Science Questions: What processes control atmospheric methane concentration fluctuations and trends?

What are the processes that control wetland fluxes in the tropics and Arctic?
How will these processes respond to climate change?
How is the methane flux changing from thawing permafrost in the Arctic?
How are fluxes of methane changing from anthropogenic activities, such as fracking and natural gas extraction/distribution?

Scientific Need: Observational constraints on the seasonal and interannual variation of methane fluxes, including from wetlands/rice paddies and the processes that influence them.

Scientific Background

Methane is the second most important anthropogenic greenhouse gas (GHG), though its 100-year and 20-year global warming potentials (GWP) are 28-32 times and 84-86 times, respectively, larger than that for carbon dioxide (CO_2; Myhre et al., 2013; Holmes et al., 2013). The coupled methane-carbon monoxide-hydroxyl radical (CH_4-CO-OH) system is nonlinear (e.g., Prather, 1994) and important in determining the troposphere's oxidizing capacity (e.g., Chameides et al., 1976). Shindell et al. (2009) reported that the 100-year GWPs for methane and CO are likely larger than those reported in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) when one accounts for their perturbation's impact on gas-aerosol interactions. Methane is known to contribute to background ozone, which has implications for air quality and climate (e.g., Fiore et al., 2002). It is emitted from anthropogenic and natural sources (Table 7.6 of IPCC, 2007), which has led to the high methane growth rate and doubling in concentration over the last few centuries (e.g., Stauffer et al., 1988). Overall, most emissions are associated with bacterial methanogenesis (e.g., wetlands, ruminants, and rice paddies), with much of the rest being associated with energy production and biomass burning.

