1. Introduction

This paper will cover two subjects: (1) recent and large increases in atmospheric methane and (2) how we might identify future methane emissions. This will enable characterization of the sources that lead to general methane levels and thus carbon dioxide levels, since methane degrades into CO$_2$.

I'm not sure what I was looking for when I came across an article that led me to the paper linked below (published by the American Geophysical Union). I'm guessing I was looking for information on reforming methane into hydrogen as work on "Hydrogen Futures". The article was from a site I rarely visit, ditto the paper. However it was a very good paper, and alerted me to a trend that should be of interest to anyone that is concerned about climate change.


In the first section below, I will repeat some content from an earlier paper that I posted on greenhouse gases and why we should be concerned about significant increases in methane. Then in the following sections we will review the paper and techniques for better understanding where methane emissions are coming from.

2. Atmospheric Methane Impacts

Human-caused methane emissions reporting by the EPA is no longer credible, thus I will use the referenced (end of this sentence) estimate of over 14 million tons for the U.S. or 0.35 Gt of CO$_2$ equivalent (GtCO$_2$eq).\(^1\) World emissions of methane are estimated at 7.5 GtCO$_2$eq in 2010. The following are anthropogenic (man-made) sources:\(^2\)

- Digestive fermentation, mainly by ruminant animals (2.2 GtCO$_2$eq)
- Agriculture (1.6 GtCO$_2$eq)
- Oil and gas production and distribution (1.5 GtCO$_2$eq)
- Landfills (0.8 GtCO$_2$eq)
- Wastewater (0.7 GtCO$_2$eq)
- Coal mining (0.5 GtCO$_2$eq)
- Other sources (0.2 GtCO$_2$eq)

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\(^1\) Environmental Defense Fund, "Major studies reveal 60 percent more methane emissions", [https://www.edf.org/climate/methane-studies](https://www.edf.org/climate/methane-studies)
Methane has a global warming potential 72 times greater than CO$_2$ in a 20-year time-frame, but only 25 times in a 100-year time-frame. As methane degrades it forms CO$_2$.

Future temperature rise depends on radiative forcing. Radiative forcing (hereafter “RF”) quantifies the change in energy fluxes (W/m$^2$) calculated at the tropopause (the top of the atmosphere), caused by changes in specified drivers (generally greenhouse gasses and aerosols) relative to the year 1750. Positive RF leads to surface warming; negative forcing leads to surface cooling. RF is estimated based on in-situ and remote observations, properties of greenhouse gases and aerosols, and calculations using numerical models representing observed processes.

Currently radiative forcing is approximately 2.3 W/m$^2$ for carbon dioxide, and 0.63 W/m$^2$ for methane.

3. **Observed Increases and Characterization**

Much of the content in this section comes from the paper linked above in the Introduction. Thus references will only be given for other sources.

Since methane degrades to CO$_2$ with a half-life of seven years, assuming constant emissions, its level will stabilize very quickly. In the year 2000 its level was approximately 1750 parts per billion (ppb), up from 700 ppb in 1750. Its level remained relatively constant for the first decade of the 21$^{st}$ century (reaching 1775 ppb in 2006, but it rapidly increased in the years from 2007 to the present (see chart below).

![CH$_4$ Chart](chart.png)

Note that the red & blue line shows seasonal variations, and the solid blue line filters these out.

The obvious question is: where are these coming from?

There are several lines of evidence that we need to follow. The first is a metric represented by $\delta^{13}$C$_{\text{CH}_4}$. This stands for a measure of the ratio of stable carbon isotopes $^{13}$C: $^{12}$C, reported in parts per thousand ($\permil$). Methane has a very light $\delta^{13}$C signature: biogenic methane of $\sim$60$,\permil$, thermogenic methane $\sim$40$,\permil$. Biogenic methane comes from

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3 Gravity Wiki article on methane, [http://gravity.wikia.com/wiki/Methane](http://gravity.wikia.com/wiki/Methane)

biological sources (biogas). Thermogenic methane is primarily produced by geological processes (heat and pressure), and the primary sources for the latter are natural gas, and methane from coal mines.

