Global
Methane Budget
2013

Three Decades of Global Methane Sources and Sinks

Version 24 October 2013

Acknowledgements

The work presented here has been possible thanks to the enormous observational and modeling efforts of the institutions and networks below:

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

- TM5-4DVAR (Bergamaschi et al., 2009)
- LMDZ-MIOP (Bousquet et al., 2011)
- CarbonTracker-CH4 (Bruhwiler et al., 2012)
- GEOS-Chem (Fraser et al., 2013)
- TM5-4DVAR (Beck et al., 2012)
- LMDZt-SACS (Pison et al., 2009; Bousquet et al., 2011)
- MATCH model (Chen & Prinn, 2006)
- TM2 model (Hein et al., 1997)
- GISS model (Fung et al. 1991)

Bottom-up studies data and modeling

- LPJ-wsl (Hodson et al, 2011)
- ORCHIDEE (Ringeval et al., 2011)
- LPJ-WhyMe (Spahni et al., 2011)
- GICC (Mieville et al., 2010)
- RETRO (Schultz et al., 2007)
- GFEDv2 (Van der Werf et al., 2004)
- GFEDv3 (Van der Werf et al., 2010)
- FINNv1 (Wiedinmyer et al., 2011)
- IIASA (Dentener et al., 2005)
- EPA, 2011
- EDGARv4.1 (EDGAR4.1, 2009)
- EDGARv4.2 (EDGAR4.2, 2011)
- Description of models contributing to the Atmospheric Chemistry and Climate Model
- Intercomparison Project (ACCMIP, Lamarque et al., 2013; Voulgarakis et al., 2013; Naik et al., 80 2013)
- TM5 full chemistry model (Williams et al., 2012; Huijnen et al., 2010)

Full references provided in Kirschke et al. 2013, Nature Geoscience

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The Activity

- The Global Methane Budget is the new companion activity of the Global Carbon Budget activity http://www.globalcarbonproject.org/carbonbudget of the Global Carbon Project, a project of the IGBP, WCRP, IHDP, and Diversitas.

- The activity aims to update the budget on a regular basis (annually or bi-annually) and extend its analysis.

- It focuses on analyses and syntheses of existing data, models, and estimates from bottom-up approaches (inventories, models) and top-down approaches (atmospheric inversions).

- It relies on contributions from a number of networks and institutions (see Acknowledgements)
  - Observational networks (NOAA, CSIRO, UCI, AGAGE)
  - Inventories (EDGAR, EPA, IIASA)
  - Wetland models, biomass burning data sets
  - Inverse modeling systems for atmospheric transport
  - Chemical transport models for OH sink

- Global Methane Budget Website http://www.globalcarbonproject.org/methanebudget

- This effort has contributed to the IPCC 5th Assessment Report, Working Group I, Chapter 6

The First Effort

nature geoscience

REVIEW ARTICLE

PUBLISHED ONLINE: 22 SEPTEMBER 2013 | DOI: 10.1038/NGEO1955

Three decades of global methane sources and sinks

Stefanie Kirschke *et al.**

Methane is an important greenhouse gas, responsible for about 20% of the warming induced by long-lived greenhouse gases since pre-industrial times. By reacting with hydroxyl radicals, methane reduces the oxidizing capacity of the atmosphere and generates ozone in the troposphere. Although most sources and sinks of methane have been identified, their relative contributions to atmospheric methane levels are highly uncertain. As such, the factors responsible for the observed stabilization of atmospheric methane levels in the early 2000s, and the renewed rise after 2006, remain unclear. Here, we construct decadal budgets for methane sources and sinks between 1980 and 2010, using a combination of atmospheric measurements and results from chemical transport models, ecosystem models, climate chemistry models and inventories of anthropogenic emissions. The resultant budgets suggest that data-driven approaches and ecosystem models overestimate total natural emissions. We build three contrasting emission scenarios — which differ in fossil fuel and microbial emissions — to explain the decadal variability in atmospheric methane levels detected, here and in previous studies, since 1985. Although uncertainties in emission trends do not allow definitive conclusions to be drawn, we show that the observed stabilization of methane levels between 1999 and 2006 can potentially be explained by decreasing-to-stable fossil fuel emissions, combined with stable-to-increasing microbial emissions. We show that a rise in natural wetland emissions and fossil fuel emissions probably accounts for the renewed increase in global methane levels after 2006, although the relative contribution of these two sources remains uncertain.

Reconstructions of atmospheric methane (CH_4) concentrations between 1850 and the 1970s have been made using air trapped in polar ice cores and compacted snow. The data reveal an exponential increase in CH_4 levels in the atmosphere from 830 ppb to 1500 ppb in the late 1970s[1]. Direct measurements of CH_4 in the atmosphere began in 1978[2], and reached global coverage after 1983. Today, CH_4 concentrations can be assessed using discrete air samples collected regularly at the surface, continuous measurements made at the surface[2–6] or in the troposphere[7–9], and remotely sensed measurements of atmospheric CH_4 columns retrieved from the surface or from space[10–12] (see Supplementary Section ST1). Surface-based observations from four networks (National Oceanic and Atmospheric Administration, NOAA[13]; Advanced Global Atmospheric Gases Experiment, AGAGE[14]; Commonwealth Scientific and Industrial Research Organization, CSIRO[5]; and University of California Irvine, UCI[15]) show consistent changes in the global growth rate of annual CH_4 concentrations since 1980 (Fig. 1 and Supplementary Section ST1). The agreement between these networks has improved with increasing coverage. The standard deviation for the global annual growth rate decreased from ±3.3 ppb yr^{-1} in the 1980s to ±1.3 ppb yr^{-1} in the 2000s. These data reveal a sustained increase in atmospheric CH_4 levels in the 1980s (by an average of 12 ± 6 ppb yr^{-1}), a slowdown in growth in the 1990s (6 ± 8 ppb yr^{-1}), and a general stabilisation from 1999 to 2006 to 1773 ± 3 ppb. Since 2007, CH_4 levels have been rising again[14], and reached 1799 ± 2 ppb in 2010. This increase reflects a recent imbalance between CH_4 sources and sinks that is not yet fully understood[13].

Previous reviews of the global CH_4 budget have focused on results from a few studies only[13,16–19]. These studies covered different time windows and employed different assumptions, making it difficult to interpret the decadal changes presented. Only very few studies addressed multi-decadal changes in CH_4 levels[20,21]. Here we construct a global CH_4 budget for the past three decades by combining bottom-up and top-down estimates of CH_4 sources and the chemical CH_4 sink (Box 1). We use chemical transport models — constrained by atmospheric CH_4 measurements — to estimate CH_4 fluxes using top-down atmospheric inversions. We compare these fluxes with those simulated by ecosystem models of wetland and biomass burning emissions and by data-driven approaches for other natural sources (Methods and Supplementary Section II). We also gather recent data from fossil fuel CH_4 emission inventories based on energy use statistics, and from agricultural and waste inventories based on livestock and rice paddy statistical data.

Sources and sinks

The global atmospheric CH_4 budget is determined by many terrestrial and aquatic surface sources, balanced primarily by one sink in the atmosphere. CH_4 emissions can be broadly grouped into three categories: biogenic, thermogenic and pyrogenic. Biogenic sources contain CH_4-generating microbes (methanogens)[17], and comprise anaerobic environments such as natural wetlands and rice paddies, oxygen-poor freshwater reservoirs (such as dams), digestive systems of ruminants and termites, and organic waste deposits (such as manure, sewage and landfills). Thermogenic CH_4, formed over millions of years through geological processes, is a fossil fuel. It is vented from the subsurface into the atmosphere through natural features (such as terrestrial seeps, marine seeps and mud volcanoes), and through the exploitation of fossil fuels, that is, through the exploitation of coal, oil and natural gas. Pyrogenic CH_4 is produced by the incomplete combustion of biomass and soil carbon during wildfires, and of biofuels and fossil fuels. These three types of emissions have different isotopic $\delta^{13}C$ signatures ($\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard}] - 1) \times 1000$): −55 to −70‰ for biogenic emissions, −25 to −55‰ for thermogenic emissions, and −13 to −25‰ for pyrogenic emissions[20,22,23]. The isotopic composition of atmospheric CH_4 — measured at a subset of surface stations — has therefore been used to constrain its source[20–24]. CH_4 emissions by living plants under aerobic conditions do not seem to play a significant role in the global CH_4 budget (Supplementary Section ST8); some very large[25] estimates of this source published in 2006 have not been confirmed[26].

The primary sink for atmospheric CH_4 is oxidation by hydroxyl radicals (OH), mostly in the troposphere, which accounts for around 90% of the global CH_4 sink. Additional oxidation sinks include methanotrophic bacteria in aerated soils[27,28] (~4%), reactions with

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http://www.nature.com/ngeo/journal/vaop/ncurrent/full/ngeo1955.html

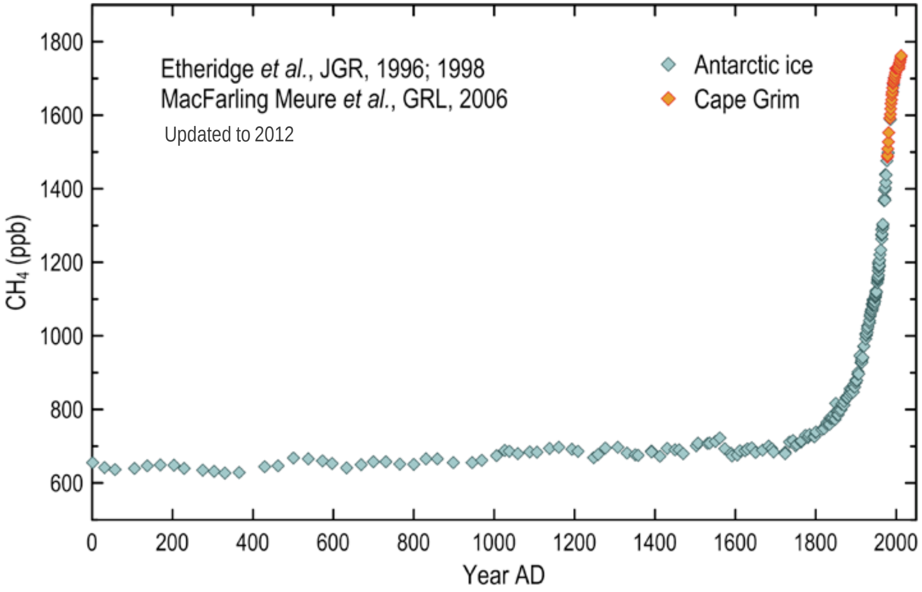
The Context

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

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

- CH_4 is responsible for 20% of the global warming produced by all well-mixed greenhouse gases, and constitutes 60% of the climate forcing by CO_2 (0.97 Wm^{-2} vs 1.68 Wm^{-2}) since pre-Industrial time.

- Annual globally averaged CH_4 concentration was 1803±4 parts per billion in 2011 and 722 ppb in 1750. 150% increase since pre-Industrial time.



- CH_4 contributes to water vapor in the stratosphere, and to ozone production in the troposphere, the latter a pollutant with negative impacts on human health and ecosystems.

- The atmospheric life time of CH_4 is approximately 10±2 years.

IPCC WGI 2013; Voulgarakis et al. 2013, Atmos. Chem. Phys.

Atmospheric Observations

Emission Inventories

Biogeochemistry Models

Inverse Models

OH Sink

The Tools and Data

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

Airborne observations.

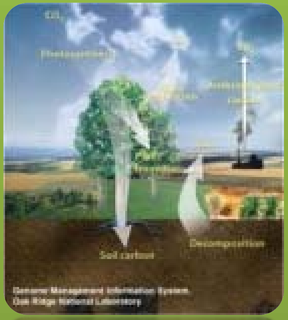
Satellite data.

Agriculture and waste related emissions, fossil fuel emissions (EDGAR, EPA, IIASA).

Fire emissions (GFED, GICC, FINN, RETRO).

Ensemble of different wetland models, (LPJ-WHyMe, LPJ-wsl, ORCHIDEE).

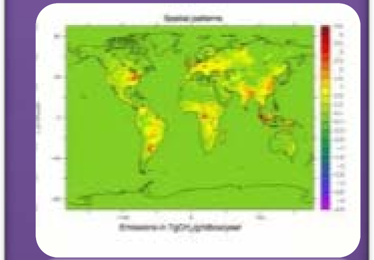
Data and models to calculate annual flooded area.



Genome Management Information System,
Oak Ridge National Laboratory

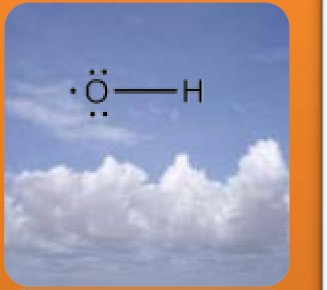
Suite of different atmospheric inversion models (TM5-4DVAR, LMDZ-MIOP, CarbonTracker-CH_4, GEOS-Chem, LMDZt-SACS, MATCH, TM2, GISS).