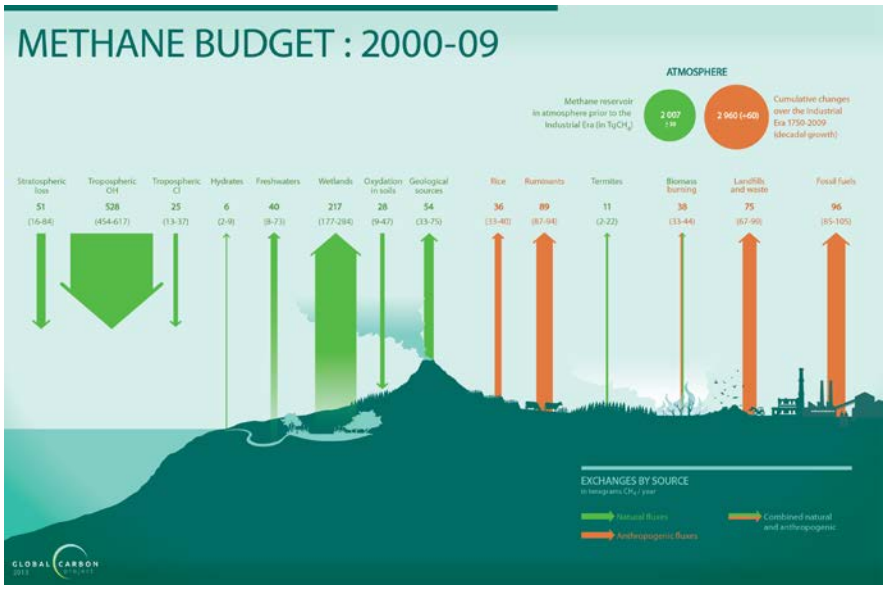


Figure credit: http://www.globalcarbonproject.org/methanebudget/index.htm

Surface measurements from the NOAA Earth System Research Laboratory (ESRL) Global Monitoring Division (GMD) network (Dlugokencky et al., 2010) *show that the global methane growth rate began to level off in the 1990s and 2000s, but there is only limited understanding of the causes of the slowdown in the growth rate* (e.g., the review article by Kirschke et al., 2013). A decrease in the anthropogenic fossil fuel and livestock emission rates (Dlugokencky et al., 1998, 2003; Wang et al., 2004; Khalil et al., 2007; Patra et al., 2011; Simpson et al., 2012) and the trend toward more El Niño than La Niña events (i.e., lower wetland emissions; Hodson et al., 2011) may have contributed. *There is clearly a need for better constraint of anthropogenic methane emissions, particularly given that the slowdown in methane's growth rate in the mid-1990s to mid-2000s has been largely attributed in several recent studies* (Patra et al., 2011; Kirschke et al., 2013) *to a decrease in anthropogenic sources*. Reaction with OH is the primary sink for methane, but inferred long-term trends in global OH using, for instance, observed methyl chloroform concentrations are generally too small (e.g., Prinn et al., 2005; Bousquet et al., 2005; Montzka et al., 2011) to explain the slowdown in the growth. *After 2006, the methane growth rate began to rise again and continues to do so, but the causes are not well understood* (Nisbet et al., 2014).

On top of this general decline in the observed methane growth rate in recent decades, there have been substantial global anomalies, with many being attributed to fluctuations in wetland emissions (e.g., the review article by Kirschke et al., 2013). Causes of the anomalies are sometimes attributed to specific events, for instance, the eruption of Mt. Pinatubo and associated fluctuations in wetland emissions and OH abundance, the economic contraction of the former Soviet Union, and large biomass burning events (e.g., Wang et al., 2004; Butler et al., 2005; Bousquet et al., 2006; Dlugokencky et al., 2009). Patra et al. (2011) concluded that up to 60% of the interannual variation in methane observations can be explained by variations in biomass burning and wetland emissions, and meteorology. The results of Bousquet et al. (2006) indicate that wetland emissions dominate the interannual variation of methane emissions with biomass burning playing a smaller role, except during the 1997–1998 El Niño. The growth rate reached a minimum in 2003-4, but accelerated again as indicated by both *in situ* and space-borne observations (e.g., Rigby et al., 2008; Schneising et al., 2011; Frankenberg et al., 2011). This recent growth appears to be associated with increases in boreal and tropical wetland emissions, but not climate feedbacks such as thawing permafrost (Dlugokencky et al., 2009; Bousquet et al., 2011). **Figure 1** shows some of the major Arctic/boreal and tropical wetland regions.

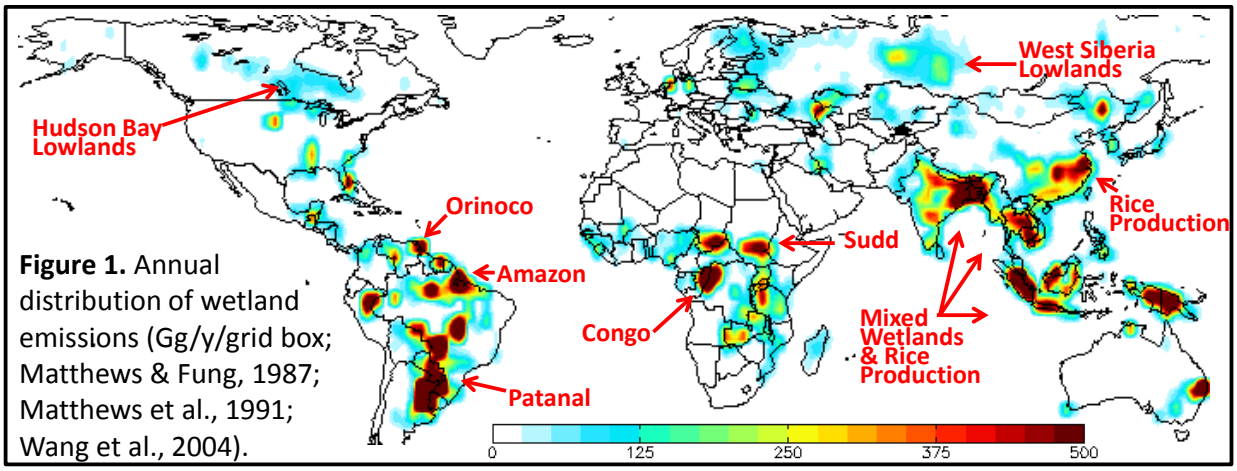


Figure 1. Annual distribution of wetland emissions (Gg/y/grid box; Matthews & Fung, 1987; Matthews et al., 1991; Wang et al., 2004).

