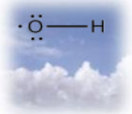
GLOBAL CARBON PROJECT



Global Methane Budget 2020

The Global Methane budget for 2000-2017

The GCP is a Global Research Project of futurearth Research. Innovation. Sustainability. and a Research Partner of WCRP World Climate Research Programme

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Atmospheric CH_4 datasets

- NOAA/ESRL (Dlugokencky et al., 2011)
- AGAGE (Rigby et al., 2008)
- CSIRO (Francey et al., 1999)
- UCI (Simpson et al., 2012)

Top-down atmospheric inversions

- CarbonTracker-Europe CH_4 (Tsuruta et al., 2017)
- GELCA (Ishizawa et al., 2016)
- LMDz-SACS- PYVAR (Zheng et al., 2018a; 2018b;Yin et al., 2015)
- MIROC4-ACTM (Patra et al., 2016; 2018)
- NICAM-TM (Niwa et al., 2017b;2017b)
- TM5-4DVAR (Houweling et al., 2014)
- NIES-TM- Flexpart (Maksyutov et al., 2020; Wang et al., 2019a)
- TM5-CAMS (Pandey et al., 2016; Segers and Houwelling, 2018)
- TM5-4DVAR (Bergamaschi et al., 2013;2018)

Bottom-up modeling

- Description of models contributing to the Chemistry Climate Model Initiative (CCMI) (Morgenstern et al., 2017)
- Description of OH fields from CCMI (Zhao et al., 2019)

Bottom-up studies data and modeling

- CLASS-CTEM (Arora et al. 2018; Melton and Arora, 2016)
- DLEM (Tian et al., 2010;2015)
- ELM (Riley et al., 2011)
- JSBACH (Kleinen et al., 2019)
- JULES (Hayman et al., 2014)
- LPJ-GUESS (McGuire et al., 2012)
- LPJ-MPI (Kleinen et al., 2012)
- LPJ-wsl (Zhang et al., 2016)
- LPX-Bern (Spahni et al., 2011)
- ORCHIDEE (Ringeval et al., 2011)
- TEM-MDM (Zhuang et al., 2004)
- TRIPLEX-GHG (Zhu et al., 2104; 2015)
- VISIT (Ito ad Inatomi, 2012)
- FINNv1.5 (Wiedinmyer et al., 2011)
- GFASv1.3 (Kaiser et al., 2012)
- GFEDv4.1s (Giglio et al., 2013)
- QFEDv2.5 (Darmenov and da Silva, 2015)
- CEDS (Hoesly et al., 2018)
- IIASA GAINS ECLIPSEv6 (Höglund-Isaksonn, 2012)
- EPA, 2012
- EDGARv4..3.2FT (Janssens-Maenhout et al. 2019)
- FAO (Tubiello et al., 2013; 2019)

Full references provided in Saunois et al. 2020, ESSD

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Publications

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Open Access Earth System Science Data

The Global Methane Budget 2000–2017

Marielle Saunois[1], Ann R. Stavert[2], Ben Poulter[3], Philippe Bousquet[1], Josep G. Canadell[2], Robert B. Jackson[4], Peter A. Raymond[5], Edward J. Dlugokencky[6], Sander Houweling[7,8], Prabir K. Patra[9,10], Philippe Ciais[1], Vivek K. Arora[11], David Bastviken[12], Peter Bergamaschi[13], Donald R. Blake[14], Gordon Brailsford[15], Lori Bruhwiler[6], Kimberly M. Carlson[16,17], Mark Carrol[70], Simona Castaldi[18,19,20], Naveen Chandra[9], Cyril Crevoisier[21], Patrick M. Crill[22], Kristofer Covey[23], Charles L. Curry[24,71], Giuseppe Etiope[25,26], Christian Frankenberg[27,28], Nicola Gedney[29], Michaela I. Hegglin[30], Lena Höglund-Isaksson[31], Gustaf Hugelius[32], Misa Ishizawa[33], Akihiko Ito[33], Greet Janssens-Maenhout[13], Katherine M. Jensen[34], Fortunat Joos[35], Thomas Kleinen[36], Paul B. Krummel[37], Ray L. Langenfelds[37], Goulven G. Laruelle[38], Licheng Liu[39], Toshinobu Machida[33], Shamil Maksyutov[33], Kyle C. McDonald[34], Joe McNorton[40], Paul A. Miller[41], Joe R. Melton[42], Isamu Morino[33], Jurek Müller[35], Fabiola Murguia-Flores[43], Vaishali Naik[44], Yosuke Niwa[33,45], Sergio Noce[20], Simon O'Doherty[46], Robert J. Parker[47], Changhui Peng[48], Shushi Peng[49], Glen P. Peters[50], Catherine Prigent[51], Ronald Prinn[52], Michel Ramonet[1], Pierre Regnier[38], William J. Riley[53], Judith A. Rosentreter[54], Arjo Segers[55], Isobel J. Simpson[14], Hao Shi[56], Steven J. Smith[57,58], L. Paul Steele[37], Brett F. Thornton[22], Hanqin Tian[56], Yasunori Tohjima[72], Francesco N. Tubiello[59], Aki Tsuruta[60], Nicolas Viovy[1], Apostolos Voulgarakis[61,62], Thomas S. Weber[63], Michiel van Weele[64], Guido R. van der Werf[8], Ray F. Weiss[65], Doug Worthy[66], Debra Wunch[67], Yi Yin[1,27], Yukio Yoshida[33], Wenxin Zhang[41], Zhen Zhang[68], Yuanhong Zhao[1], Bo Zheng[1], Qing Zhu[53], Qiuan Zhu[69], and Qianlai Zhuang[39]

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PERSPECTIVE

Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources

R B Jackson[1], M Saunois[2], P Bousquet[2], J G Canadell[3], B Poulter[4], A R Stavert[5], P Bergamaschi[6], Y Niwa[7,8], A Segers[9] and A Tsuruta[10]

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Data access

http://www.globalcarbonproject.org/methanebudget

https://www.icos-cp.eu/GCP-CH4/2019

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Global Methane Budget Website

http://www.globalcarbonproject.org/methanebudget

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All data are shown in

teragrams CH_4 ($TgCH_4$) for emissions and sinks

parts per billion (ppb) for atmospheric concentrations

1 teragram (Tg) = 1 million tonnes = 1×10^{12}g

2.78 Tg CH_4 per ppb

Disclaimer

The Global Methane Budget and the information presented here are intended for those interested in learning about the carbon cycle, and how human activities are changing it. The information contained herein is provided as a public service, with the understanding that the Global Carbon Project team make no warranties, either expressed or implied, concerning the accuracy, completeness, reliability, or suitability of the information.

Context & Methods

The methane context

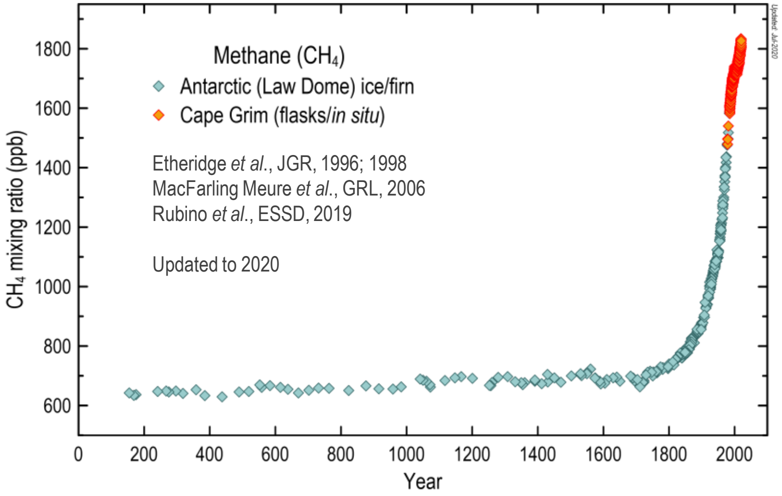
- After carbon dioxide (CO_2), methane (CH_4) is the most important greenhouse gas contributing to human-induced climate change.

- For a time horizon of 100 years, CH_4 has a Global Warming Potential 28 times larger than CO_2.

- Methane is responsible for 23% of the global warming produced by CO_2, CH_4 and N_2O.

- The concentration of CH_4 in the atmosphere is 150% above pre-industrial levels (cf. 1750).

- The atmospheric lifetime of CH_4 is 9±2 years, making it a good target for climate change mitigation



- Methane also contributes to tropospheric production of ozone, a pollutant that harms human health, foof production and ecosystems.

- Methane also leads to production of water vapor in the stratosphere by chemical reactions, enhancing global warming.

Sources : Saunois et al. 2016; 2020, ESSD; IPCC 2013 5AR; Etminan et al. 2016

An ensemble of tools and data to estimate the global methane budget

GLOBAL CARBON PROJECT

Bottom-up budget ← Emission inventories, Biogeochemistry models & data-driven methods, Methane sinks

Top-down budget ← Atmospheric observations, Emission inventories, Biogeochemistry models & data-driven methods, Methane sinks; Inverse models

Atmospheric observations

Ground-based data from observation networks (AGAGE, CSIRO, NOAA, UCI, LSCE, others).

Satellite data (GOSAT)

Emission inventories

Agriculture and waste related emissions, fossil fuel emissions (EDGARv4.3.2,CEDS, USEPA, GAINS, FAO).

Fire emissions (GFED4s, FINN, GFAS,QFED, FAO).