TransCom intercomparison.



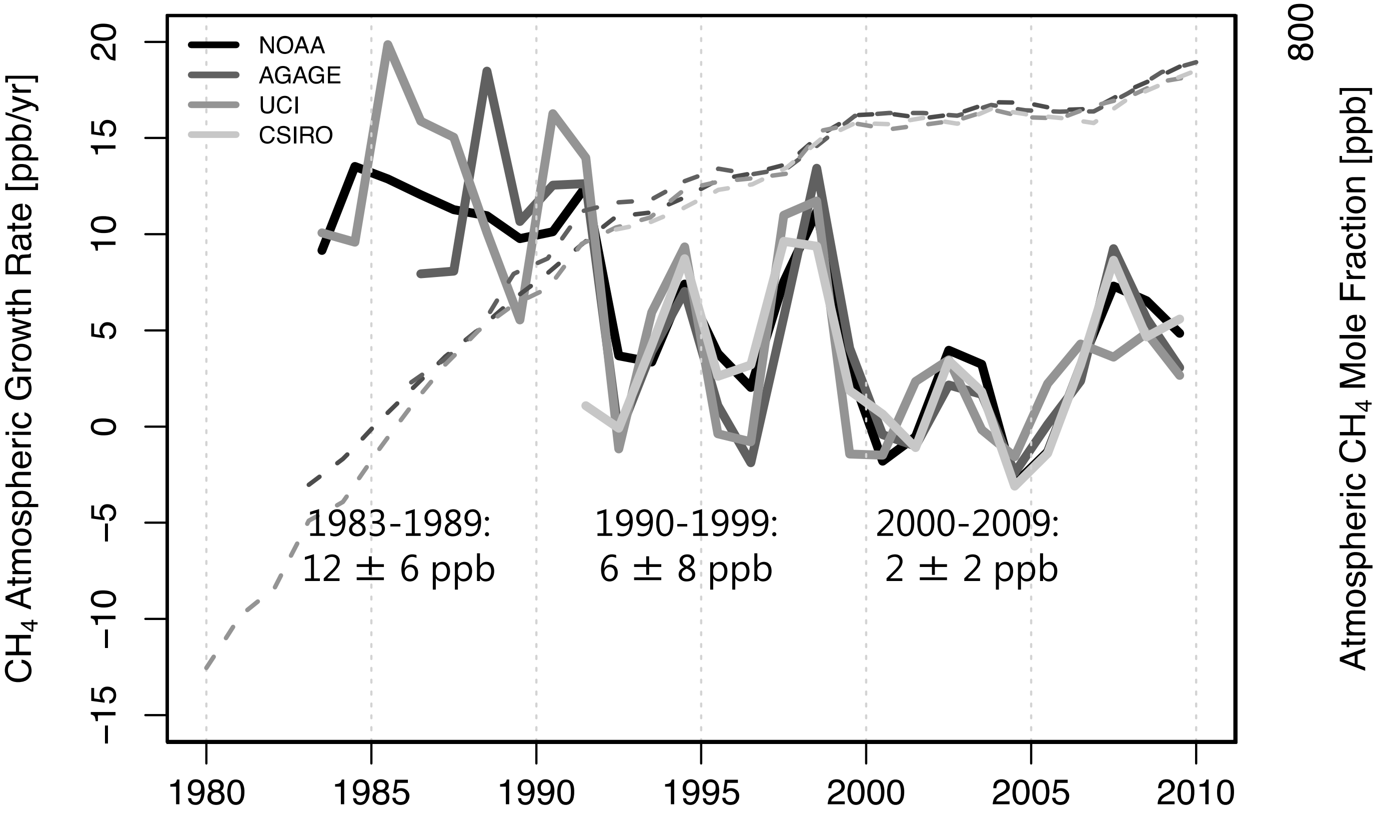
Long-term trends and decadal variability of the OH sink.

ACCMIP CTMs intercomparison.



Decadal Budgets

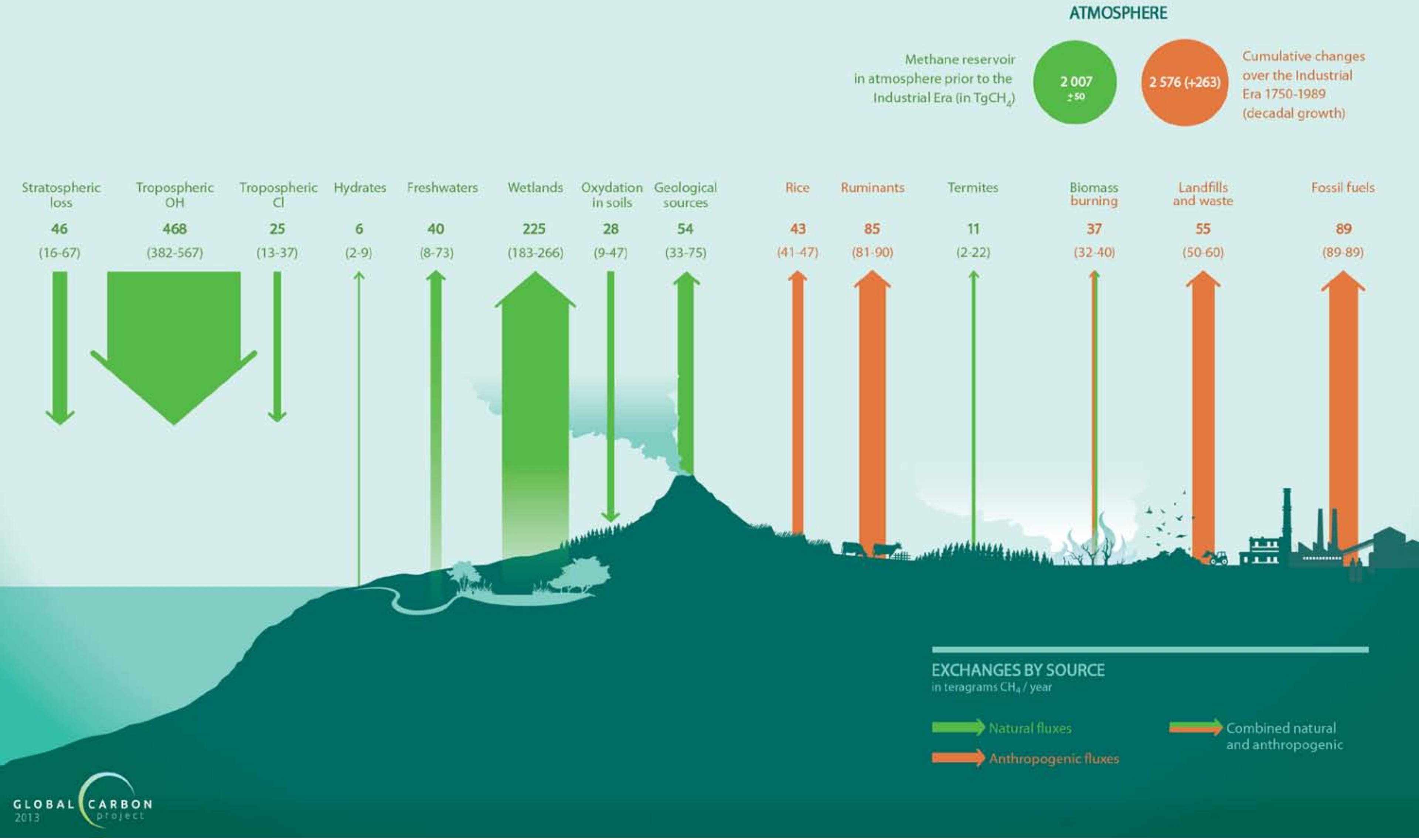
CH_4 Atmospheric Growth Rate, 1983-2009



- Slowdown of atmospheric growth rate before 2005
- Resumed increase after 2006

Kirschke et al. 2013, Nature Geoscience; Data from NOAA, CSIRO, AGAGE, UCI atmospheric networks

METHANE BUDGET : 1980-89



ATMOSPHERE

Methane reservoir in atmosphere prior to the Industrial Era (in $TgCH_4$): 2 007 ±50

Cumulative changes over the Industrial Era 1750-1989 (decadal growth): 2 576 (+263)

Stratospheric loss	46	(16-67)
Tropospheric OH	468	(382-567)
Tropospheric Cl	25	(13-37)
Hydrates	6	(2-9)
Freshwaters	40	(8-73)
Wetlands	225	(183-266)
Oxydation in soils	28	(9-47)
Geological sources	54	(33-75)
Rice	43	(41-47)
Ruminants	85	(81-90)
Termites	11	(2-22)
Biomass burning	37	(32-40)
Landfills and waste	55	(50-60)
Fossil fuels	89	(89-89)

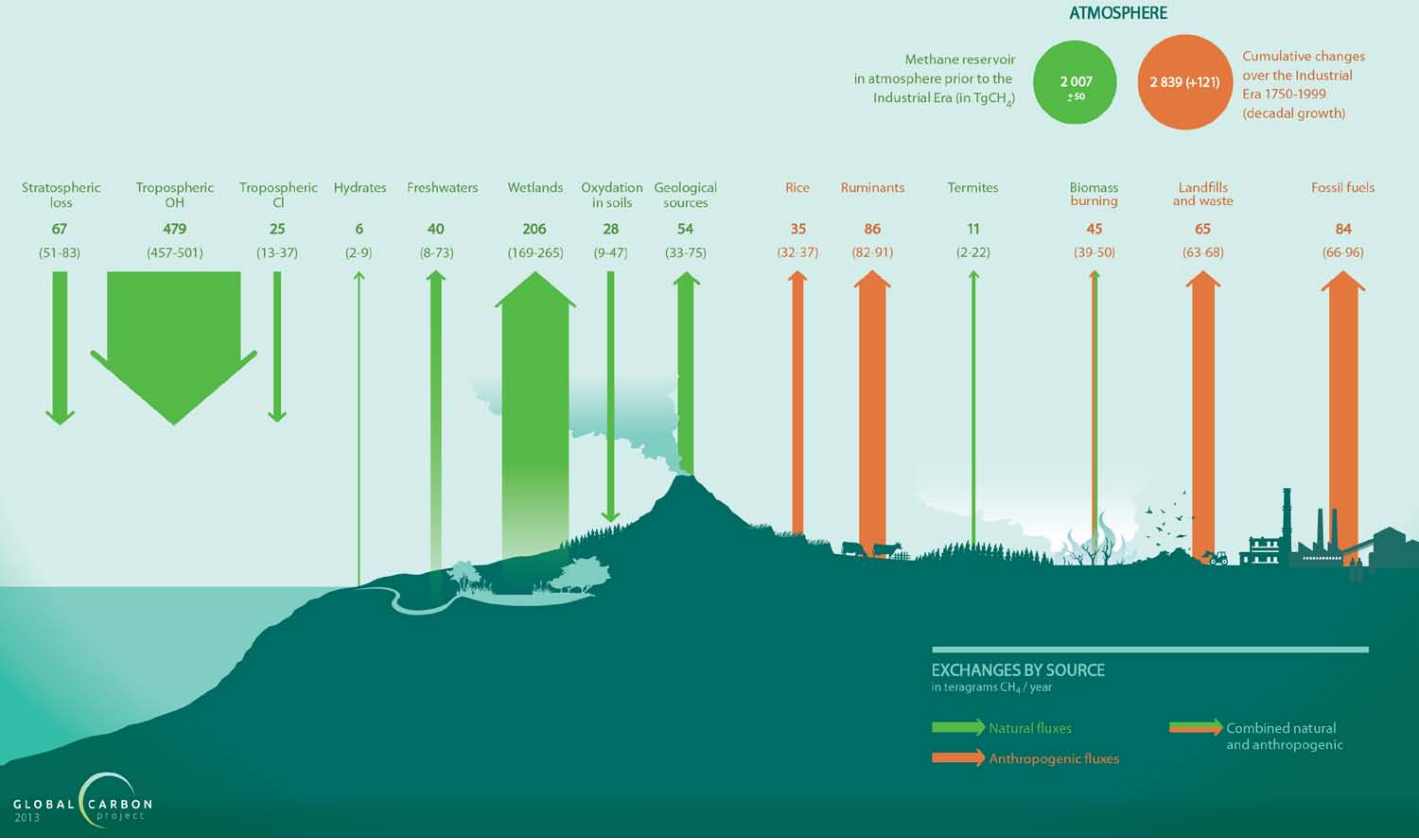
EXCHANGES BY SOURCE
in teragrams CH_4 / year

- 🟩 Natural fluxes
- 🟧 Anthropogenic fluxes
- Combined natural and anthropogenic

GLOBAL CARBON project 2013

Global Carbon Project 2013; Figure based on Kirschke et al. 2013, Nature Geoscience