A fundamental reason for the considerable uncertainty about the causes of variability in observed methane is that the variability of methane sources remains poorly understood, particularly for wetlands (Ringeval et al., 2010; Melton et al., 2013; Dlugokencky et al., 2011). For instance, the factors that affect microbial methane production are not well constrained (e.g., Meng et al., 2012), and land cover, including wetlands, is not always well categorized (e.g., Frey and Smith, 2007). Not surprisingly, current process-based models predict a wide range of emission estimates (e.g., ± 40% for annual global emissions) as shown in the recent Wetland and Wetland CH_4 Inter-comparison of Models Project (WETCHIMP; Melton et al., 2013). *There could be important climate feedbacks in the near future from thawing permafrost, the destabilization of marine hydrates, wetlands (e.g., O'Connor et al., 2010, and references therein; Ciais et al., 2013), and Arctic sea ice changes (Kort et al., 2012). In addition, there is considerable debate concerning the potential impact of fracking activities associated with natural gas extraction.*

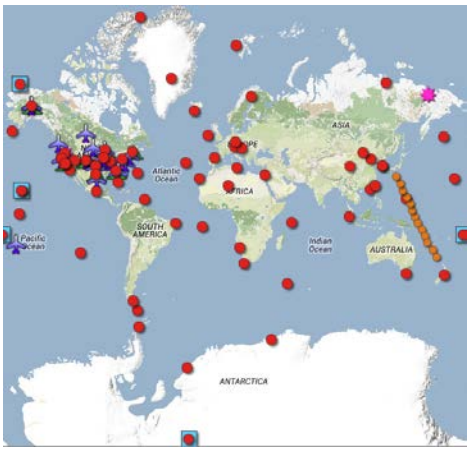


Figure 2. The locations of in situ methane measurement sites in the Greenhouse Gas Reference Network.

Our ability to estimate emission fluxes with inverse modeling studies (e.g., Wang et al., 2004; Butler et al., 2005; Bousquet et al., 2006; Bergamaschi et al., 2009; Bergamaschi et al., 2013) is limited because their results depend on the methane observations used as the constraint and current data are sparse. The Greenhouse Gas Reference Network surface observational network has sparse coverage and the locations of the stations are often far from emission source regions, such as wetlands (**Figure 2**). In addition, the sparseness of this network may not allow for the identification and adequate quantification of new sources, such as from a warming Arctic. Methane column data, which are retrieved from near-infrared/shortwave infrared (NIR/SWIR) wavelengths, have been used to infer methane fluxes from space (Bergamaschi et al., 2009; Bloom et al., 2010; Fraser et al., 2013; Zhang et al., 2013). However, there remain substantial limitations of the column data. For instance, **Figure 3** shows that Greenhouse gases Observing SATellite (GOSAT) Thermal and Near Infrared Sensor for carbon Observation (TANSO) coverage is sparse, particularly over wetlands in the tropics and the Arctic, regions which are generally cloudy. The main column data products are from the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY – now defunct), the GOSAT TANSO (2009 – present), and the Sentinel 5 Precursor (expected launch in 2016). Methane observations from thermal infrared (TIR) instruments, such as the Aqua Atmospheric InfraRed Sounder (AIRS) and Aura Tropospheric Emission Spectrometer (TES), lack sensitivity in the lower troposphere, near where methane emissions occur. *Another confounding issue for inverse modeling is that methane has numerous sources that are often closely located or co-located. Isotopic measurements (e.g., ratio of $^{13}CH_4$ to $^{12}CH_4$) provide powerful information on methane's sources, however, routine observations are currently very limited (Dlugokencky et al., 2011). Therefore, quantification of different methane source sources depends on high resolution observations in both space and time as well as credible models of atmospheric transport and the processes that affect methane fluxes, such as from permafrost thaw and wetlands.*