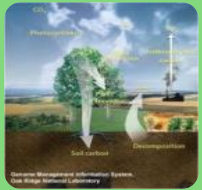
Biofuel estimates

Biogeochemistry models & data-driven methods

Ensemble of 13 wetland models

Model for termites emissions

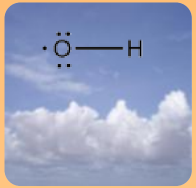
Other sources from literature (inland water, geological, wild animal…)



Methane sinks

OH sink from CCMI experiment.

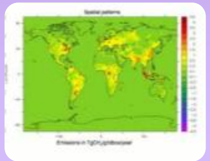
Soil uptake & chlorine sink taken from the literature



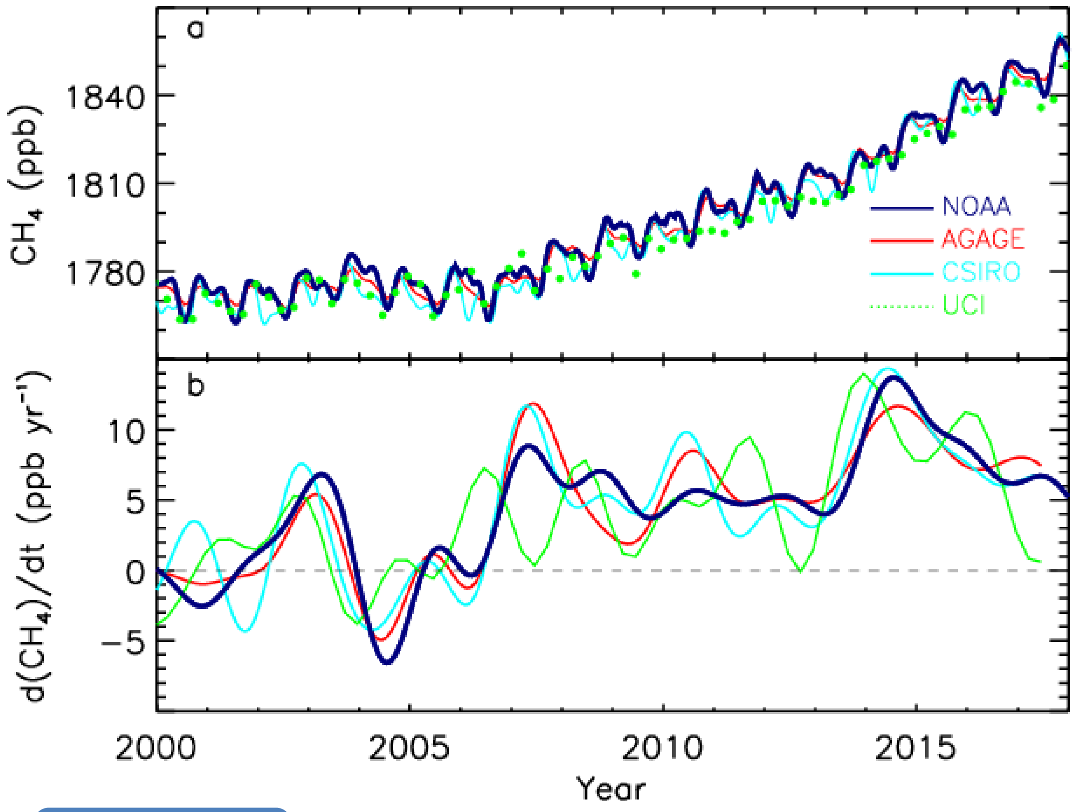
Inverse models

Suite of 9 atmospheric inversion models ($CTE\text{-}CH_4$, GELCA, PYVAR-LMDz, MIRO4-ACTM, NICAM-TM, NIES-TM FLEXPART, TM5-CAMS, TM5-4DVAR-NIES, TOMCAT).

Ensemble of 22 inversions (diff. obs & setup)



CH_4 Atmospheric Growth Rate 2000-2017



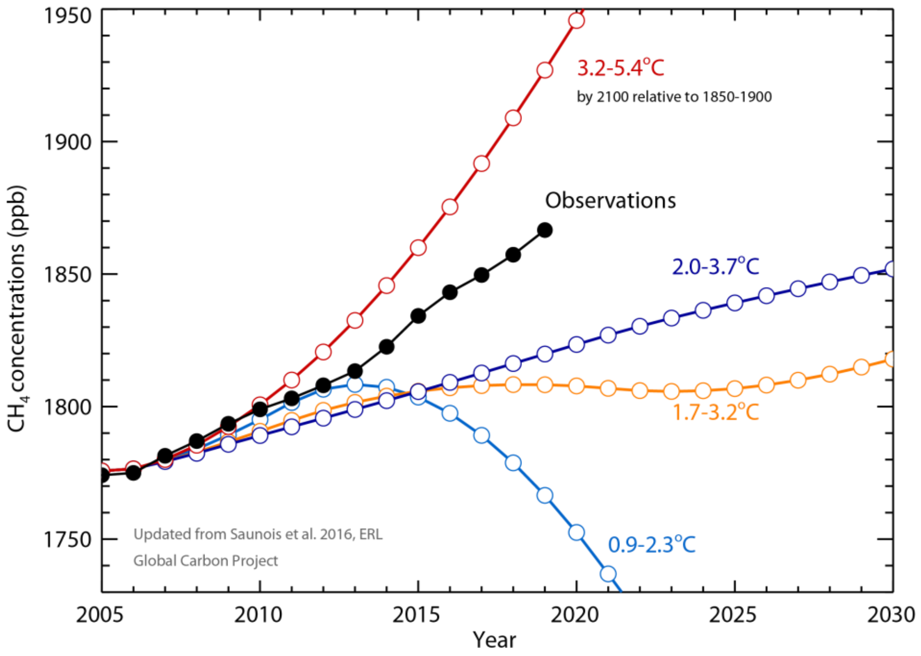
- Slowdown of atmospheric growth rate before 2006
- Resumed increase after 2006

Atmospheric observations

Source: Saunois et al. 2020, ESSD (Fig. 1)

Observed Concentrations Compared to IPCC Projections

The projections represented here correspond to RCPs defined for IPCC 5th Assessment Report



Observations: Globally averaged marine surface annual mean data from NOAA

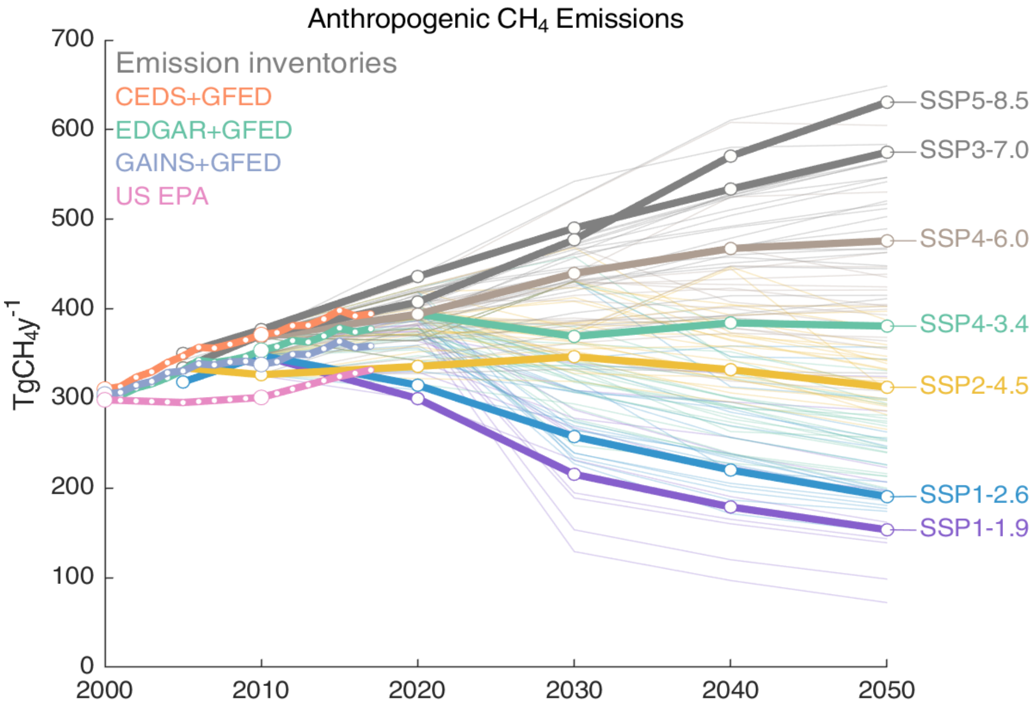
- Methane concentrations rose faster in 2014, 2015 and 2019 with more than 10 ppb/yr.
- Since 2013, the atmospheric increase is approaching the warmest scenario of IPCC AR5 report

Anthropogenic Methane Emissions & Socioeconomic Pathways (SSPs)

The projections represented here correspond to SSPs defined for IPCC 6th Assessment Report

Anthropogenic emissions:

- All inventories, except EPA, infers an increase in emissions as fast as the warmest scenarios between 2005 and 2017.