METHANE BUDGET : 1990-99



ATMOSPHERE

Methane reservoir in atmosphere prior to the Industrial Era (in $TgCH_4$): 2 007 ±50

Cumulative changes over the Industrial Era 1750-1999 (decadal growth): 2 839 (+121)

Stratospheric loss	Tropospheric OH	Tropospheric Cl	Hydrates	Freshwaters	Wetlands	Oxydation in soils	Geological sources	Rice	Ruminants	Termites	Biomass burning	Landfills and waste	Fossil fuels
67	479	25	6	40	206	28	54	35	86	11	45	65	84
(51-83)	(457-501)	(13-37)	(2-9)	(8-73)	(169-265)	(9-47)	(33-75)	(32-37)	(82-91)	(2-22)	(39-50)	(63-68)	(66-96)

EXCHANGES BY SOURCE

in teragrams CH_4 / year

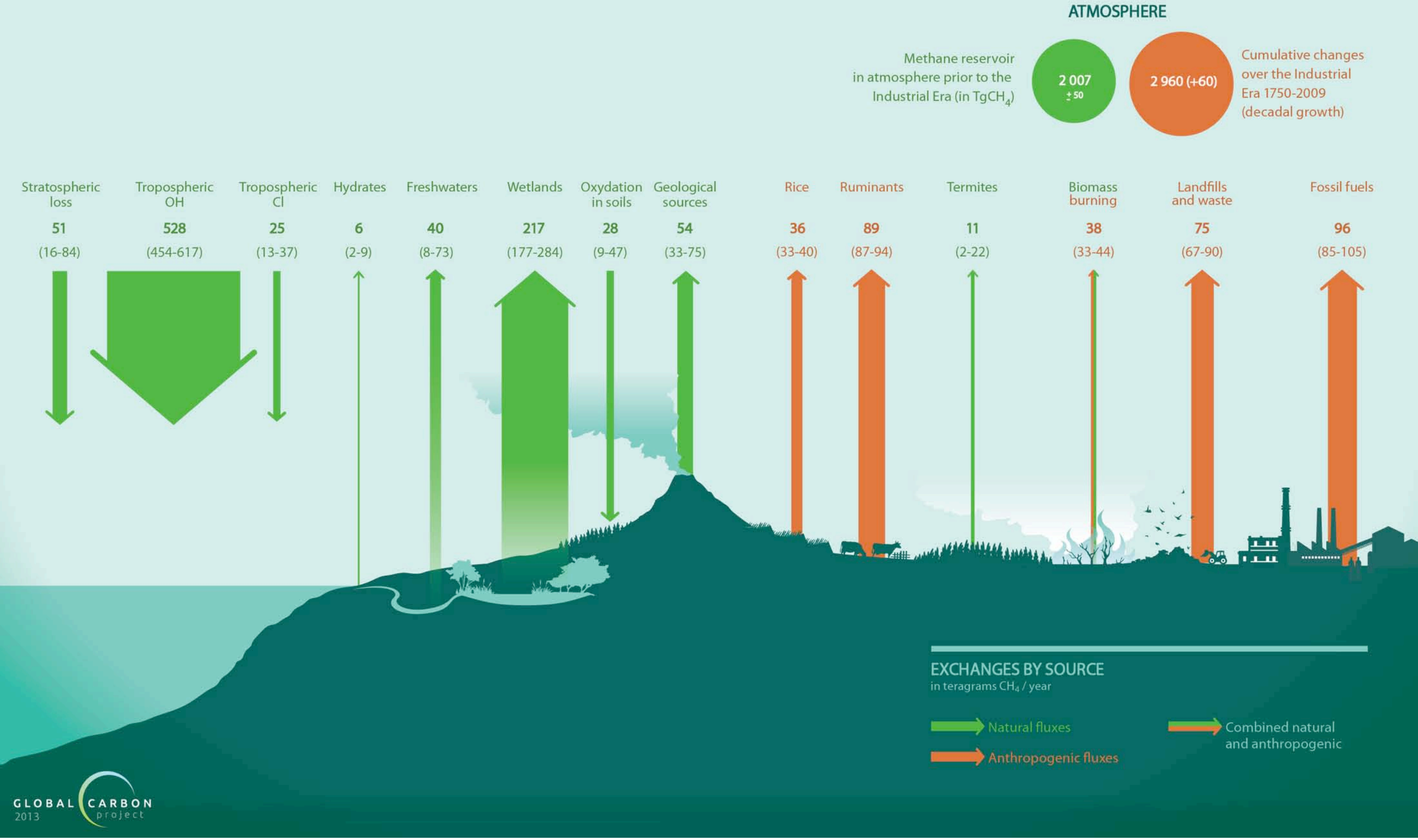
🟩 Natural fluxes

🟥 Anthropogenic fluxes

Combined natural and anthropogenic

Global Carbon Project 2013; Figure based on Kirschke et al. 2013, Nature Geoscience

METHANE BUDGET : 2000-09



ATMOSPHERE

Methane reservoir in atmosphere prior to the Industrial Era (in $TgCH_4$): 2 007 ± 50

Cumulative changes over the Industrial Era 1750-2009 (decadal growth): 2 960 (+60)

Stratospheric loss	Tropospheric OH	Tropospheric Cl	Hydrates	Freshwaters	Wetlands	Oxydation in soils	Geological sources	Rice	Ruminants	Termites	Biomass burning	Landfills and waste	Fossil fuels
51	528	25	6	40	217	28	54	36	89	11	38	75	96
(16-84)	(454-617)	(13-37)	(2-9)	(8-73)	(177-284)	(9-47)	(33-75)	(33-40)	(87-94)	(2-22)	(33-44)	(67-90)	(85-105)

EXCHANGES BY SOURCE

in teragrams CH_4 / year

🟩 Natural fluxes

🟧 Anthropogenic fluxes

🟩🟧 Combined natural and anthropogenic

GLOBAL CARBON project
2013

Global Carbon Project 2013; Figure based on Kirschke et al. 2013, Nature Geoscience

Tg CH_4 yr^{-1}	1980–1989		1990–1999		2000–2009	
	Top-Down	Bottom-Up	Top-Down	Bottom-Up	Top-Down	Bottom-Up
Sources						
Natural Sources	203 [150–267]	355 [244–466]	182 [167–197]	336 [230–465]	218 [179–273]	347 [238–484]
Natural Wetlands	167 [115–231]	225 [183–266]	150 [144–160]	206 [169–265]	175 [142–208]	217 [177–284]
Other Sources	36 [35-36]	130 [61-200]	32 [23-37]	130 [61-200]	43 [37-65]	130 [61-200]
Anthropogen. Sources	348 [305–383]	308 [292-323]	372 [290–453]	313 [281–347]	335 [273–409]	331 [304–368]
Agriculture & Waste	208 [187-220]	185 [172-197]	239 [180-301]	187 [177-196]	209 [180-241]	200 [187-224]
Rice		43 [41-47]		35 [32-37]		36 [33-40]
Ruminants		85 [81-90]		86 [82-91]		89 [87-94]
Landfills & Waste		55 [50-60]		65 [63-68]		75 [67-90]
Biomass Burning	46 [43-55]	34 [31-37]	38 [26-45]	42 [38-45]	30 [24-45]	35 [32-39]
Fossil Fuels	94 [75-108]	89 [89-89]	95 [84-107]	84 [66-96]	96 [77-123]	96 [85-105]
Sinks						
Total Chemical Loss	490 [450–533]	539 [411–671]	525 [491–554]	571 [521–621]	518 [510–538]	604 [483–738]
Global						
Sum of Sources	551 [500–592]	663 [536-789]	554 [529–596]	649 [511-812]	548 [526–569]	678 [542-852]
Sum of Sinks	511 [460–559]	539 [420-718]	542 [518–579]	596 [530–668]	540 [514–560]	632 [592–785]
Imbalance (Sources-Sinks)	30 [16–40]		12 [7–17]		8 [-4–19]	
Atmospheric Growth Rate	34		17		6	

○ Larger global total emissions from Bottom-Up (inventories, models) than Top-Down (atmospheric inversions) because of larger natural emissions

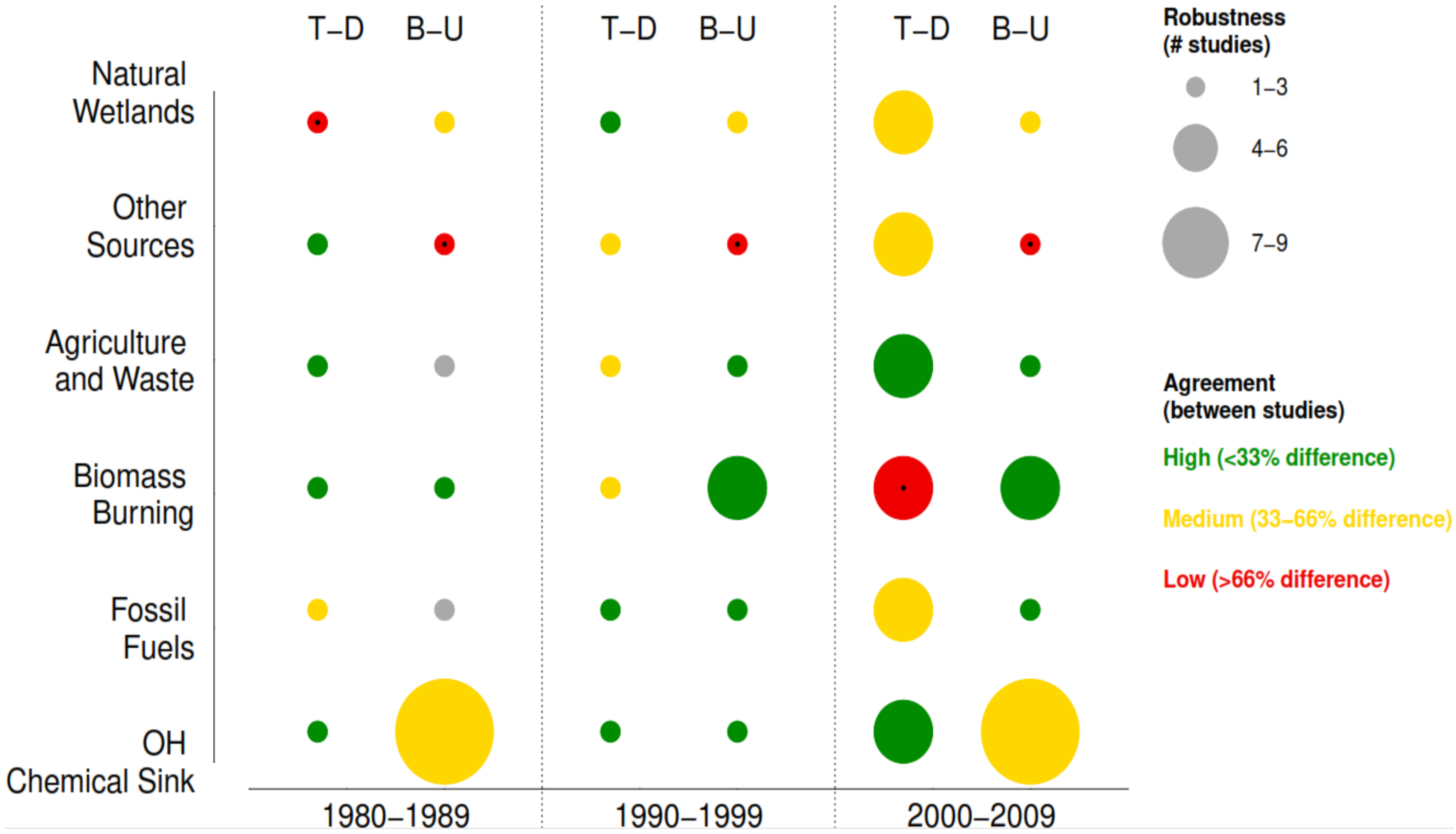
○ Large uncertainties remain for wetland emissions (min-max range)

○ ~50 Tg global imbalance in B-U approaches (T-D constrained by atmosphere)

○ Increasing OH loss between decades in B-U (not clear in T-D)