The measured $\delta^{13}$C$_{CH_4}$ over the period in question is shown by the chart below.

Note that the $\delta^{13}$C$_{CH_4}$ trended strongly negative as the emissions increase. Given this, the possible culprits for increased atmospheric methane are:

- An increase has occurred in biogenic emissions, whether from wetlands or ruminants (cattle and the like) or waste, or all of these. If so, an increase in the proportion of global emissions from these microbial sources may have driven both the increase in the methane burden and the shift in $\delta^{13}$C$_{CH_4}$.

- Strong rise in methane emissions from the use of natural gas and oil has taken place. Fossil fuel methane emissions are mostly somewhat more positive in $\delta^{13}$C$_{CH_4}$ than -47‰ to -53‰. Thus this hypothesis is only consistent with the observed isotopic shift if either: a) the new fossil fuel emissions have $\delta^{13}$C$_{CH_4}$ markedly more negative than -47‰; or b) if there has been a concurrent decline in a source of much more $^{13}$C rich emissions, such as from biomass burning or c) both changes have occurred. Note that it is possible that both this and the above hypotheses may be valid: that both microbial and fossil fuel emissions have increased. This would explain the observations provided the increase in microbial emissions is sufficiently larger than that in fossil fuels, so that the bulk $\delta^{13}$C$_{CH_4}$ value of the total source has become more negative.

- Or the oxidative capacity – that is, the cleansing power of the atmosphere has declined, and hence the destruction of methane has slowed. A change in methane destruction has strong isotopic impact.

Other evidence comes from methane emission and $\delta^{13}$C$_{CH_4}$ concentrations on a regional basis. A thorough analysis of regional measurements did not yield any conclusive results. Methane emissions migrate rapidly, and these are also rapidly being converted to CO$_2$. Given the multiple potential (or likely) sources of methane, there were no likely regional candidates.

The above candidate sources (above bulleted list) are evaluated below:
An increase has occurred in biogenic emissions: Several factors stand out – wetlands are a major source of natural biogenic emissions as are land-fills and the warmer it is, the higher these emissions from these sources become (the little microbes happily increase their methane production). The years 2014, 2015 and 2016 were of exceptional warmth, each year surpassing the previous as the warmest on record. Then 2017, which was 1.16°C above 1880-1909 norms, was the warmest non-El Niño year on record. The very strong methane growth in 2014 may thus reflect the very warm temperatures compared to previous years. Also substantial flooding occurred in the years 2014 to 2017. This increases the land area of temporary wetlands, further increasing methane emissions. There has been a rapid increase in the number of landfills, especially unregulated landfills. This, coupled with increased temperature, also argues for biogenic emissions.

Although it's possible that increased emissions from ruminants may have contributed to emissions, there is no evidence of this.

New fossil fuel emissions have $\delta^{13}C_{CH_4}$ markedly more negative than -47‰; or there has been a concurrent decline in a source of much more $^{13}C$-rich emissions. There is one trend in fossil fuel production that may support these assumptions. This is a shift from deep (anthracite) mines to open-pit (bituminous) mines. $\delta^{13}C_{CH_4}$ values for bituminous coals is -65‰ for open-pit mines and -55‰ for deep mines, while methane from anthracite mines ranged from -40‰ to -30‰. Thus replacing anthracite coal with bituminous coal will drive the $\delta^{13}C_{CH_4}$ more negative.

A trend that may negate the above is the shift from coal to natural gas which would tend to drive the $\delta^{13}C_{CH_4}$ more positive (natural gas $\delta^{13}C_{CH_4}$ ranges from -30 to -50).

Possible methane sink strength and lifetime changes driven by a decline in the oxidative capacity of the atmosphere. The paper linked in the Introduction performed a detailed literature evaluation of this possibility, but to make a (very) long story short, they found it unlikely.

In conclusion, it is highly probable that the record global temperature increases resulting from climate change are driving biogenic methane emissions higher, and changes in coal and natural gas use patterns may also be contributing slightly to this rise.