Forcing target & scenario temperature range in 2100
Median temperatures using MAGICC (ECS=3°C)
Baseline (3.0–5.1°C)
6.0W/m² (3.2–3.3°C)
4.5W/m² (2.5–2.7°C)
3.4W/m² (2.1–2.3°C)
2.6W/m² (1.7–1.8°C)
1.9W/m² (1.3–1.4°C)

Atmospheric observations

Emission inventories

Source: Saunois et al. 2020, ESSD (Fig. 2)

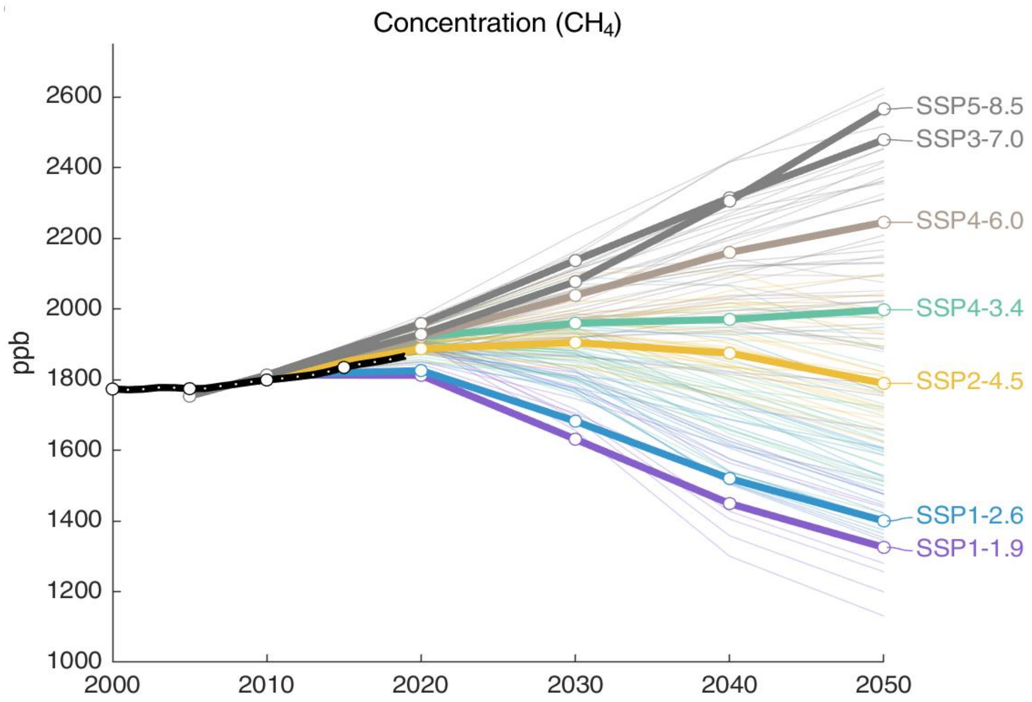
Methane Concentrations & Socioeconomic Pathways (SSPs)

The projections represented here correspond to SSPs defined for IPCC 6th Assessment Report

Atmospheric concentrations:

- Atmospheric observations (black line) fall between the estimates of the different scenarios

=> Monitoring of future years trends in emissions and concentration is critical to assess mitigation policy efficiency



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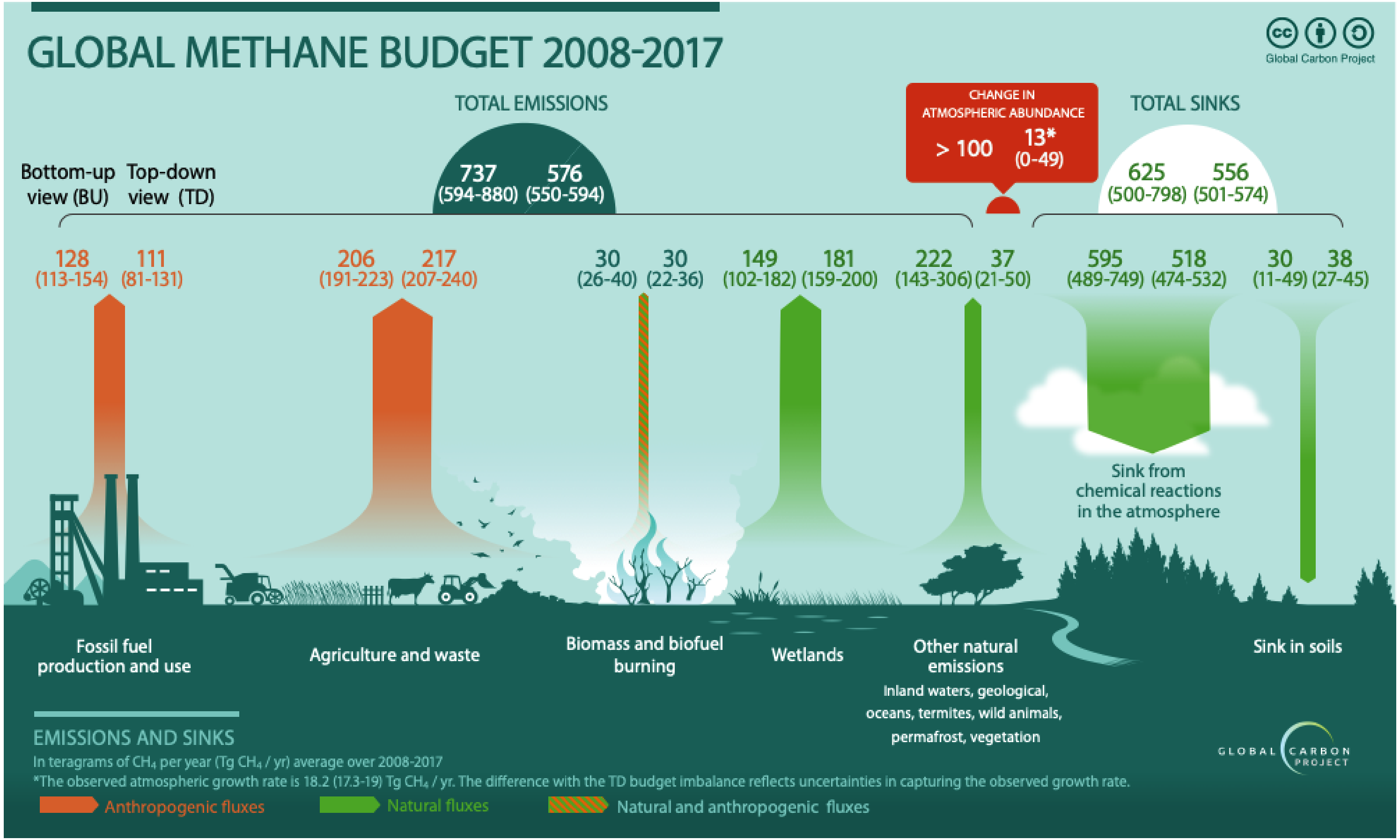
Atmospheric observations

Emission inventories

Source: Saunois et al. 2020, ESSD (Fig. 2)

Decadal emissions & sinks

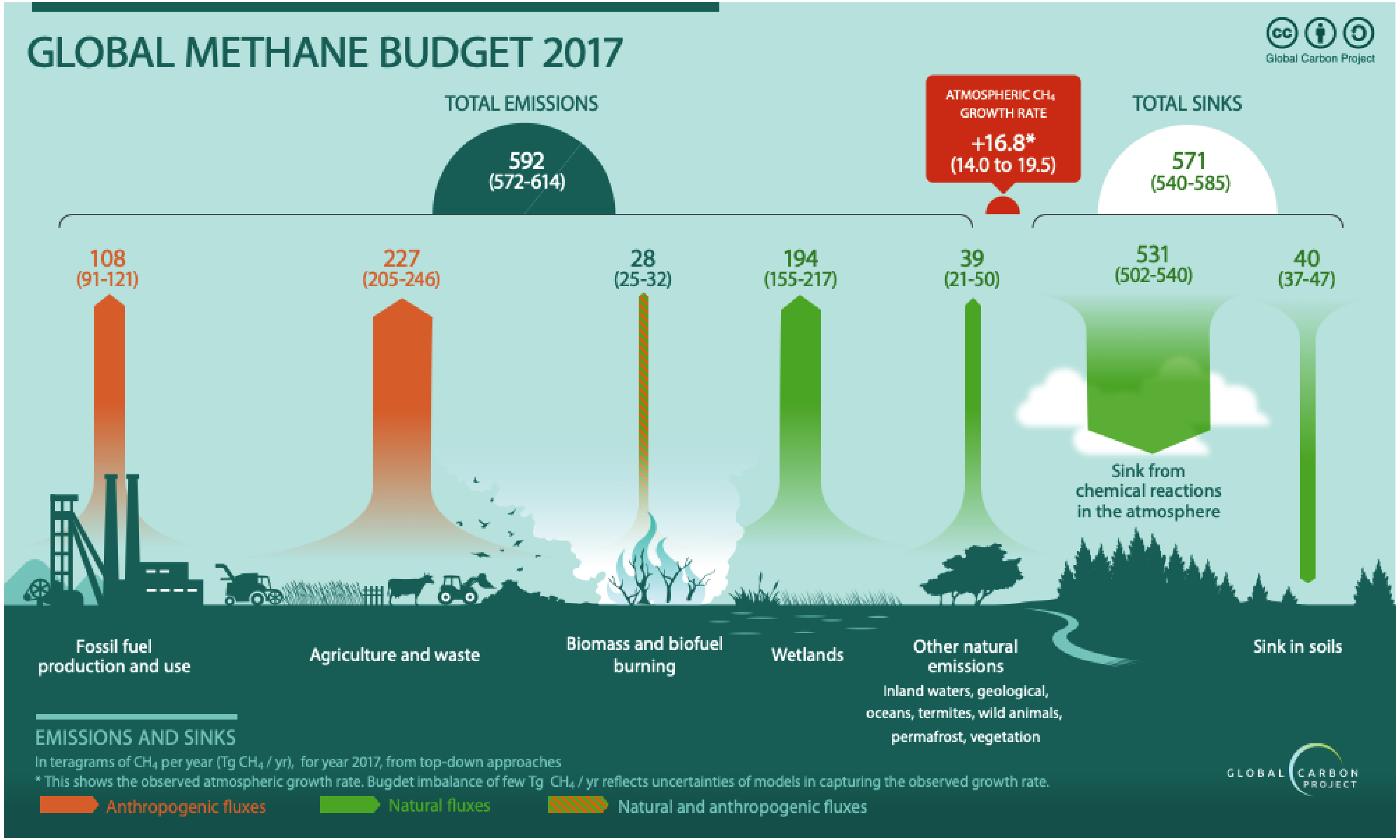
Global Methane Budget 2008-2017



Source: Saunois et al. 2020, ESSD (Fig. 6)