Evolution of Uncertainty: Decadal Budgets

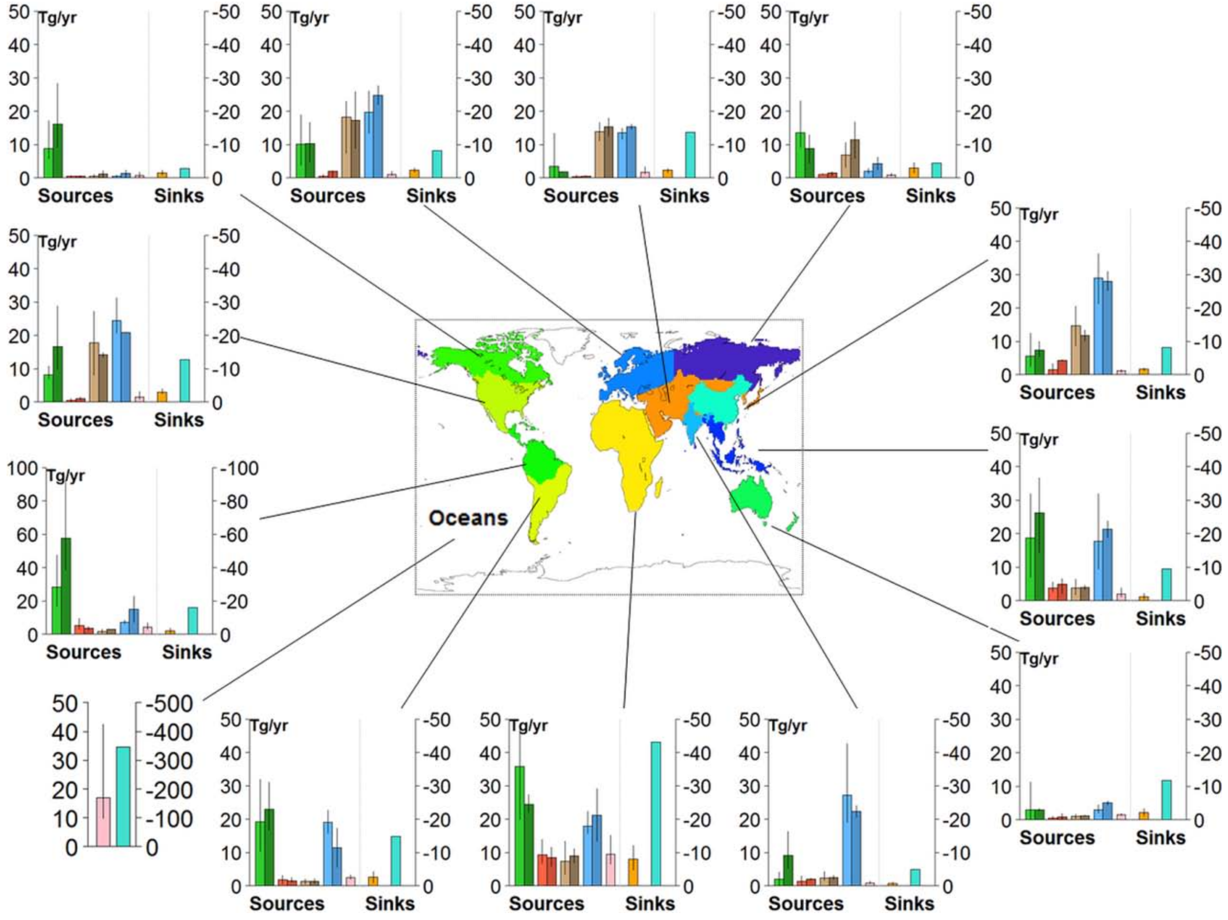
- No source or sink reaches the maximum level of confidence (large green circle)
- Robustness is larger in the 2000s than in previous decades
- Agreement can go down as more studies appear (e.g. fire, wetlands, OH, …)



Kirschke et al. 2013, Nature Geoscience

Regional Methane Budget

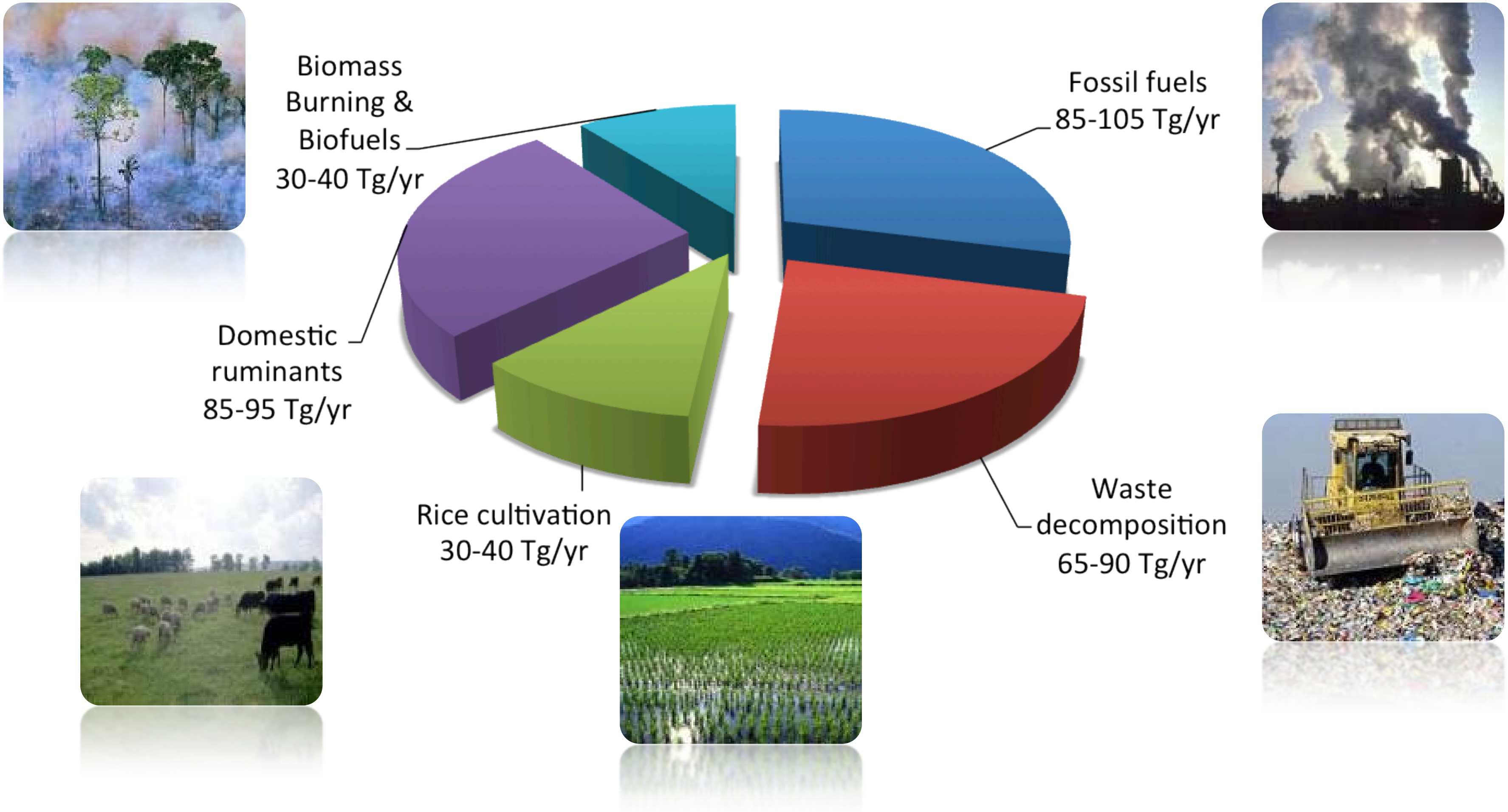
- Dominance of wetland emissions in the tropics and boreal regions
- Dominance of agriculture & waste in India and China
- Balance between agriculture & waste and fossil fuels at mid-latitudes
- Uncertain magnitude of wetland emissions in tropical South America between T-D and B-U



Kirschke et al. 2013, Nature Geoscience

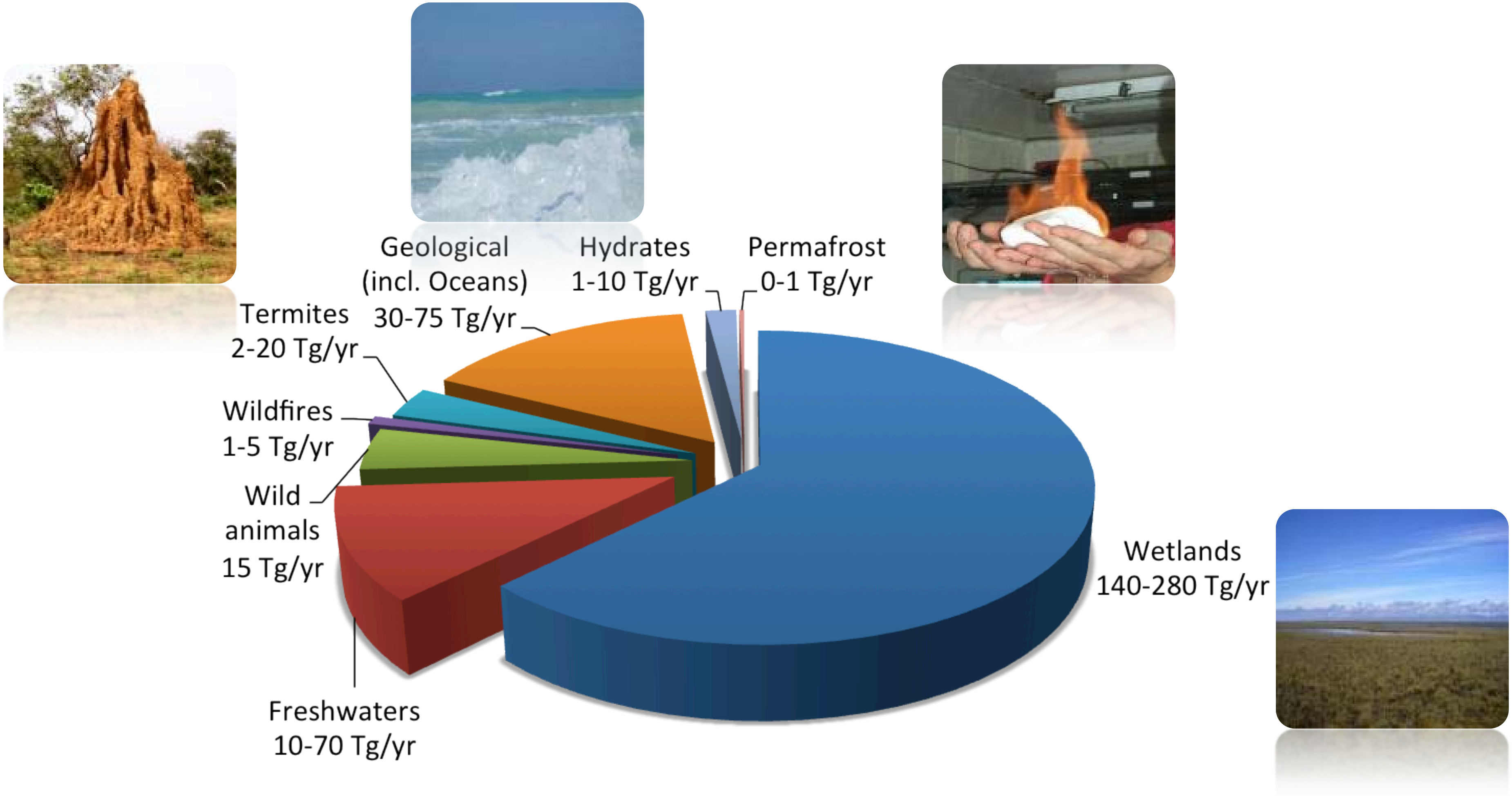
Emissions
& Sinks

Anthropogenic Methane Sources (2000s)



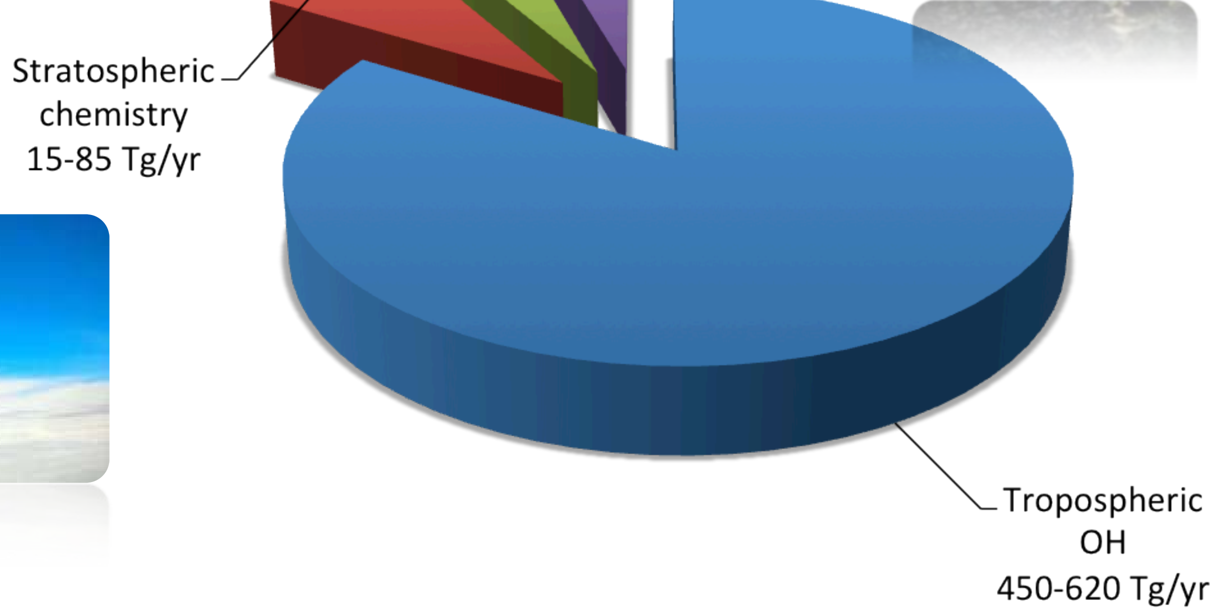
Global Carbon Project 2013; Figure based on Kirschke et al. 2013

