estimation of magnitude and trend of OH radicals by better quantifying its sources and sinks in chemistry climate models (e.g. Dalsøren *et al* 2016). The latter will benefit from a recent intercomparison of chemistry climate models (the Chemistry

Climate Model Initiative (CCMI) update of Lamarque *et al* 2013) and CMIP6 simulations scheduled for the next IPCC report. Breakthrough technologies already allow high precision measurements of methane and its isotopes at the surface, for instance using cavity ring down spectrometers such as in Maher *et al* (2014). Future LIDAR measurements from space will provide the first low-bias global estimate of methane atmospheric columns all year round beginning in ~2020 (Kiemle *et al* 2014). The partitioning of emissions will also benefit from efforts to improve and regularly update anthropogenic inventories.

Third, uncertainties in the modelling of atmospheric transport and chemistry limit the optimal assimilation of atmospheric observations and increase the uncertainties of the inversion-derived flux estimates. Key steps should include the improvement of OH fields and other methane sinks (e.g., methane oxidation by other radicals), refinements in the horizontal and vertical model grids, parameterization of vertical mixing and representation of stratospheric concentrations. Such modelling improvements could be accomplished through regular inter-comparisons such as TRANSCOM (e.g., Patra *et al* 2011) or CCMI (Lamarque *et al* 2013) and through additional efforts for model validation (Bergamaschi *et al* 2013).

Mitigation opportunities

Despite important uncertainties in methane sources and sinks, the recent increase in methane concentrations suggests a dominant anthropogenic contribution (either biogenic or thermogenic). Methane therefore offers growing opportunities for climate change mitigation that could allow a return to lower emission trajectories such as RCP6 or RCP4.5. Because of methane's high global warming potential and short lifetime in the atmosphere compared to CO_2, its mitigation offers the possibility to slow climate change efficiently in a shorter time horizon. In addition to climate benefits, reducing methane emissions could help improve human health and crop production through simultaneous reductions in ozone production (West *et al* 2013; Shindell 2016) and provide business and employment opportunities. A diverse set of strategies already exists, as proposed by multilateral partnerships such as the Global Methane Initiative (www.globalmethane.org) and the Climate and the Clean Air Coalition (www.ccacoalition.org), and supported further by the G7 Leaders Declaration in May 2016 (www.whitehouse.gov/the-press-office/2016/05/27/g7-ise-shima-leaders-declaration) to 'recognize the importance of mitigating emissions of short-lived climate pollutants'. These opportunities include (i) venting and flaring of methane in coal-mines, while also improving worker safety, (ii) detecting and removing natural gas leaks, from wellpads upstream through the distribution chain downstream (e.g., McKain *et al* 2015), (iii) covering landfills, which reduces methane emissions while producing biogas for energy and transport usage, and (iv) developing farm bio-digesters, which has been extensively applied in Germany and is spreading to other European countries (e.g., Lebuhn *et al* 2014). Other strategies are being developed but need more research on potential unintended consequences. For example, modifying ruminants' diet (e.g., linseed fed) to limit methane emissions is currently being examined but needs evaluation against the quality of meat and milk (e.g., Marette and Millet 2014) and against emissions of other greenhouse gases such as N_2O. Modification of rice agriculture practices (e.g., semi-inundated paddies, dry cultivation) is well tested and promising, assuming yield and quality of the staple food for more than 3 billion people can be guaranteed (e.g., Sun *et al* 2016). Such mitigation policies in the agriculture and waste sectors are key to reducing methane emissions in most of the high emitting regions (figure 2).

Conclusions

Methane appears to play an increasing role in on-going anthropogenic climate change, particularly in light of the slowdown of CO_2 fossil fuel emissions over the past three years (figure 1, bottom right). Methane emissions from increasing agricultural activities seem to be a major, possibly dominant, cause of the atmospheric growth trends of the past decade (e.g., Herrero *et al* 2016). The rapid increase in methane concentrations offers a growing mitigation opportunity, acknowledging the need to balance food security and environmental protection (Wollenberg *et al* 2016). Keeping global warming below 2 °C is already a challenging target, with most of the attention placed primarily on CO_2 emissions. Such a target will become increasingly difficult if reductions in methane emissions are not also addressed strongly and rapidly.

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