Global Methane Budget 2017

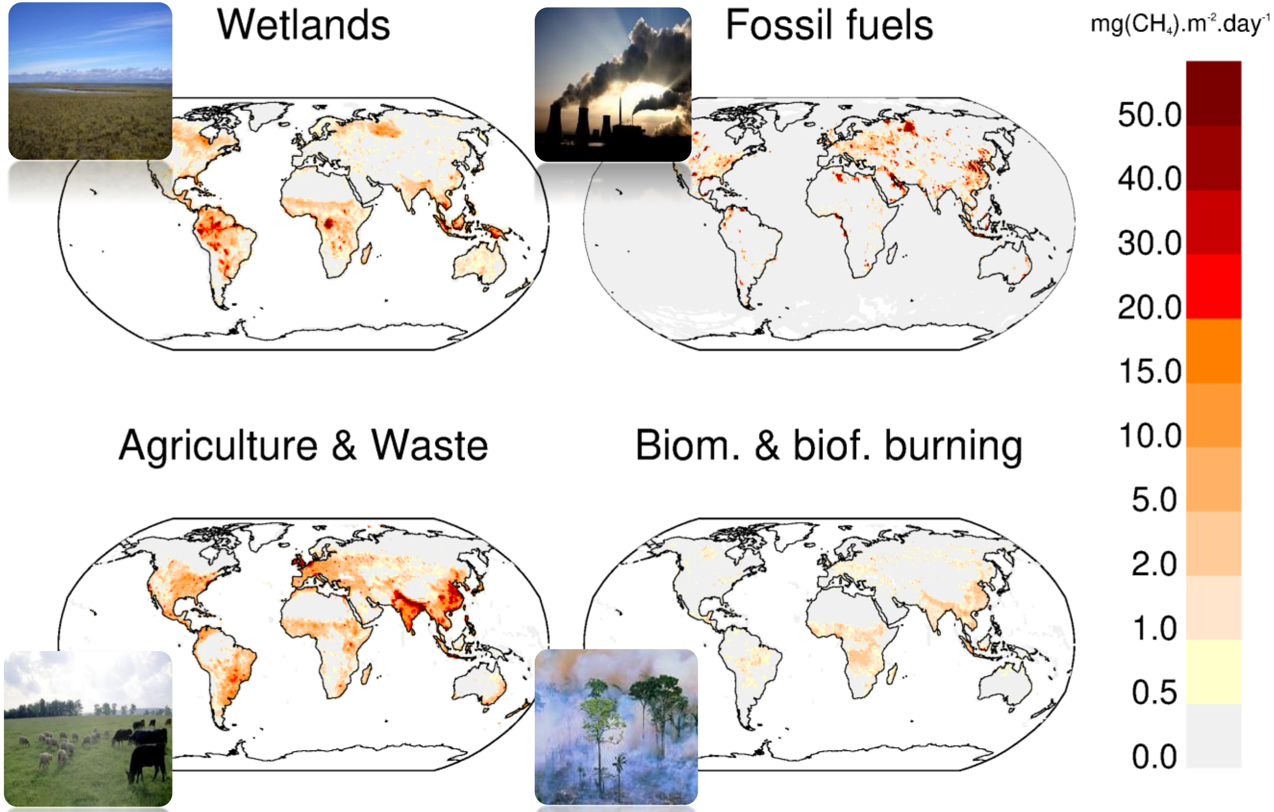
Top-down budget



Source: *Jackson et al. 2020, ERL (Fig. 1)*

Mapping of the largest methane source categories

Bottom-up budget



Emission inventories

Biogeochemistry models & data-driven methods

Source: Saunois et al. 2020, ESSD (Fig 3);

Wetland methane emissions

- Wetlands are the largest natural global CH_4 source

- Vegetated wetland emissions are estimated using an ensemble of land-surface models constrained with remote-sensing based surface water and inventory based vegetated wetlands

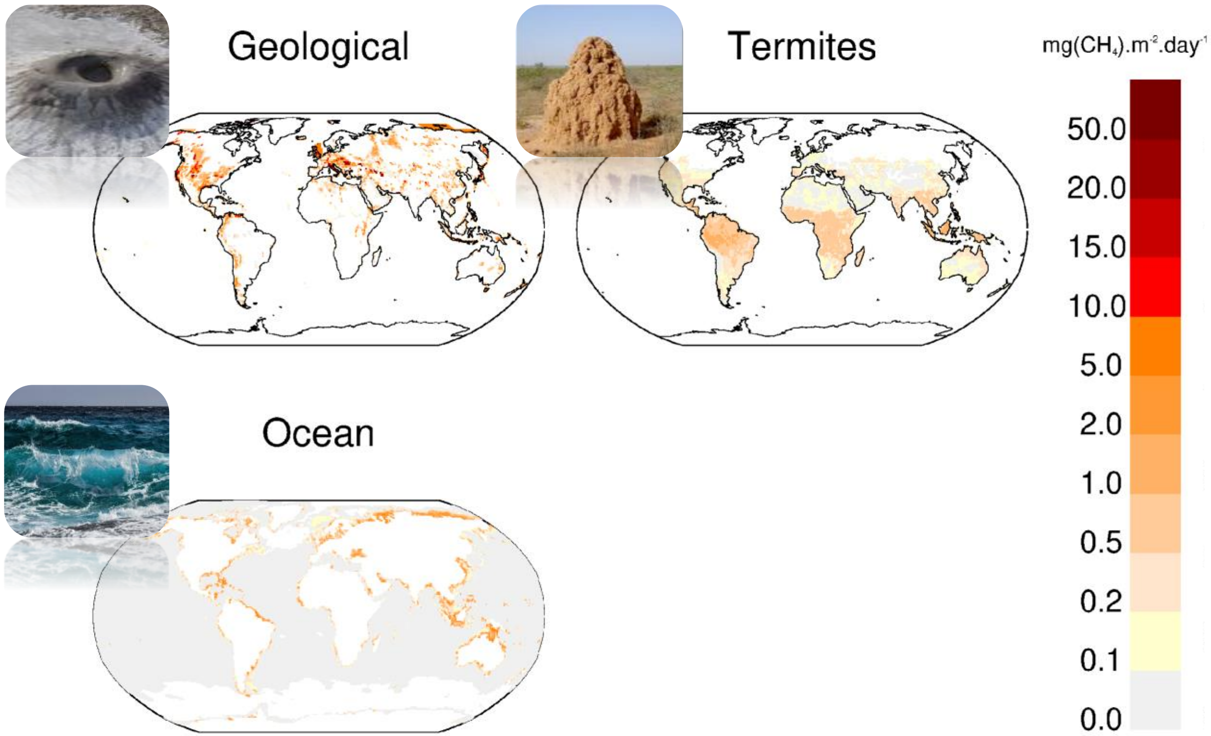
- The resulting global flux range for natural wetland emissions is 102–182 $TgCH_4$/yr for the decade of 2008–2017, with an average of 149 TgCH4/yr.

Biogeochemistry models & data-driven methods

Source: *Saunois et al. 2020, ESSD*

Mapping other natural sources

Bottom-up budget



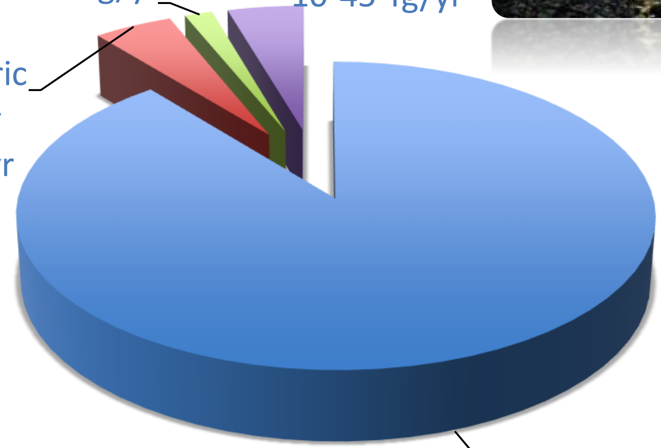
Other natural sources not mapped here are inland water emissions, permafrost and hydrates

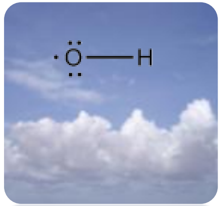
Biogeochemistry models & data-driven methods

Source: Saunois et al. 2020 (Fig 4)

Methane Sinks (2000s)

Bottom-up budget





Source : Saunois et al., 2020

Methane sinks

Global Methane Emissions 2008-2017

Bottom-up budget | ($TgCH_4$/yr) | **Top-down budget**

	Bottom-up budget	Top-down budget
Natural wetlands	**149 [50%]**	**181 [20%]**
Agriculture & waste	**206 [15%]**	**217 [15%]**
Rice	30 [40%]	
Enteric ferm & manure	111 [10%]	
Landfills & waste	65 [15%]	
Fossil fuel	**128 [30%]**	**111 [50%]**
Coal	42 [80%]	
Gas & oil	80 [30%]	
Industry and transport	7 [250 %]	
Biomass/biofuel burning	**30 [30%]**	**30 [50%]**
Other natural emissions	**222 [70%]**	**37 [80%]**
Inland waters	209 [70%]	
Geological	45 [100%]	
Termites	9 [100%]	
Oceans	6 [100%]	
Wild animals	2 [100%]	
Permafrost	1 [100%]	