Satellite instruments can detect variability in factors known to control wetland fluxes that lend additional constraints and are necessary for quantifying fluxes. Inundation depth data have been collected by microwave instruments which have the advantage of detecting through clouds, which is an advantage for wetlands and the Arctic which tend to be cloudy environments. Bloom et al. (2010) used spaceborne observations of gravity anomalies from the Gravity Recovery and Climate Experiment (GRACE) as a proxy for water table depth, which can be used to estimate inundation extent. They used the data to infer that variations in methane column data are best explained by surface temperature over boreal wetlands and soil moisture over tropical wetlands. They found that variations in tropical wetland emissions are largely correlated with water table depth, but higher-latitude variations are better correlated with surface temperature. Data of surface temperature, snow cover, and vegetation cover can all be used to help constrain wetland fluxes.

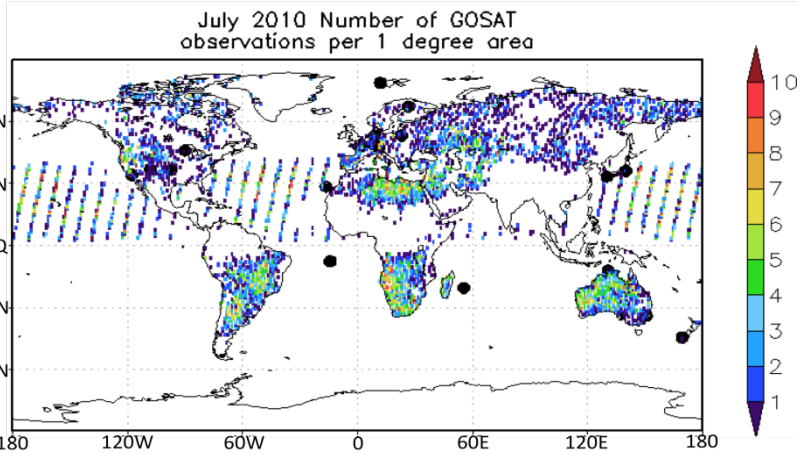


Figure 3. GOSAT methane column data are sparse, particularly over wetlands which tend to be cloudier environments. Therefore, our ability to estimate wetland fluxes from methane satellite data is limited. *However, inundation depth data are not affected by clouds as they are measured in the microwave wavelengths.* GOSAT data are limited over the oceans as the glint mode is restricted to within a certain number of degrees from solar zenith, which is why there aren't data over the Southern Hemisphere tropical ocean in July. However, the signal-to-noise ratios of these data are high.

Observational requirements. Ultimately, the spatial and temporal resolution and coverage requirements and precision needs of methane observations are dependent on the application, such as inverse modeling of flux sources, regional trend calculations, etc. **Figure 4** shows data from the NOAA ESRL GMD network for the Seychelles station in the tropical Indian Ocean, which illustrates the typical seasonal variations (~5%) experienced at a surface site far from emission sources.

