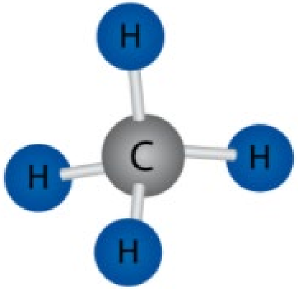
西湖大學
WESTLAKE UNIVERSITY

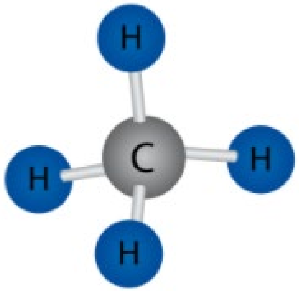
温室气体甲烷

全球及中国排放分布和趋势



张 羽 中
zhangyuzhong@westlake.edu.cn

提纲

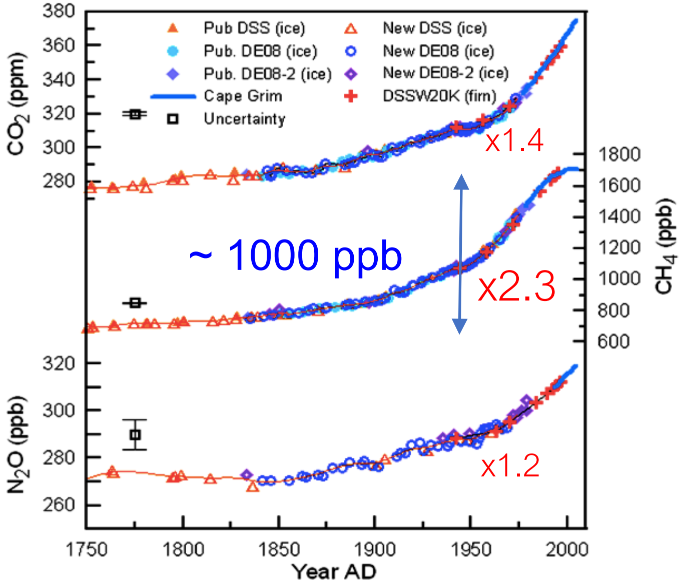


CH_4

1. 温室气体甲烷
2. 全球大气甲烷收支
3. 中国甲烷排放：分布和趋势
4. 观测系统模拟实验(OSSE)