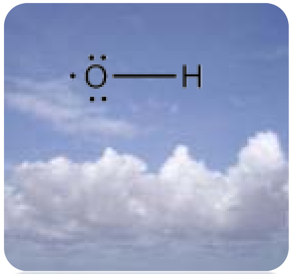
Natural Methane Sources (2000s)



Global Carbon Project 2013; Figure based on Kirschke et al. 2013

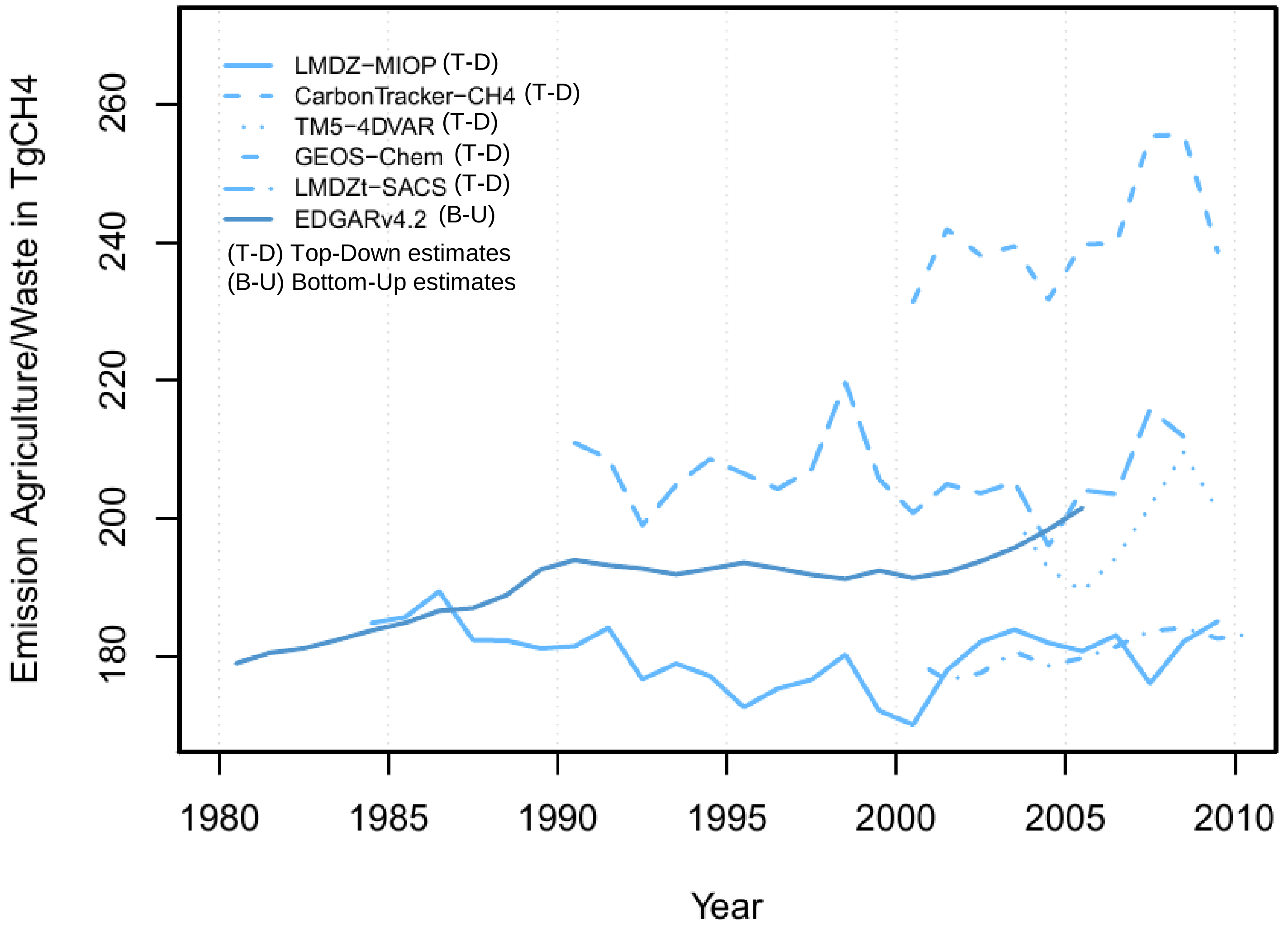
Methane Sinks (2000s)





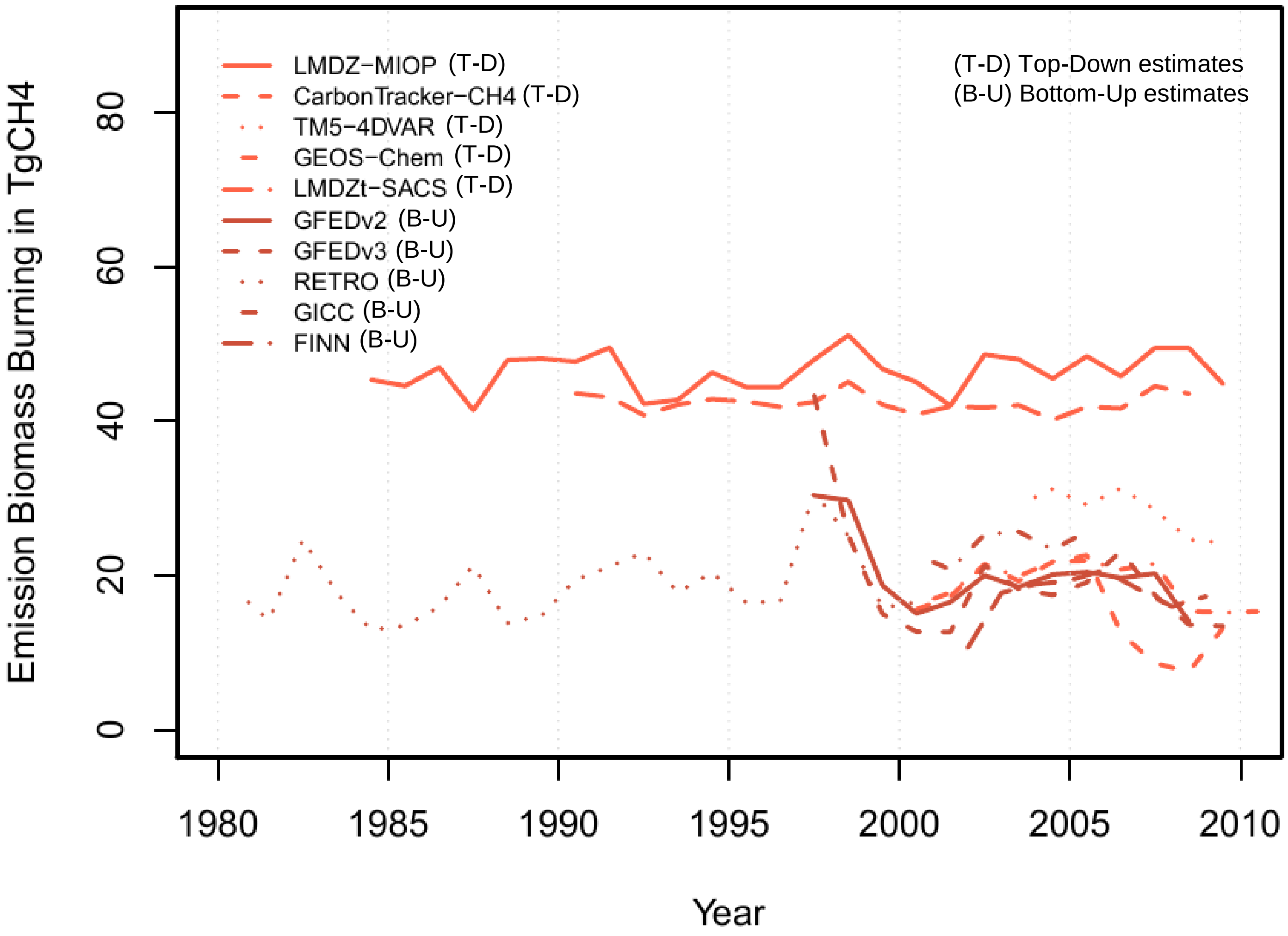
Global Carbon Project 2013; Figure based on Kirschke et al. 2013

Agriculture/Waste CH_4 Emissions



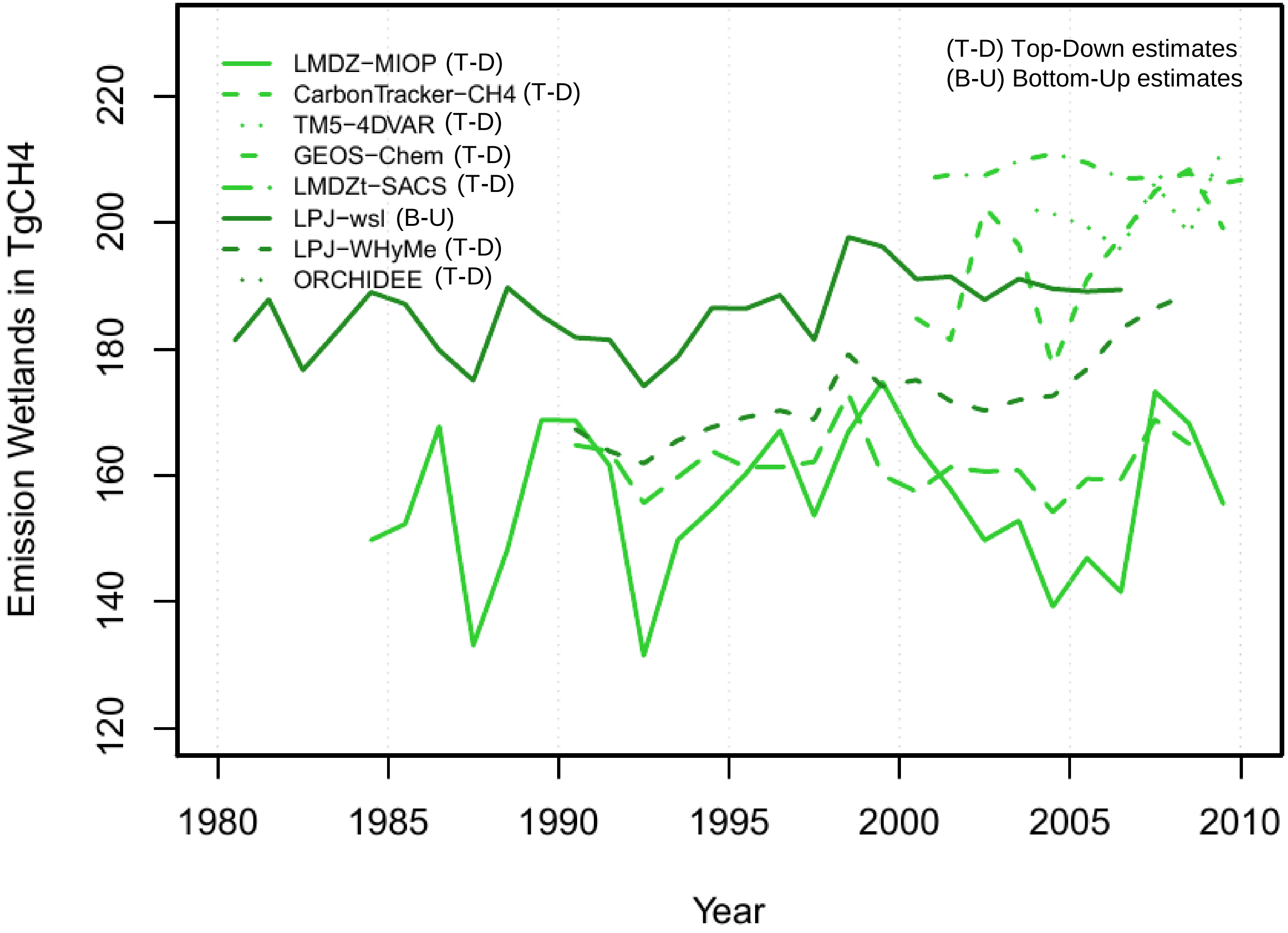
Global Carbon Project 2013; Figure based on Kirschke et al. 2013. Data sources shown in figure.