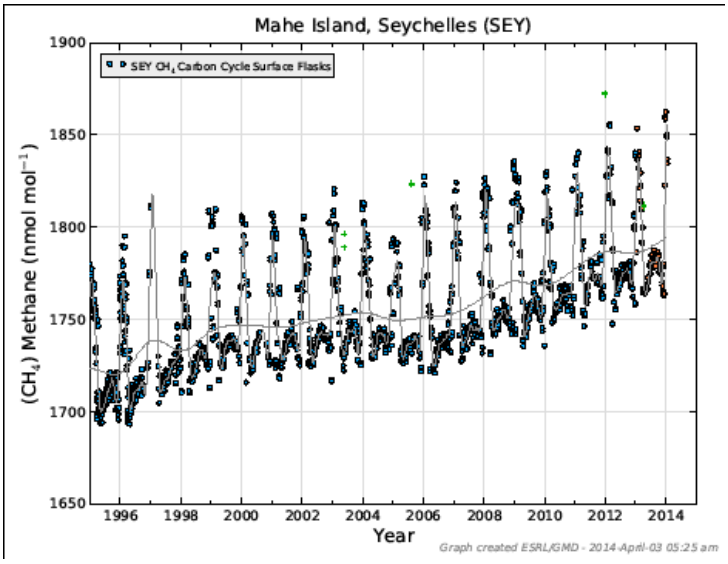
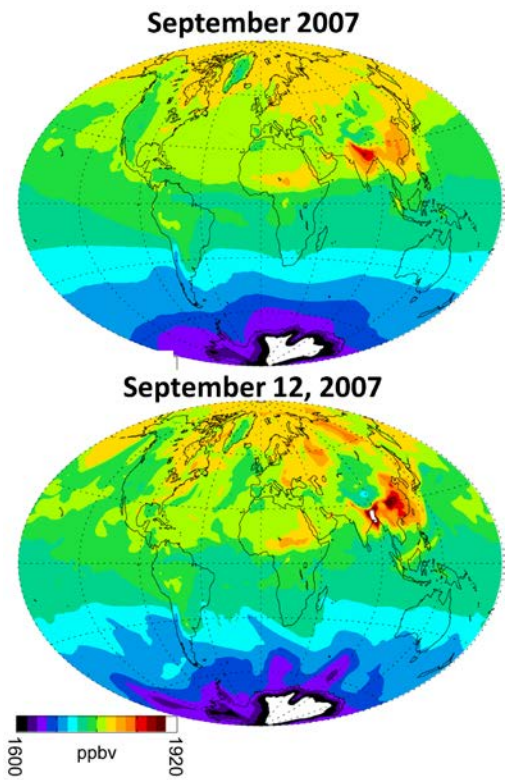


Figure 4. NOAA ESRL GMD network data for the remote Seychelles station over nearly two decades. Even at this remote site, the seasonal variation is generally ~ 100 ppbv and is driven by the seasonal passage of the ITCZ which exposes the station to more polluted Northern Hemispheric air. The interannual variation in the seasonal cycle is about 60-100 ppbv. *The seasonal and interannual variations near source regions are much greater.*



Typical spatial gradients and temporal variations within the atmospheric methane column from a model are shown in **Figure 5**. At a 1° x 1° spatial resolution, the gradients over 1000 km are as high as 60 ppbv (~0.5% of background concentration) but often smaller, therefore a precision of 10 ppbv or better would be helpful for capturing most of the important flux signals.

Figure 5. Model output of the methane column-average mixing ratio (XCH_4; ppbv) at pressures >300 mb as a monthly average an as an average for one day. The model used monthly average emissions from the TransCom intercomparison (Patra et al., 2011), so the concentration gradients on September 12 are the result of day-to-day weather variations in transport. Additional variations are expected from day-to-day variations in emissions. The spatial resolution is 1° x 1°. The colorbar is in increments of 20 ppbv.

Appendix: Potentially useful information.

Descriptions of Methane Column Data Products Used for Inferring Wetland Fluxes

Buchwitz et al. (2013) describe the effort of the Greenhouse Gas Climate Change Initiative (GHG-CCI), which includes reconciling differences and biases among current algorithms so as to improve accuracy of the data products, such as SCIAMACHY and GOSAT methane.

SCIAMACHY was launched in 2002 into a sun-synchronous orbit on Envisat. There are two main column retrievals. Schneising et al. (2009) describes the WFM-DOAS retrieval and Frankenberg et al. (2011) describes the IMAP-DOAS algorithm. These data products show some differences, such as data density and sometimes different methane distributions for some regions (Buchwitz et al., 2013). The instrument experienced detector degradation in October 2005. Modifications to minimize the impact of this degradation were made to the two main retrieval algorithms (Frankenberg et al., 2011; Schneising et al., 2012; Buchwitz et al., 2013). Frankenberg et al. showed time series of methane for various regions and concluded that "consistent methane retrievals from 2003 through 2009 are now possible", though the data collected after the detector degraded are of lower quality. The quality of the SCIAMACHY data for 2003-2005 and 2006-2009 is summarized in Table 5 of Buchwitz et al. (2013). In short, the single observation precision almost doubled due to the detector degradation. For example, Schneising et al. (2012) found a latitude-dependent bias after 2005 (e.g., highest in tropics), which they attribute to spectroscopic interference with water vapor.