Mean [uncertainty= min-max range %]

Mean [uncertainty = min-max range %]

Bottom-up budget

Process models, inventories, data driven methods

737 $TgCH_4$/yr [584-881]

Mean [min-max range %]

Top-down budget

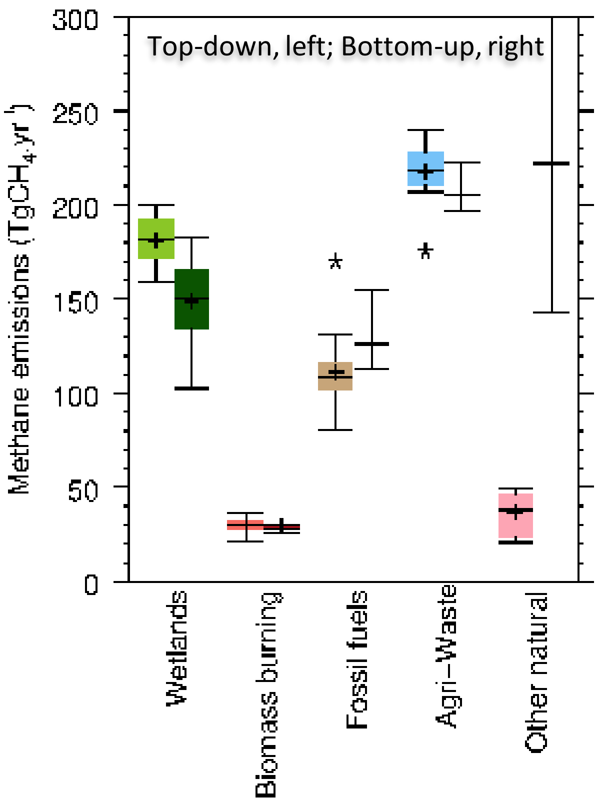
Atmospheric inversions

576 $TgCH_4$/yr [550-594]

Source : Saunois et al. 2020, ESSD

Global Methane Emissions 2008-2017

- Global emissions:
  576 $TgCH_4$/yr [550-594] for TD
  737 $TgCH_4$/yr [594-881] for BU
- TD and BU estimates generally agree for agricultural emissions
- Estimated fossil fuel emissions are lower for TD than for BU approaches
- Estimated wetland emissions are higher for TD than for BU approaches
- Large discrepancy between TD and BU estimates for freshwaters and natural geological sources ("other natural sources")



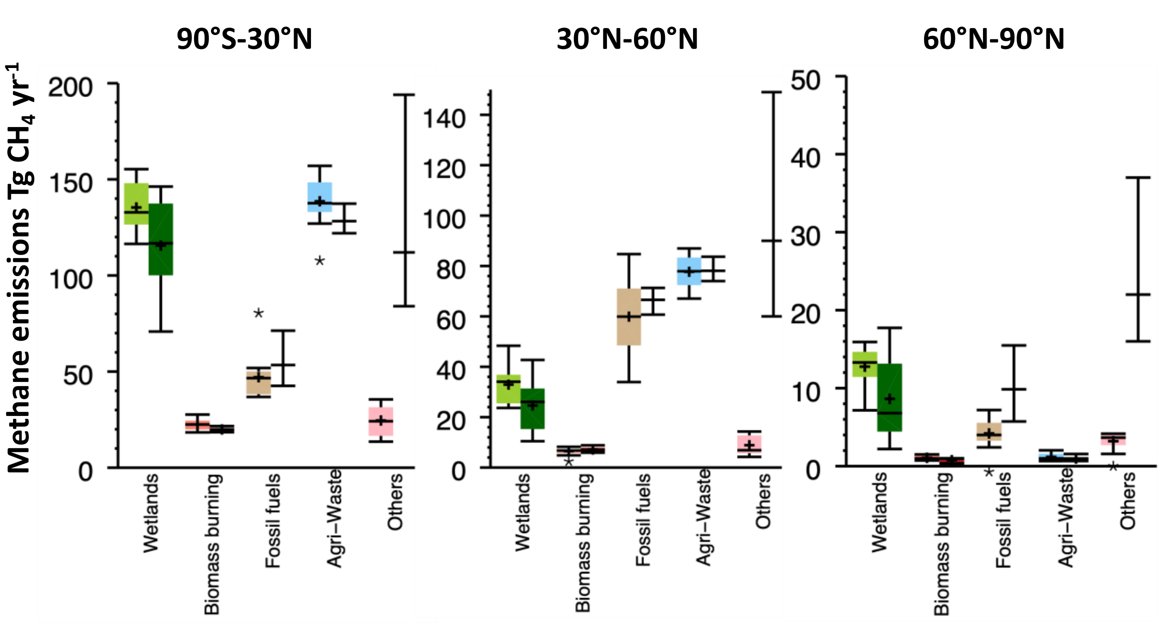
Source: Saunois et al. 2020, ESSD (Fig 5)

Emission inventories

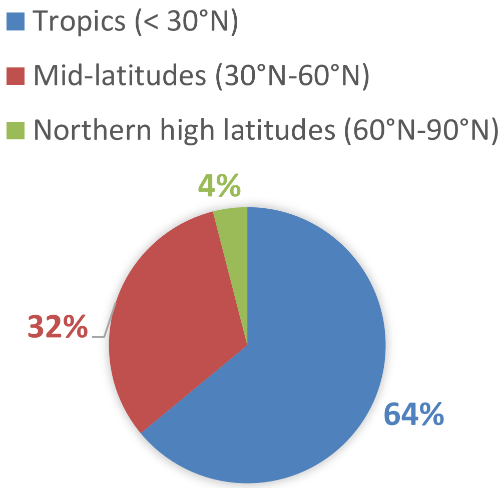
Biogeochemistry models & data-driven methods

Inverse models

Methane emissions by latitudinal bands 2008-2017



Contribution to global emissions



Source: Saunois et al. 2020, ESSD (Fig 7)

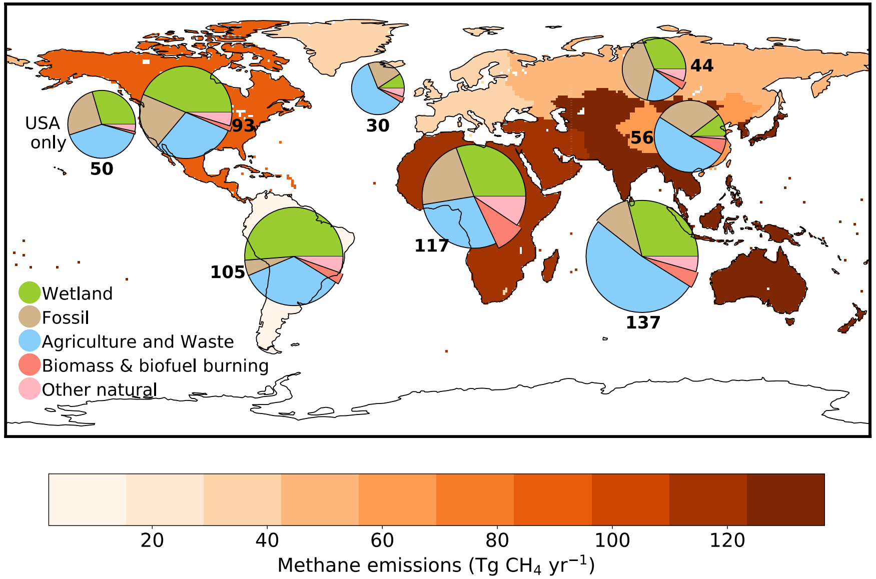
Emission inventories

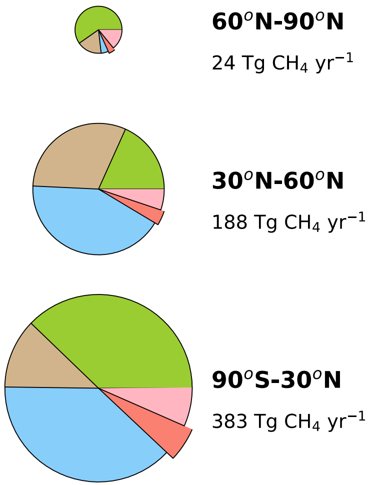
Biogeochemistry models & data-driven methods

Inverse models

Regional Methane Sources (2017)