Biomass Burning CH_4 Emissions



Global Carbon Project 2013; Figure based on Kirschke et al. 2013. Data sources shown in figure.

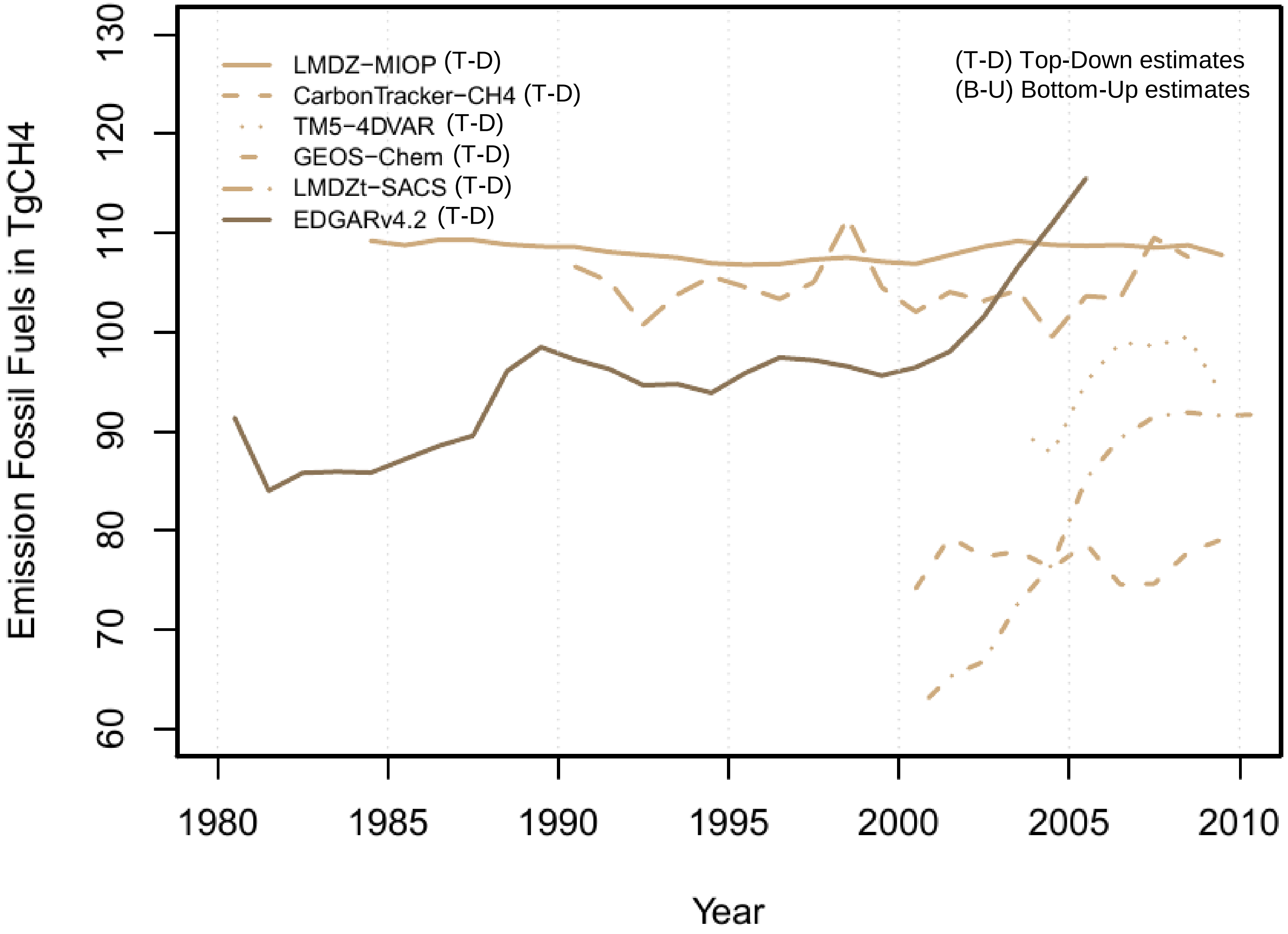
Wetland CH_4 Emissions, 1980-2009



Increase 2005-2009 in B-U models due to precipitation forcing (increase in tropical land precipitation)

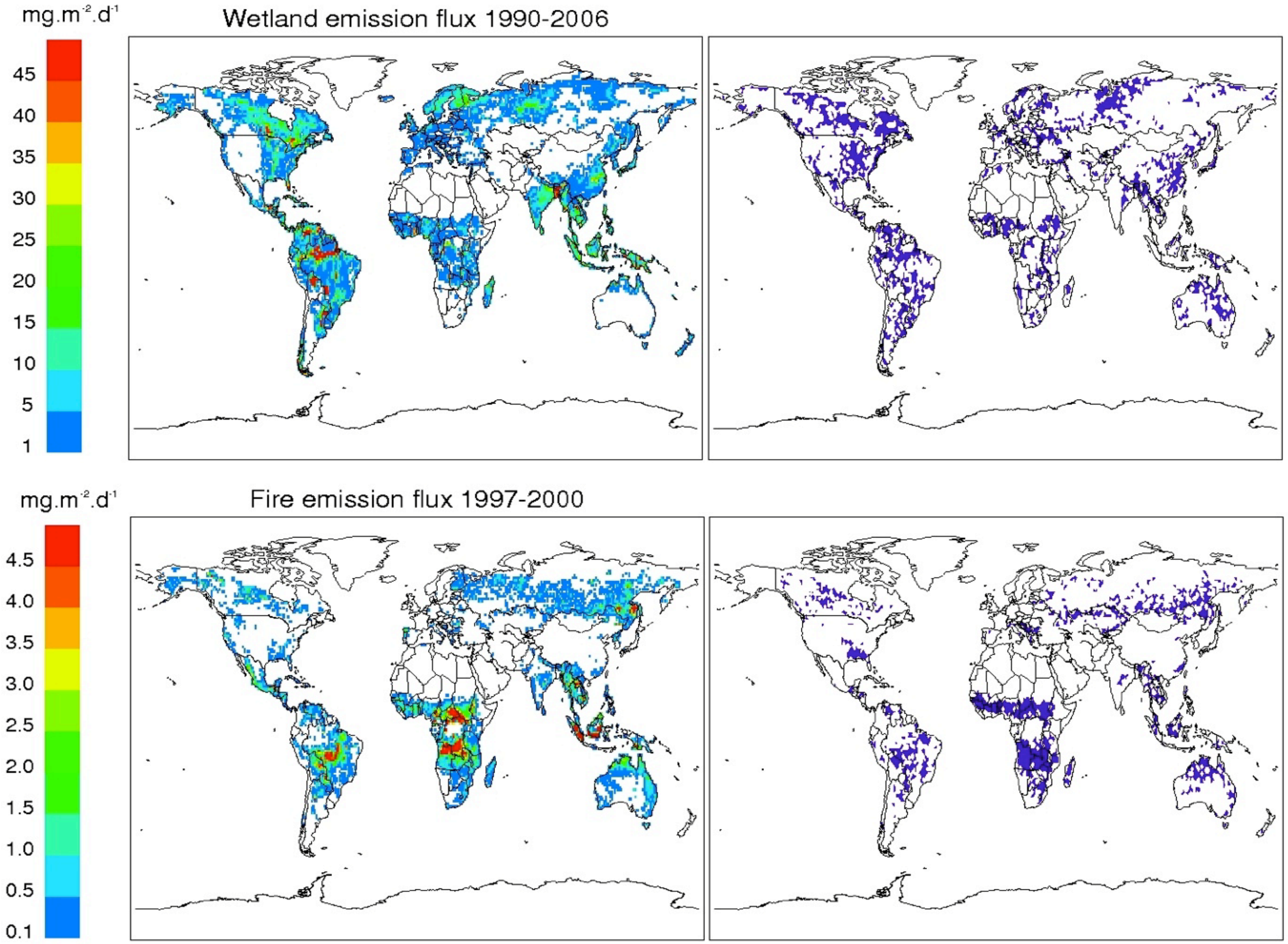
Global Carbon Project 2013; Figure based on Kirschke et al. 2013. Data sources shown in figure.

Fossil Fuel CH_4 Emissions



Global Carbon Project 2013; Figure based on Kirschke et al. 2013. Data sources shown in figure.

Spatial Distribution of Fluxes



Wetland emission flux 1990-2006

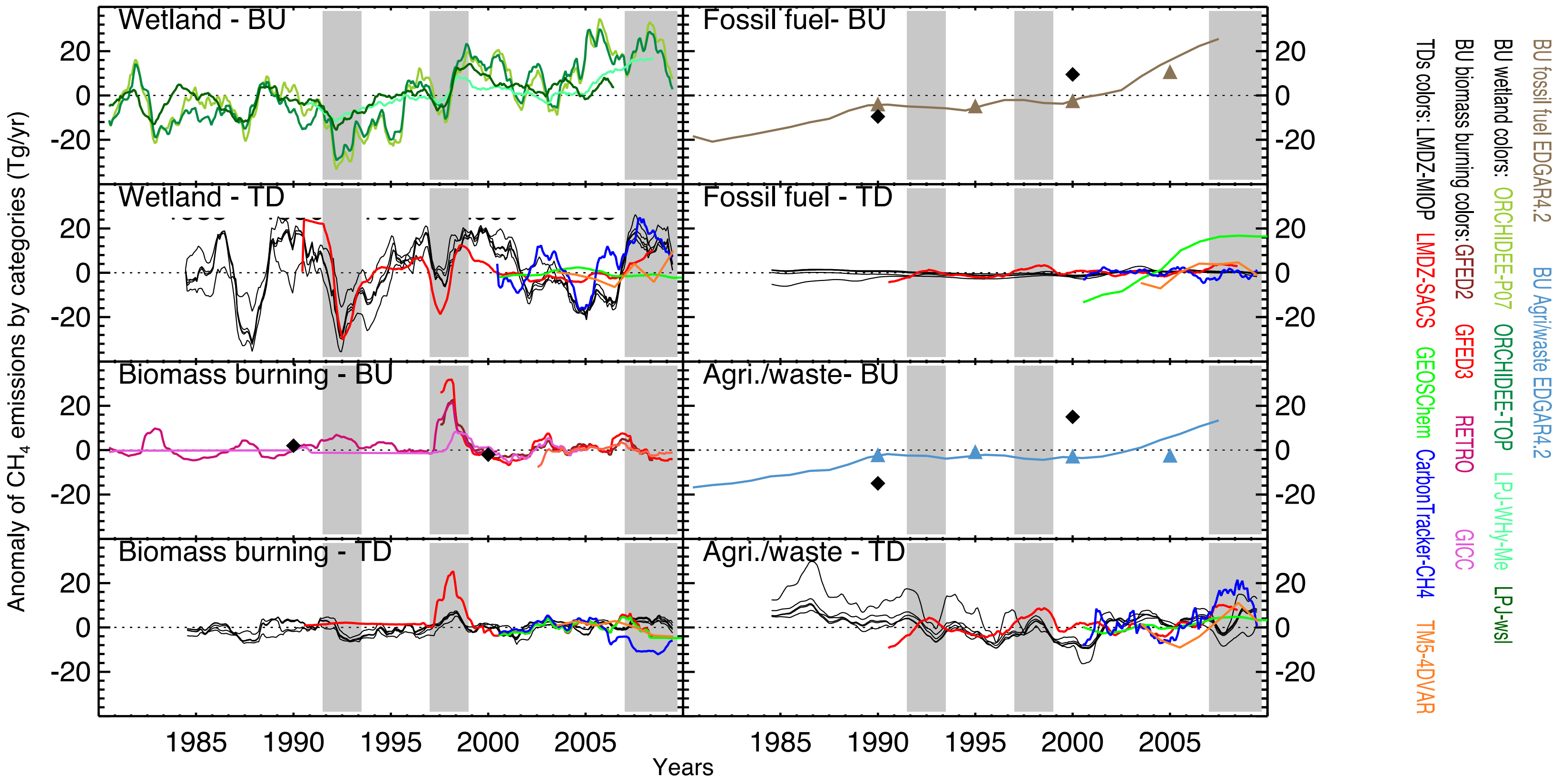
Fire emission flux 1997-2000

Kirschke et al. 2013, Supplementary Information, Nature Geoscience

Data sources: Wetland emissions (ORCHIDEE, LPJ-WHyMe, LPJ-wsl), Biomass burning emissions: GFED2, GFED3, RETRO, GICC).