The bad news in the above is, with a seven-year half-life, it is likely that the methane content in the atmosphere will plateau at a higher level if the yearly temperature increases stabilize (unlikely), but even then, this will result in:

- Higher radiative forcing resulting in more rapid future temperature increases, resulting in higher methane emissions, and so on.
- An increase in CO$_2$ emissions from the degradation of more methane

The good news is that emissions from the oil and gas industry are not increasing, and other reports indicate that they are diminishing. This is consistent with rational behavior that any industry seeks to reduce losses of their product, especially when these losses (emissions) cause a major public-image hit.

However I don't believe that this is an excuse to reduce our vigilance. Monitoring methane will increase the data we need to understand how methane and CO$_2$ emissions
are increasing, decreasing (unlikely any time soon) and interacting. In the next section we will explore methods to measure methane levels.

4. Measuring Methane Emissions

I started this paper in order to present the findings of an important paper on atmospheric methane in my usual abbreviated format (less than 3,000 words with any difficult concepts translated to (more or less) plain English and/or explained). In the process of researching this section I found a wonderful publication from the National Academies Press (NAP, which publishes content from the National Academies of Sciences, Engineering, and Medicine). I immediately loved these organizations because (1) the latter included us lowly engineers in their title (hear that, AAAS!), (2) the document I found was a wonderful exploration of: Improving Characterization of Anthropogenic Methane Emissions in the United States (2018), Almost all of the content from these organizations is available in PDF format for free. The link below is to NAP's main website.

https://www.nap.edu/

I only used content from chapter three of "Improving Characterization of Anthropogenic Methane …" which is linked below. In total, this is a 234-page long document.

https://www.nap.edu/read/24987/chapter/5

Hereafter I will only provide references for content that is not from the above chapter.

4.1. Methane Measurement Scales

Methane can be measured at all scales from point sources (say a single cow, or a single oil well) to global measurements. In between are regional measurements at various scales (for instance, a single rangeland area, or oil-production area). Global metrics usually require combining regional measurements using a simulation (modeling) tool, and these tools are also used to extract information from measurements (like the number of cattle grazing or the number of producing oil wells in a given region). In fully understanding emission-dynamics, both top-down (from larger to smaller scales) and bottom-up (like from point sources to regional scales) will be used.

4.2. Methane Measurement Methods

The following paragraph define methods used for measurements at various scales. See the above linked chapter for the pros and cons of these methods.

**Point-source:** Measurement of flow-rate, temperature, methane-composition and other variables as required from a single atmospheric outlet (pipe or similar), or device (valve or similar) over some period of time determined by the related process's variability over time.

**Enclosure:** Placement of one or more point-sources (like cattle) in a chamber. There are two variants of this technique: Static chamber – chamber is sealed and the increase in the methane concentration in the chamber over a fixed time is measured. Dynamic chamber – the chamber is ventilated, and the methane concentration of the outlet and inlet are measured.
**Micrometeorological techniques:** Placement of a series of sensors at various heights on a number of towers around the monitored area. Each sensor will measure methane concentration plus a series of meteorological variables (temperature, wind-speed, etc.). The data that is captured over time will be combined with a model to estimate the emissions in the area.

**External tracer:** This is similar to the prior technique except a tracer gases (typically nitrous oxide and/or acetylene) are released at selected locations to better quantify flow and mixing across the area.

**Facility-scale in situ aircraft measurements:** This requires multiple measurements of methane plus monitoring meteorological variables around the area. These can either use real-time measurements or sampling (the former is generally called *Aircraft mass balance measurements*, and uses infrared spectrometry).

**Remote observatories:** remote observation of monitored area, and methane measurement using infrared spectrometry.

**Satellite:** via absorption spectroscopy using reflected sunlight (sensitive to entire atmospheric column) or thermal emissions (less sensitive to atmospheric conditions near the ground).

From the first method described above to the last, each method is less accurate. Also, starting at micrometeorological techniques to the last method, these generally must be combined with modeling to characterize emissions.

Each of the above techniques (plus other similar techniques) are discussed in detail in the above linked chapter.