Top-down budget



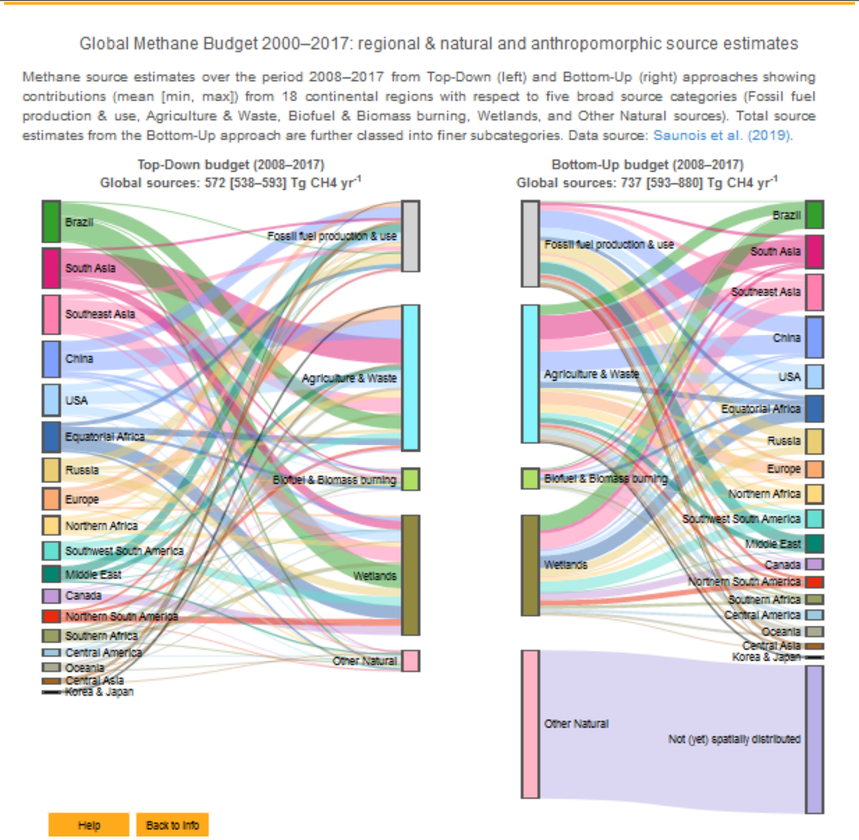


- 64% of global methane emissions come mostly from tropical sources
- Anthropogenic sources are responsible for about 60% of global emissions.
- Largest emissions in South America, Africa, South-East Asia and China (50% of global emissions)
- Dominance of wetland emissions in the tropics and boreal regions
- Dominance of agriculture & waste in Asia
- Balance between agriculture & waste and fossil fuels at mid-latitudes

Source: Jackson et al. 2020 ERL (Fig 2)

Inverse models

An interactive view of the methane budget



Source: *Carbon Atlas*

www.globalcarbonatlas.org

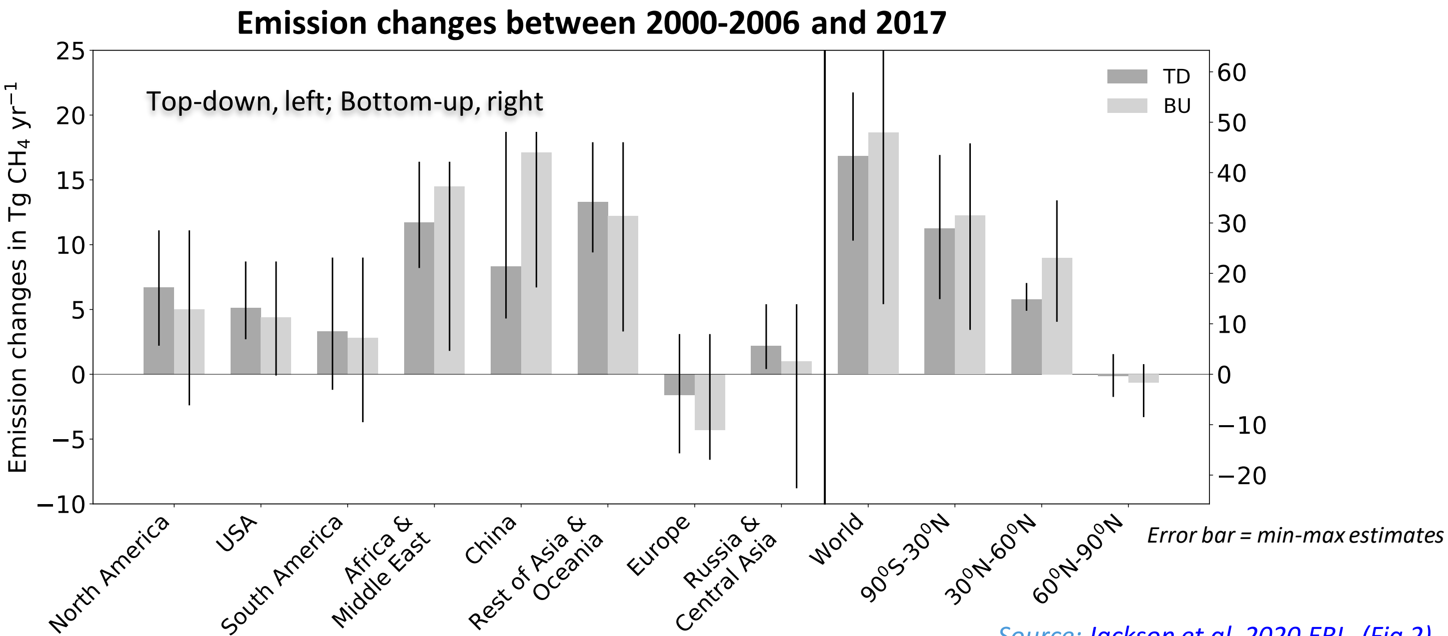
Emission inventories

Biogeochemistry models & data-driven methods

Inverse models

Emission changes

Changes in Methane Sources



Source: Jackson et al. 2020 ERL (Fig 2)

- About 50 $TgCH_4$/yr emissions increase between 2000-2006 and 2017
- Increase mainly from the Tropics (about 30 $TgCH_4$/yr), followed by mid-latitudes (15-20 $TgCH_4$/yr)
- Regional contributions from Africa and Middle East, China and rest of Asia
- Increase in North America driven by the increase from USA
- Decrease in Europe

Emission inventories

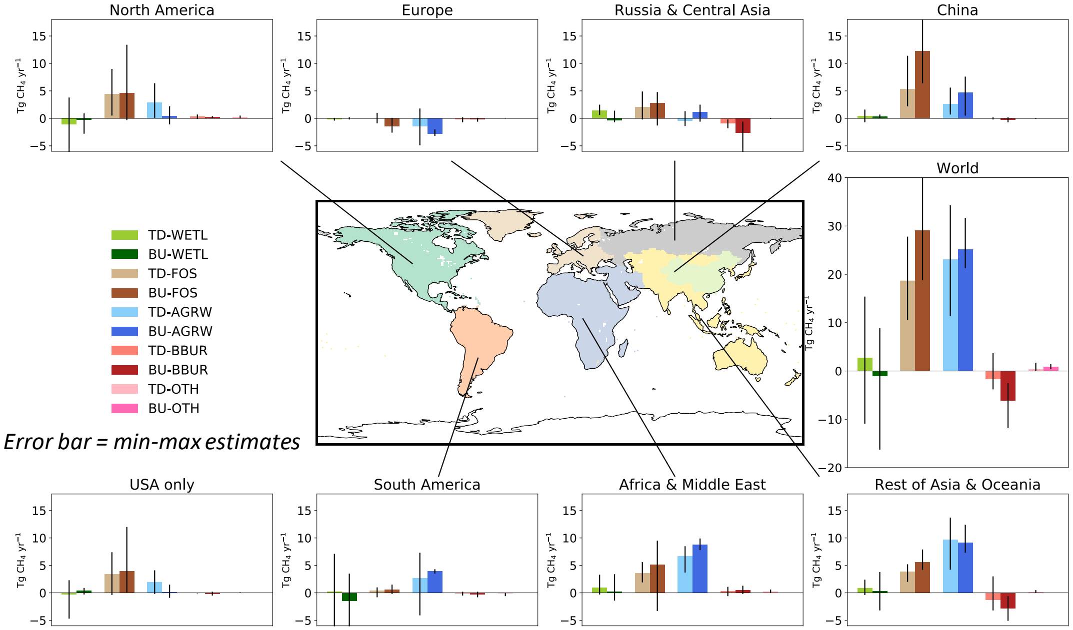
Biogeochemistry models & data-driven methods

Inverse models

Changes in Methane Sources

Emission changes between 2000-2006 and 2017

Top-down, left; Bottom-up, right



Error bar = min-max estimates

- Global increase mainly from anthropogenic sources equally between Agriculture and Waste and Fossil Fuel
- Fossil Fuel emissions increased in China, North America (USA), Africa, and Asia
- Agriculture and Waste emissions increased mostly in Africa, Southern Asia and South America
- Emissions decreased in Europe from both Fossil Fuel and Agriculture and Waste sources

Source: Jackson et al. 2020 ERL (Fig 2)

Emission inventories

Biogeochemistry models & data-driven methods

Inverse models

Sink changes

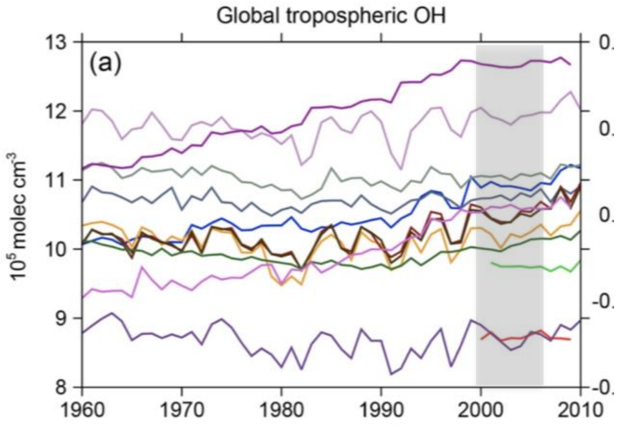
Concentrations of OH the troposphere

- Hydroxyl radical, OH is the main oxidant of CH_4, responsible of about 90% of methane removal in the atmosphere.