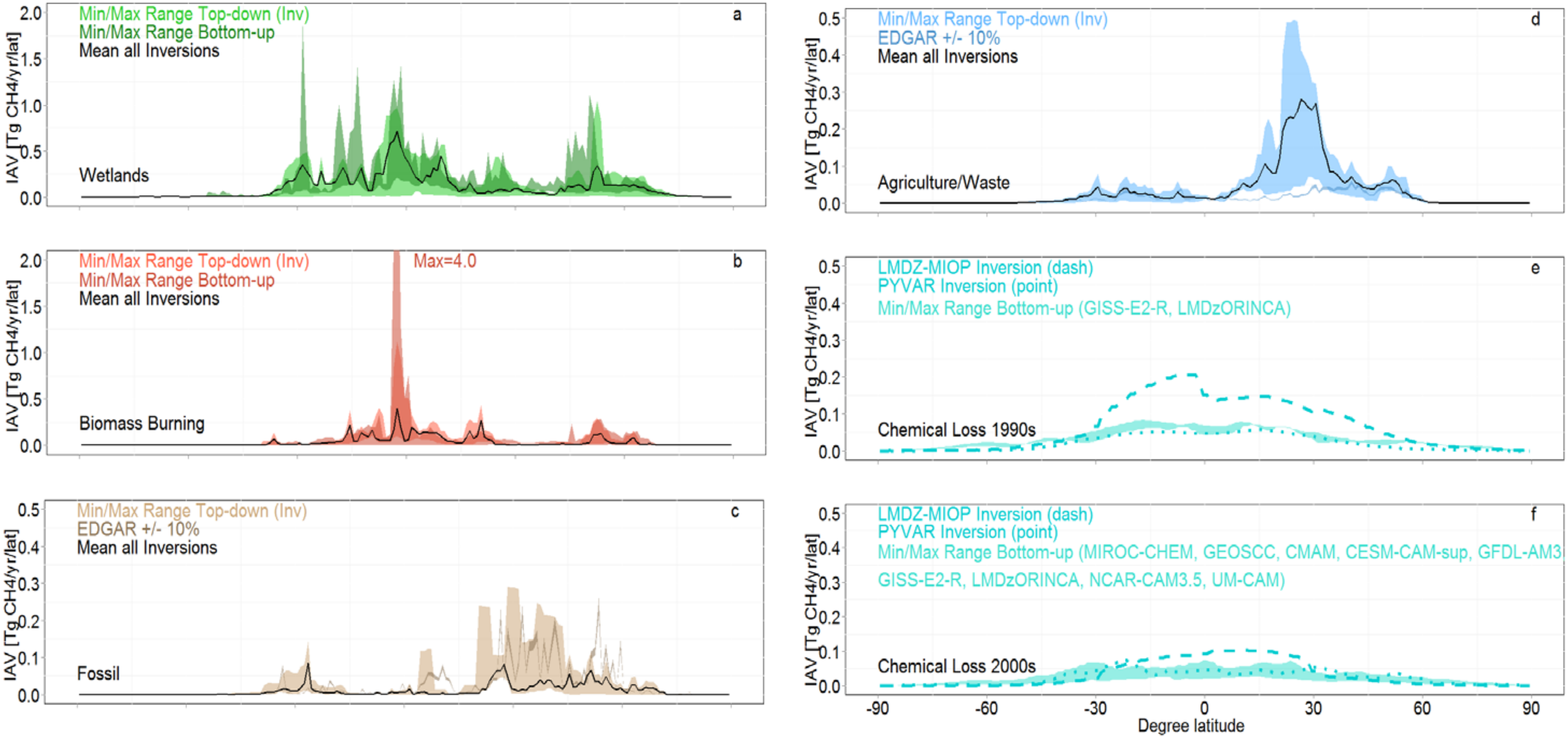
Interannual Variability of CH_4 Emissions

- *Natural wetlands dominate IAV with contribution of BBG during large fires events*
- *Trends in emissions are not fully consistent between models (cf fossil, wetlands)*
- *Causes of the stabilisation period (1999-2006) and increasing period (>2006) still uncertain (fossil / wetlands?)*



Kirschke et al. 2013, Supplementary Information, Nature Geoscience

Interannual Variability by Latitude



Kirschke et al. 2013, Supplementary Information, Nature Geoscience

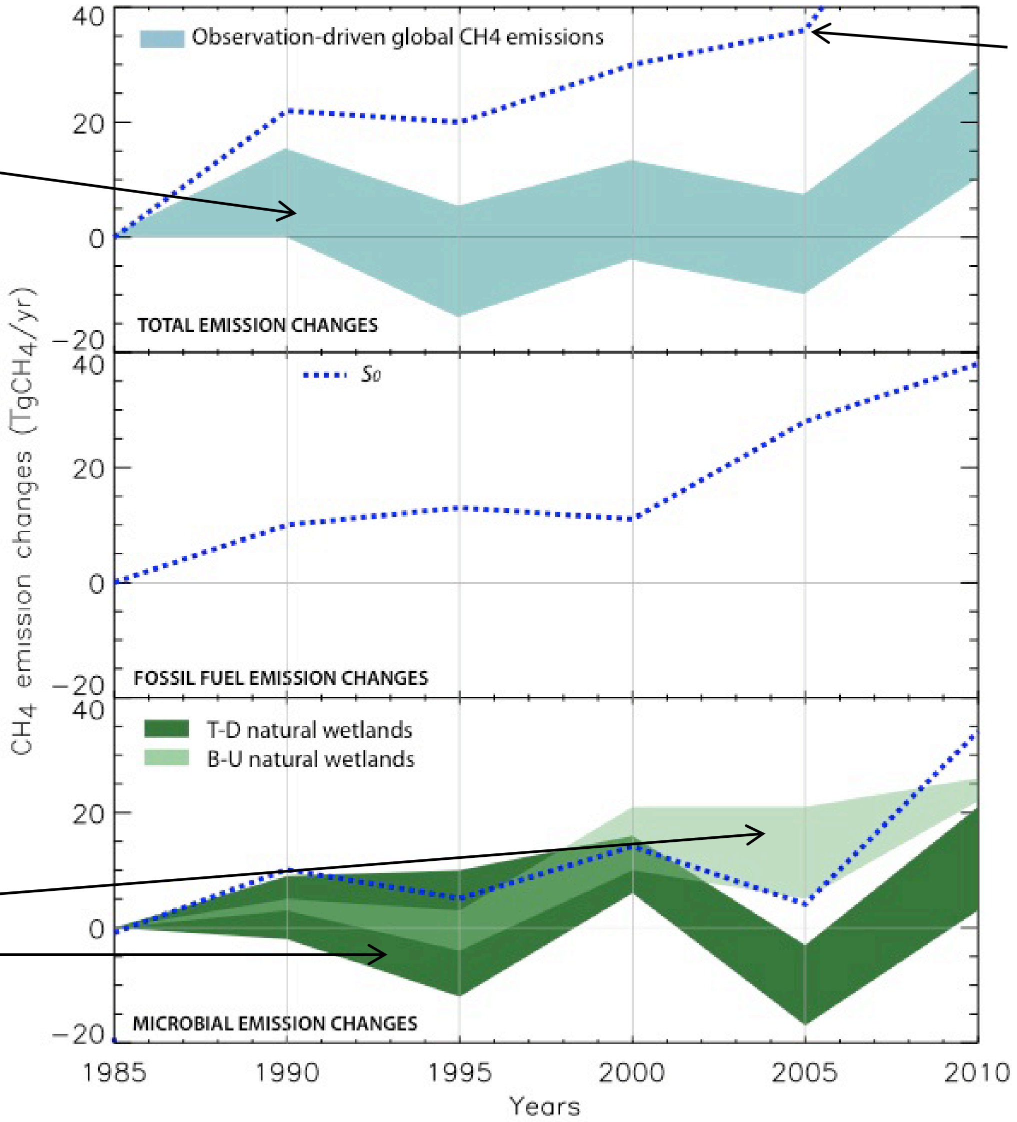
Scenarios of Temporal Change

Scenarios of Temporal Change

Range of global emissions (from atm. Obs & inversions)

S0 : EDGAR/EPA +wetlands

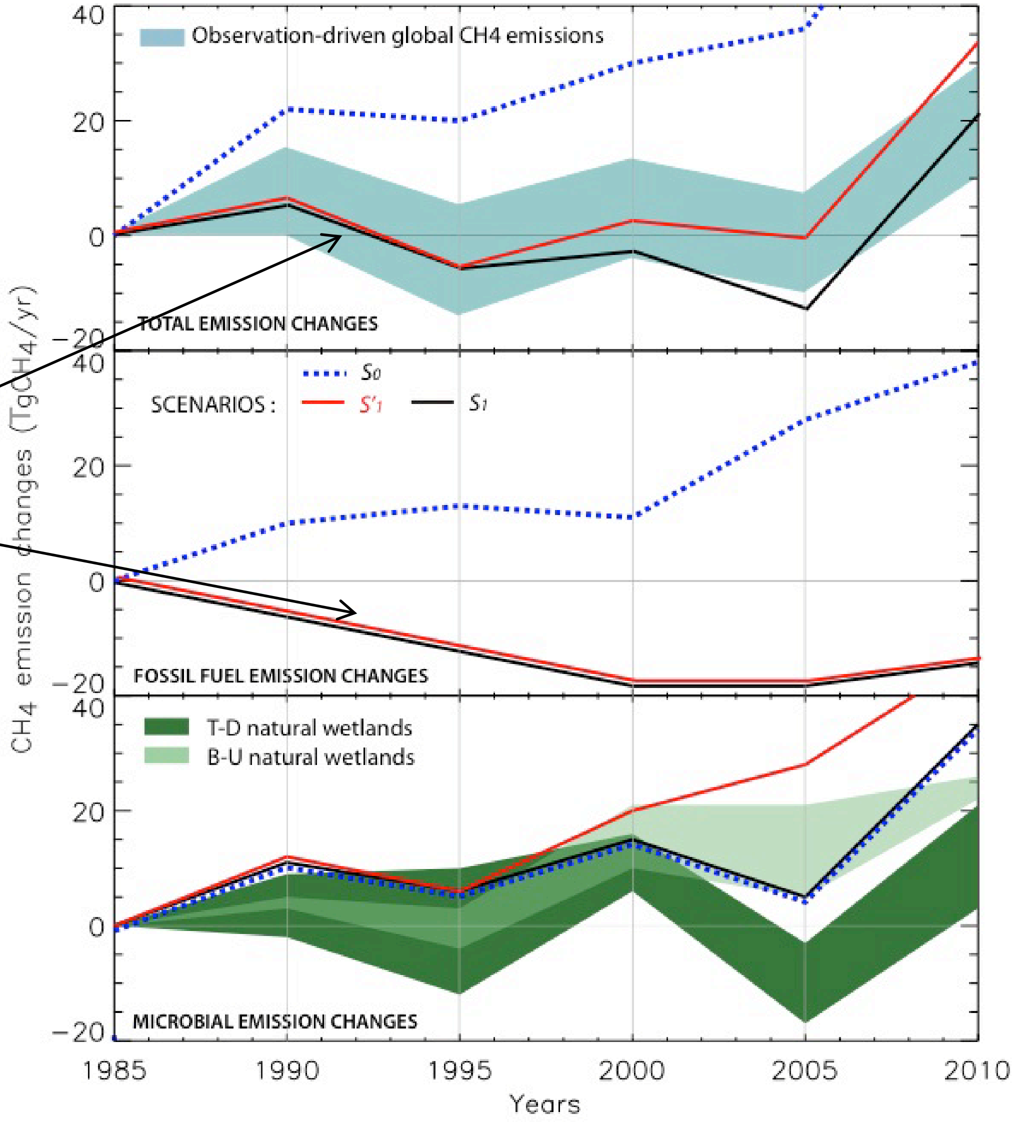
Range of wetland emissions (B-U= light green, T-D = dark green)