TANSO was launched in January 2009 into a sun-synchronous orbit on the GOSAT satellite with global coverage in three days. There are several column retrievals of methane (e.g., Butz et al., 2011; Parker et al., 2011; and Schepers et al., 2012), which are being improved over time. Although there are differences among these data products, they are significantly smaller than for the SCIAMACHY retrievals (Buchwitz et al., 2013). The precisions of these retrievals are similar (Buchwitz et al., 2013) and their columns generally show good agreement with data from the ground-based Total Carbon Column Observing Network (TCCON; Wunch et al., 2011). For example, Parker et al. (2011) showed that the methane columns from their retrievals correlate typically between 0.5 and 0.7 with measurements from six TCCON stations, but there is a latitude-dependent bias. The retrievals of Butz et al. and Parker et al. were selected by GHG-CCI for further refinement (Buchwitz et al., 2013).

Descriptions of Satellite Data Products of Variables that Control Wetland Emissions

The main factors that control wetland emissions and are observable from space are inundation, surface temperature, land cover, and snow/ice cover. Only some of the potential datasets are listed here.

Inundation/Soil Moisture: Satellite data from various instruments have been used to infer that much of the seasonal cycle and most of the interannual variation in methane fluxes is explained by variations in inundation extent (Mialon et al., 2005; Prigent et al., 2007; Bloom et al., 2010; Ringeval et al., 2010). For example, Watts et al. (2012) used daily fractional open water from the Aqua Advanced Microwave Scanning Radiometer for EOS (AMSR-E) for 2003-2010 to estimate trends in inundation, finding no overall trend for the boreal Arctic. The recent WETCHIMP exercise noted that the current remotely-sensed inundation datasets often show a wide range of estimates (Melton et al., 2013). There is an ongoing effort of the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) program to create an "inundated wetlands earth system data record" (https://earthdata.nasa.gov/our-community/community-data-system-programs/measures-projects/global-monitoring-wetlands). GRACE (2002-present) and AMSR-E (2002-2011) surface soil moisture data may be used as proxies for inundation. Upcoming missions that will provide important information include the Soil Moisture Active Passive (SMAP; https://smap.jpl.nasa.gov/) mission which will provide soil moisture and freeze/thaw measurements and the ESA Soil Moisture and Ocean Salinity (SMOS; http://www.esa.int/Our_Activities/Observing_the_Earth/SMOS/Mapping_soil_moisture_and_ocean_salinity) mission.

Surface Temperature: As surface temperature is known to influence wetland emissions, particularly in boreal regions, the "MOD11 Land Surface Temperature and Emissivity" data products from MODIS, an instrument which is on both the Terra (1999-present) and Aqua satellites (2002-present), is useful. The current NPP Visible Infrared Imaging Radiometer Suite (VIIRS) instrument is collecting data to continue the MODIS record.

Snow/Ice Cover: Pickett-Heaps et al. (2011) found that their model's prediction of wetland emissions from the Hudson Bay Lowlands was biased high in fall and spring, which they attributed to their emissions scheme disregard of snow cover. For the boreal regions, satellite data on snow cover, specifically the "MOD 10 - Snow Cover" product suite, provide fractional snow cover and snow albedo. The current NPP Visible Infrared Imaging Radiometer Suite (VIIRS) instrument is collecting data to continue the MODIS record.

Vegetation Cover: There is a 32-year record of MODIS Normalized Difference Vegetation Index (NDVI) which provides information on the greening of vegetation that is associated with surface temperatures at high latitudes and sometimes inundation in seasonal wetlands.

Precipitation: In the absence of inundation information, monthly merged precipitation analyses from the Global Precipitation Climatology Project (GPCP; http://precip.gsfc.nasa.gov/), which is based on a number of satellite data products and covers 1979 to present, may be useful. The current Global Precipitation Measurement (GPM) mission, which recently launched, will provide important information on precipitation, continuing the record of the Tropical Rainfall Measuring Mission (TRMM).

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