- Two approaches derive estimates of OH quantity in the atmosphere:
  1. Chemistry climate models that includes hundreds chemical reactions between numerous species
  2. Box-modeling based on methyl-chloroform (MCF) observations

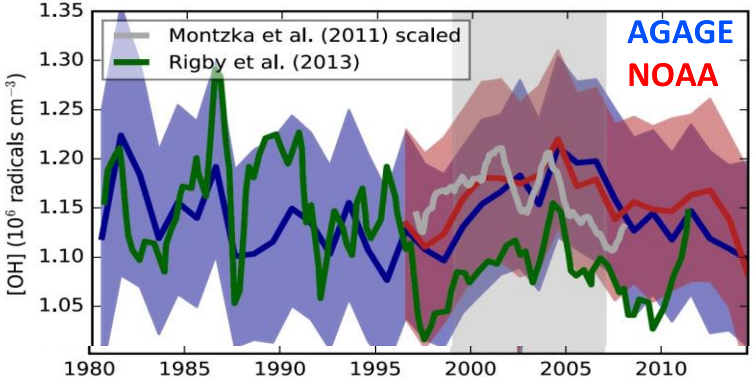
- Both approaches derive a 10-15% uncertainty on global OH mean concentrations.

Chemistry Climate models



Source: Zhao et al. 2019

MCF-based box modelling



Source: Rigby et al. 2017

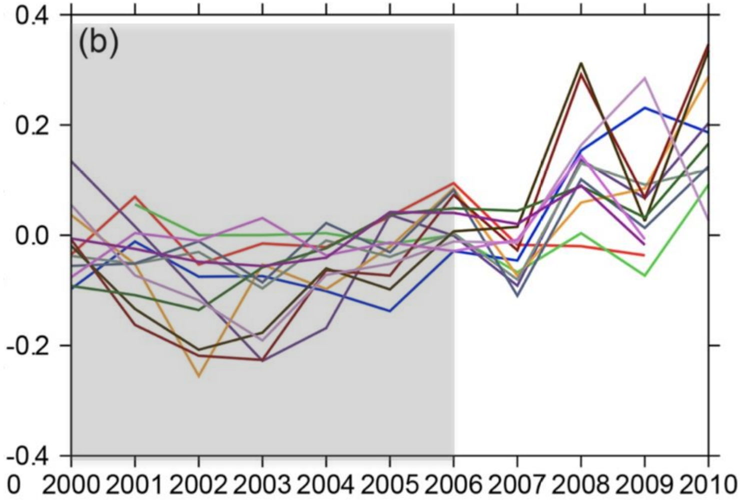
OH inter-annual variability and trend

- Chemistry climate models derive a null to positive trend in OH over 2000-2017
- MCF-based box modelling suggest a positive trend in OH over 1997-2005 followed by a negative trend from 2005 onward

⇒ High uncertainty remains on OH trend and interannual variability

<u>Chemistry climate models</u>

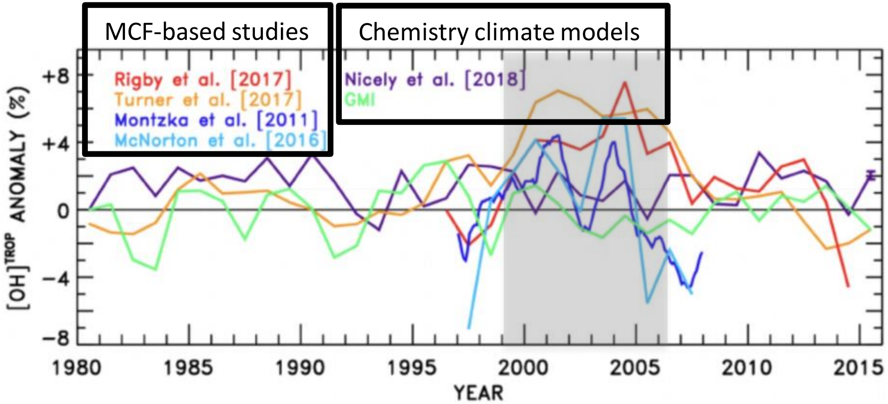
OH anomaly 2000–2010



Source: *Zhao et al. 2019*

<u>MCF-based box modelling versus chemistry climate models</u>

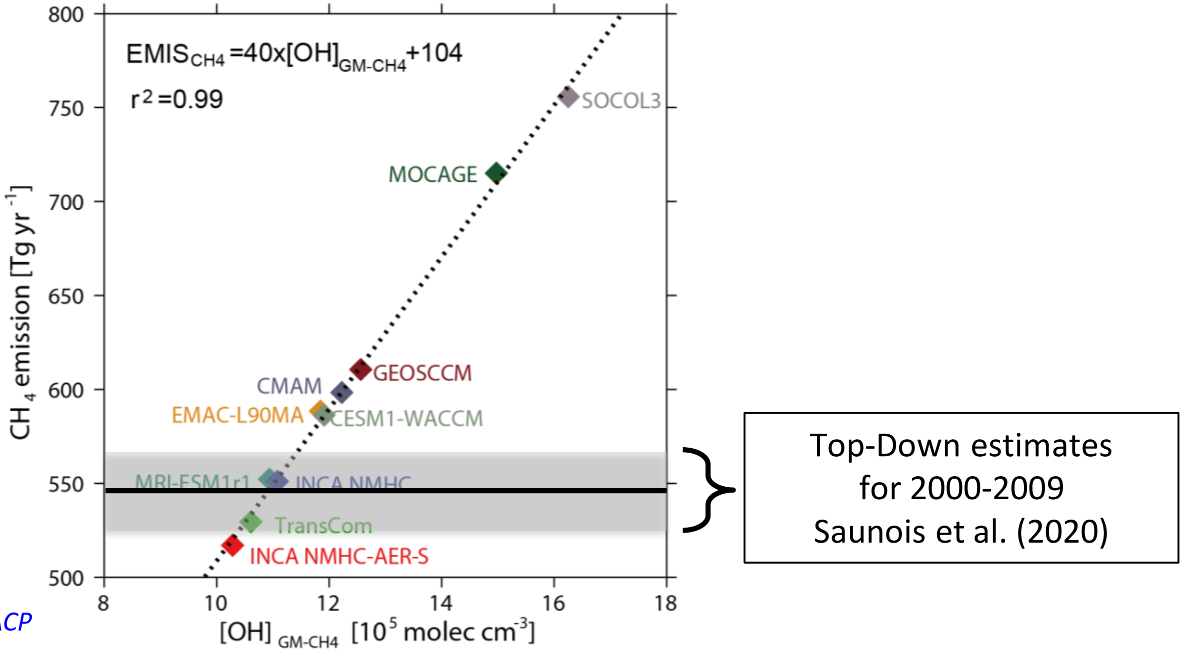
OH anomaly 1980-2015



Source: *Ganesan et al. 2020*

OH uncertainty & impact on CH_4 emissions

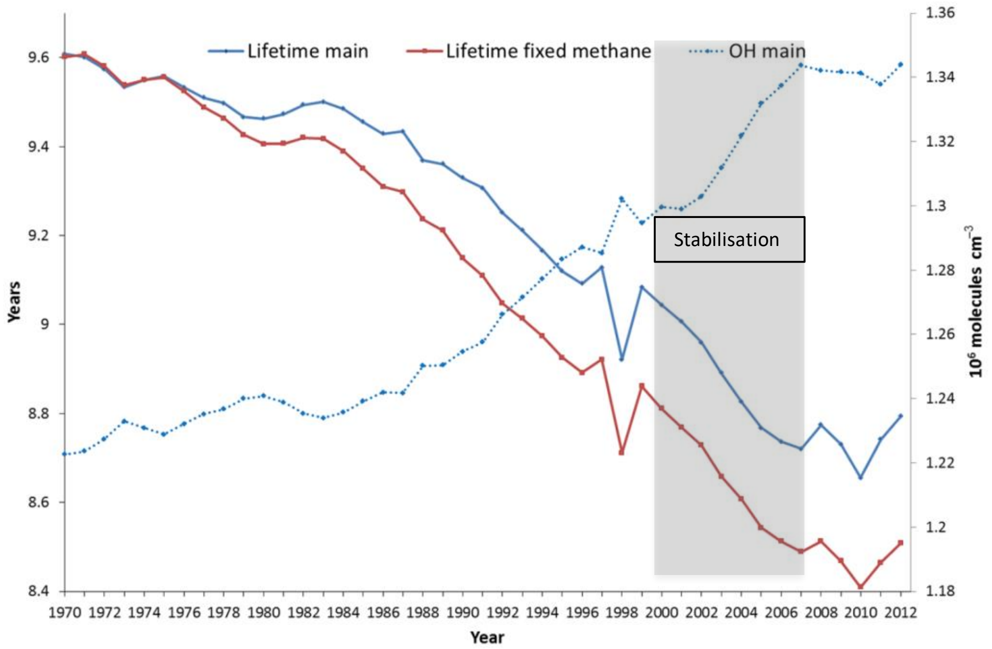
Estimated CH_4 total emissions in year 2001 by one single top-down system using different OH distributions



Source: *Zhao et al. 2020, ACP*

- Methane emissions derived by top-down systems are dependent of the OH sink prescribed
- The range derived by an ensemble of top-down approaches in Saunois et al. (2020) is narrower than the one derived by a single top-down system when testing several OH distributions (from chemistry climate models)
- The uncertainty in global total methane emissions is probably underestimated in Saunois et al. (2020)