5-year emission changes since 1985 for 3 categories

Scenarios of Temporal Change

Range of global emissions can be matched with decreasing fugitive emissions



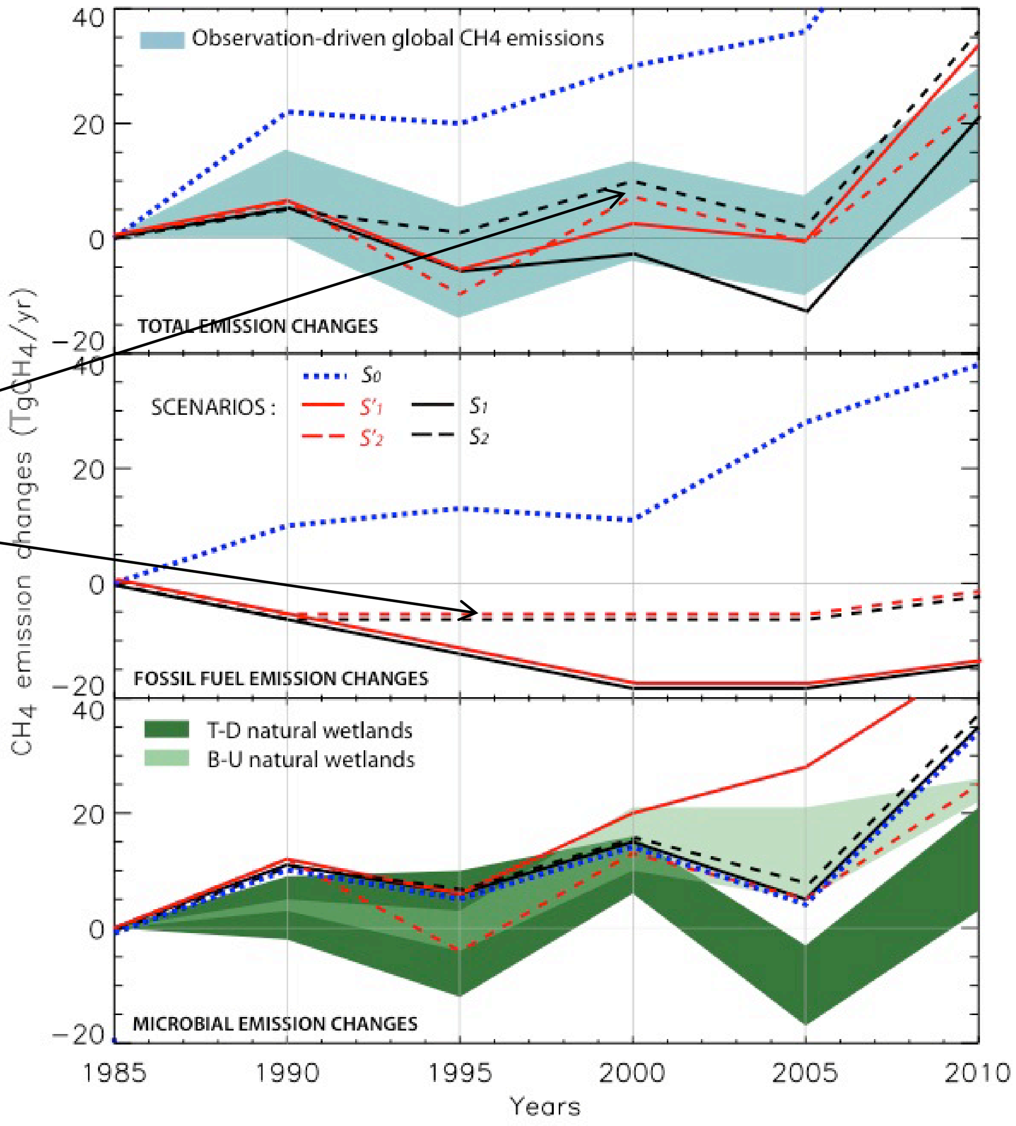
S0 : EDGAR/EPA +wetlands

S1 : Decreasing fugitive emissions from 1985 to 2000 + EDGAR/EPA + wetlands (TD or BU)

5-year emission changes since 1985 for 3 categories

Scenarios of Temporal Change

Range of global emissions can be matched with stable fossil and microbial emissions



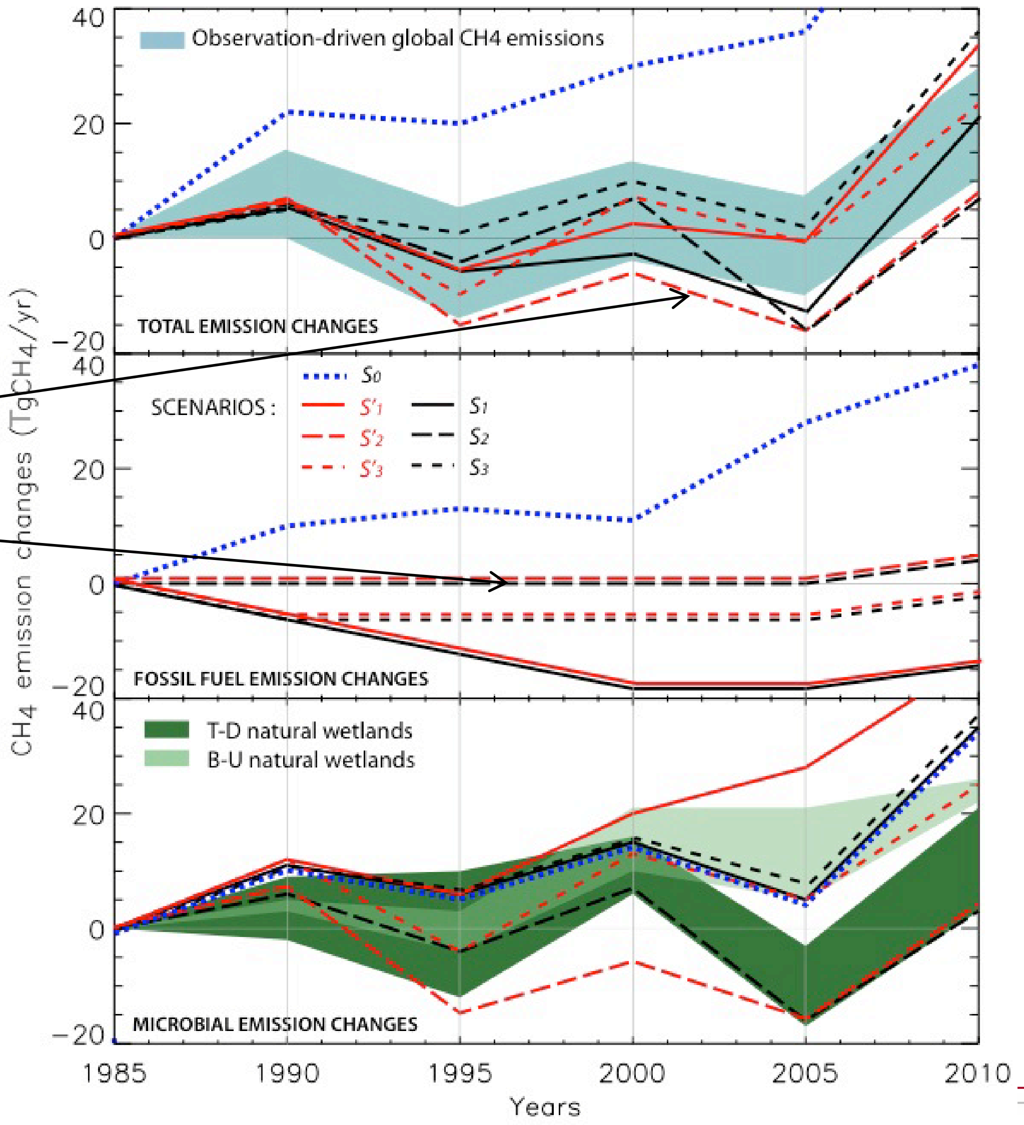
S0 : EDGAR/EPA +wetlands

S1 : Decreasing fugitive emissions from 1985 to 2000 + EDGAR/EPA + wetlands (TD or BU)

S2 : Stable fossil and microbial between 1990 and 2005 + EDGAR/EPA +wetlands (TD or BU)

5-year emission changes since 1985 for 3 categories

Scenarios of Temporal Change



Range of global emissions is less matched by stable fossil and decreasing microbial emissions

S0 : EDGAR/EPA +wetlands

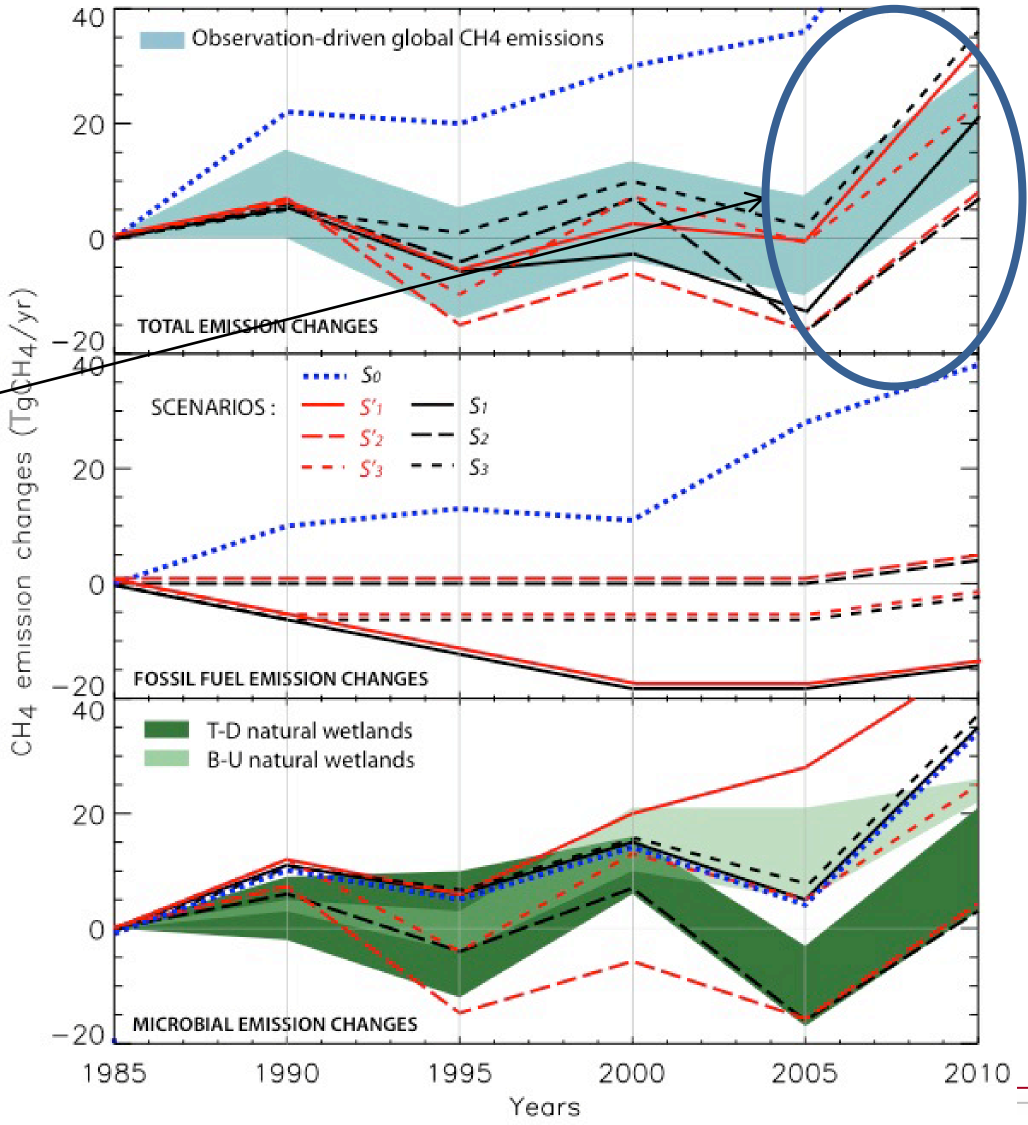
S1 : Decreasing fugitive emissions from 1985 to 2000 + EDGAR/EPA + wetlands (TD or BU)

S2 : Stable fossil and microbial between 1990 and 2005 + EDGAR/EPA +wetlands (TD or BU)

S3 : Decreasing microbial and stable fossil + EDGAR/EPA + wetlands (TD or BU)

5-year emission changes since 1985 for 3 categories

Scenarios of Temporal Change



After 2005 : Too fast increase for all scenarios !

S0 : EDGAR/EPA +wetlands

S1 : Decreasing fugitive emissions from 1985 to 2000 + EDGAR/EPA + wetlands (TD or BU)

S2 : Stable fossil and microbial between 1990 and 2005 + EDGAR/EPA +wetlands (TD or BU)

S3 : Decreasing microbial and stable fossil + EDGAR/EPA + wetlands (TD or BU)

5-year emission changes since 1985 for 3 categories

Results of the Scenario Analysis

Stabilisation period (1999-2006):

→ Decreasing to stable fossil fuel emissions and stable to increasing microbial emissions are more likely

Resumed atmospheric increase (>2006) :

→ Mix of fossil fuel and wetland emissions increase, but relative magnitude remains uncertain

Final Key Points

- Among datasets and models, consistency is higher on anthropogenic decadal emissions than natural ones.
- The large uncertainties in the mean emissions from natural wetlands limit our ability to fully close the CH_4 budget.
- Global emissions as inferred from the sum of all individual emission sources are likely too high as they cannot use the overall atmospheric constraint.
- Little ability of the top-down atmospheric inversions to partition emissions among source types.
- Still large uncertainties on decadal means but reduced compared to the IPCC 4th Assessment Report.
- Interannual variability is dominated by natural wetlands, with short-term impacts of biomass burning. More robust than decadal means.
- 1999-2006 : ➔➘ fossil fuel emissions with ➔➚ microbial emissions more likely than other tested scenarios.
- Changes after 2005 still debated between ➚ wetlands and ➚ fossil fuels
- Improved agreement for a small OH interannual variability in the 2000s between top-down and bottom-up estimates.

Global Methane Budget Website

http://www.globalcarbonproject.org/methanebudget

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