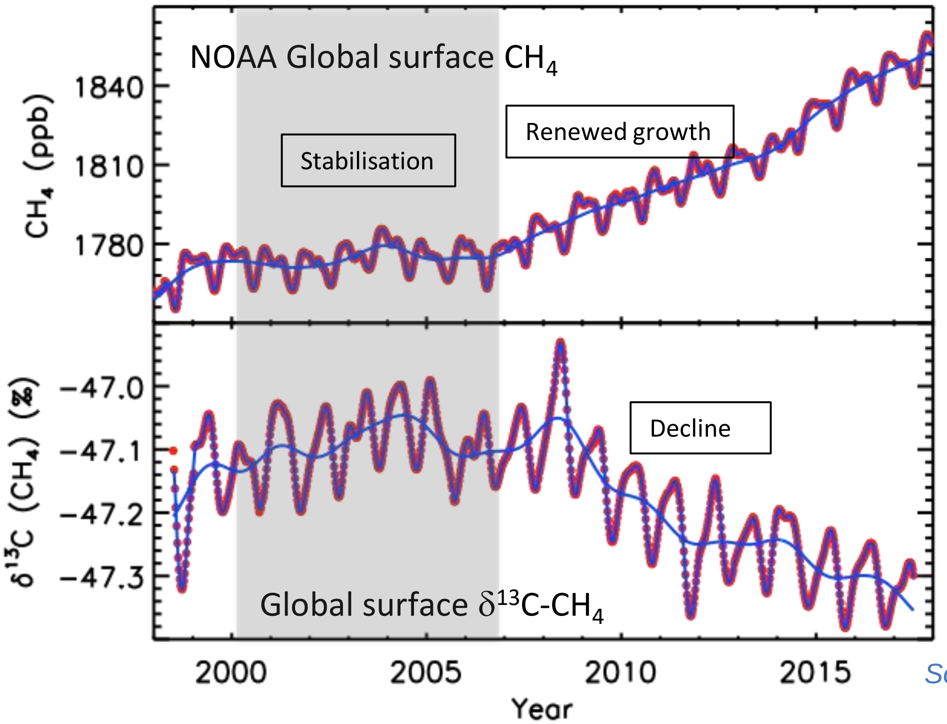
Impact of OH change in the methane sink



Source : Dalsoren et al., 2016

- OH increase before 2007 could explain part of the stabilization of atmospheric methane
- Stagnation or decrease in OH radicals can contribute to explain :
  - the renewed increase of atmospheric methane since 2007
  - The lighter atmosphere in ^{13}C isotope since 2007

Since 2007: a sustained atmospheric CH_4 growth and $\delta^{13}C-CH_4$ decrease



Source : *Nisbet et al., 2019*

1867 ppb reached in 2019 !

CH_4 Growth rates :

2014 : 12.7±0.5 ppb yr^{-1}
2015 : 10.1±0.7 ppb yr^{-1}
2016 : 7.0±0.6 ppb yr^{-1}
2017 : 7.0±0.9 ppb yr^{-1}
2018 : 8.5±0.6 ppb yr^{-1}
2019 : 10.7±0.6 ppb yr^{-1}

$\delta^{13}C-CH_4$ decreased by -0.2‰ in 10 years

- Need to understand which changes in emissions are responsible for both increasing atmospheric methane and decreasing $\delta^{13}C-CH_4$ since 2007

Highlights

- Atmospheric CH_4 concentrations are rising faster over the last decades than in the 2000s. Since 2013, the trend in atmospheric methane concentrations is closer to the most greenhouse-gas-intensive scenarios of IPCC AR5 than scenarios integrating mitigation policies.

- Anthropogenic sources are responsible for all or most of the recent rapid rise in global CH_4 concentrations, equally from agriculture and fossil fuels sources. Tropical regions play the most significant role as contributors to the atmospheric growth.

- The role of methane sinks has to be further explored as a slower destruction of methane by OH radicals in the atmosphere could have also contributed to the observed atmospheric changes of the past decade. However high uncertainties on OH burden and trend prevent any solid conclusions.

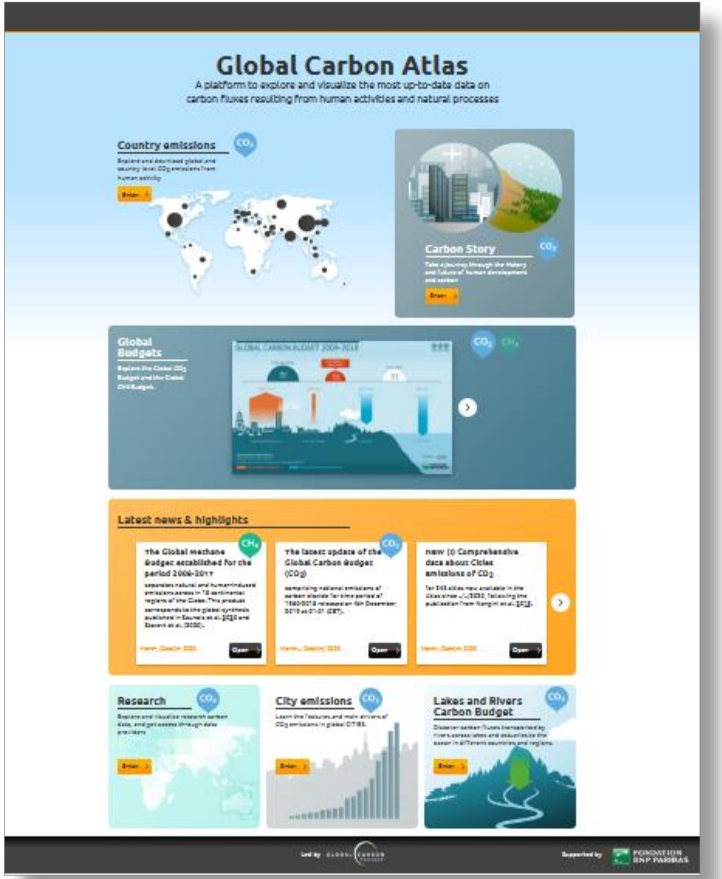
- Methane global emissions were 576 $TgCH_4$/yr [550-594] for 2008-2017 as inferred by an ensemble of atmospheric inversions (top-down approach) using an atmospheric constraint.

- Methane mitigation offers rapid climate benefits and economic, health and agricultural co-benefits that are highly complementary to CO_2 mitigation.

- Emission estimates from inventories/models (bottom-up approach) show larger global totals because of larger natural emissions. Improved emission inventories and estimates from inland water emissions are still needed.

GLOBAL CARBON PROJECT

Global Carbon Atlas

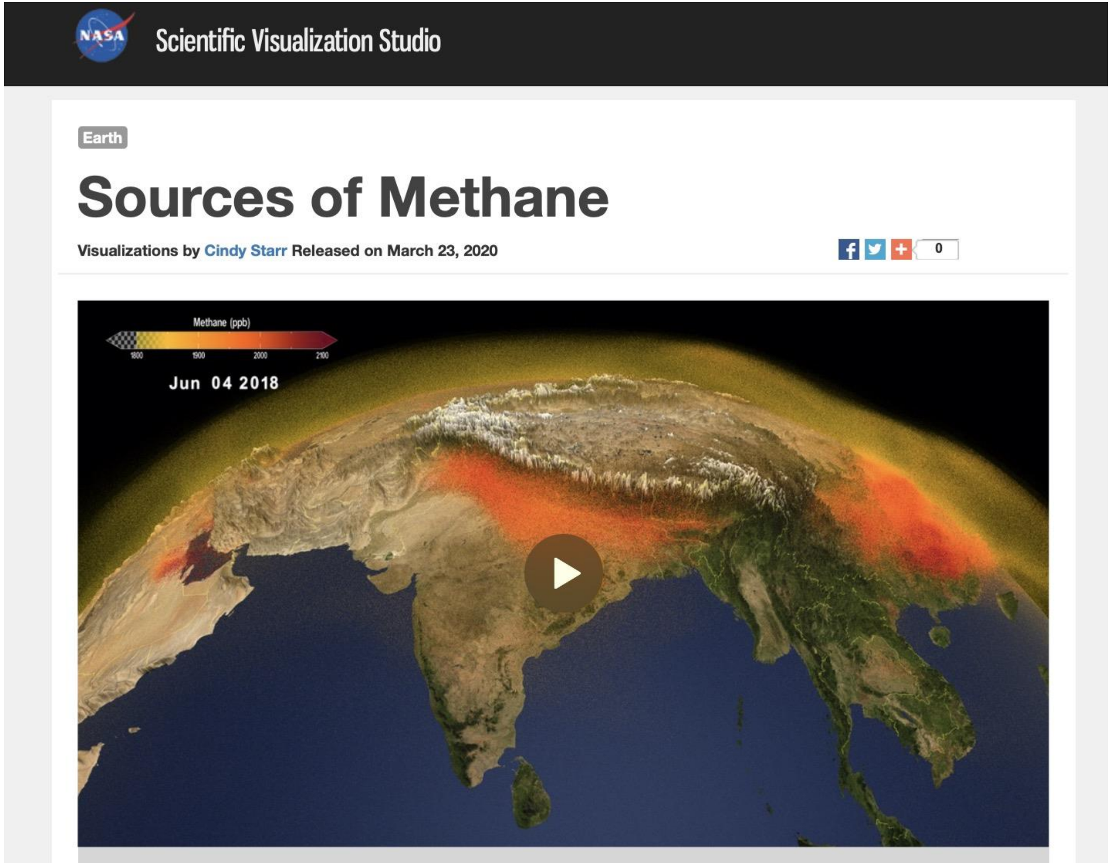


Explore GHG emissions globally and by country and download data and illustrations. Also explore ‘Outreach’ and ‘Research’.

www.globalcarbonatlas.org

NASA 3D visualization

The methane budget, using data from Saunois 2020, can be visualized in 3D at: https://svs.gsfc.nasa.gov/4799



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