温室气体甲烷

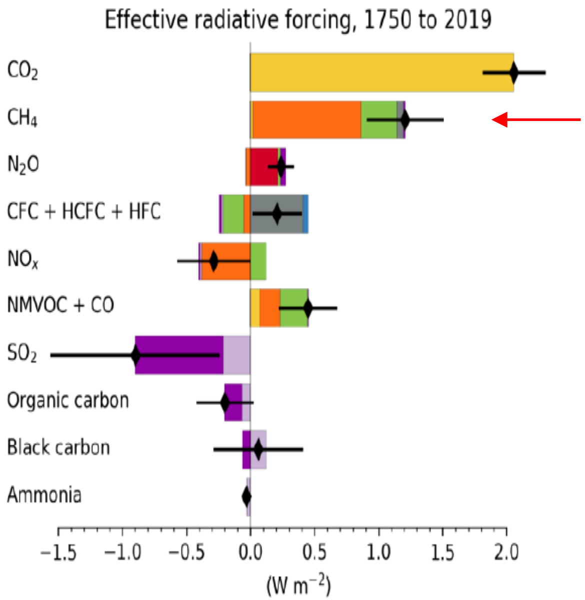
Greenhouse gases in last 300 years



Ice core record

MacFarling Meure et al., GRL，2006

Radiative forcing since industrialization



IPCC AR6 2021

全球升温潜势
Global Warming Potential

单位质量甲烷吸收红外能量的能力是二氧化碳的30倍（100年尺度）

大气甲烷的源

Wetlands

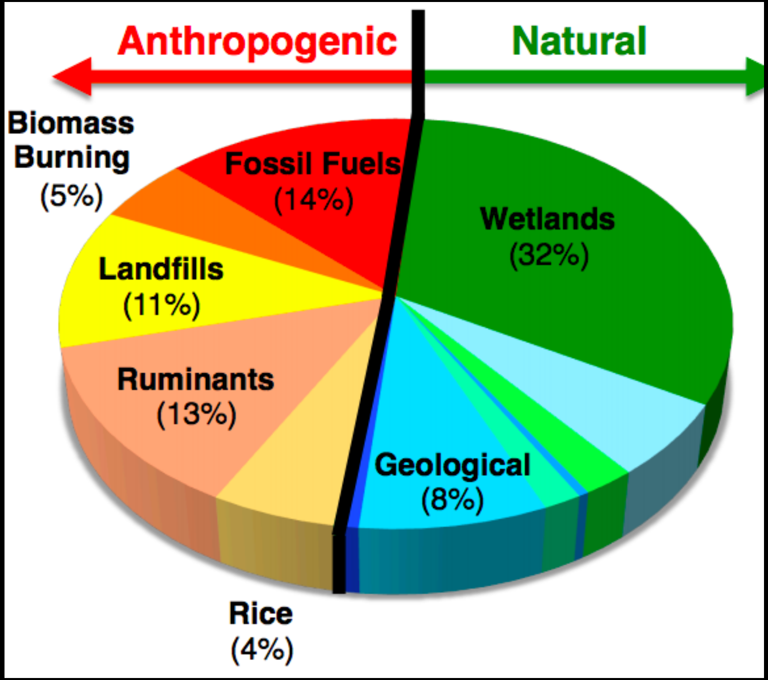
Oil/gas

Landfills,
wastewater

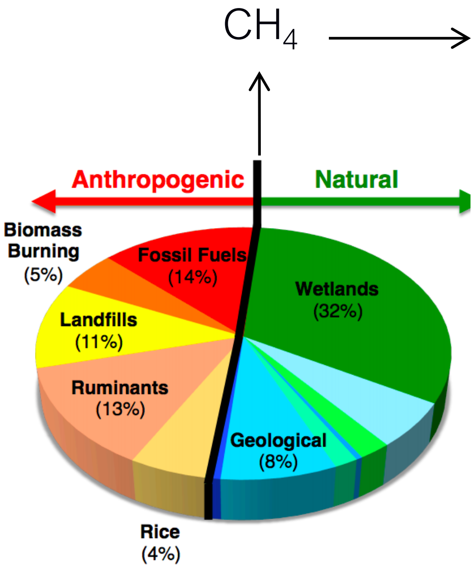
Livestock

Coal mines

Fires


Anthropogenic
Natural
Biomass Burning (5%)
Fossil Fuels (14%)
Landfills (11%)
Ruminants (13%)
Rice (4%)
Wetlands (32%)
Geological (8%)

大气甲烷的汇



源

$550 \pm 60\ Tg\ a^{-1}$

汇

大气寿命约10年

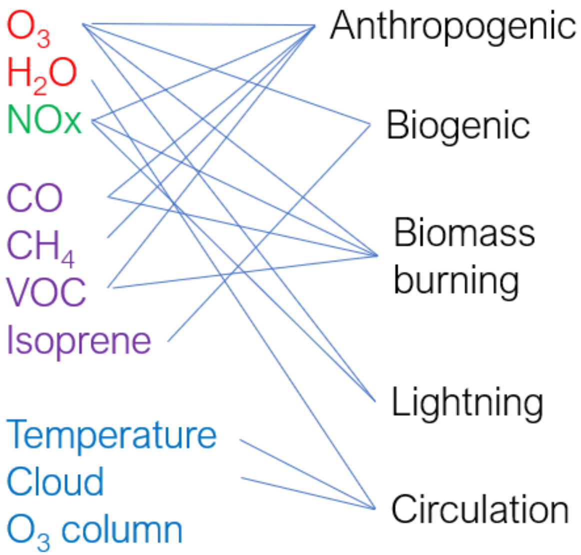
Tropospheric OH
89%

Soil Absorption

Stratospheric Loss

Tropospheric Cl

影响OH浓度的因素



O_3
H_2O
NOx

CO
CH_4
VOC
Isoprene

Temperature
Cloud
O_3 column

Anthropogenic

Biogenic

Biomass burning

Lightning

Circulation

温室气体减排

应对气候变化

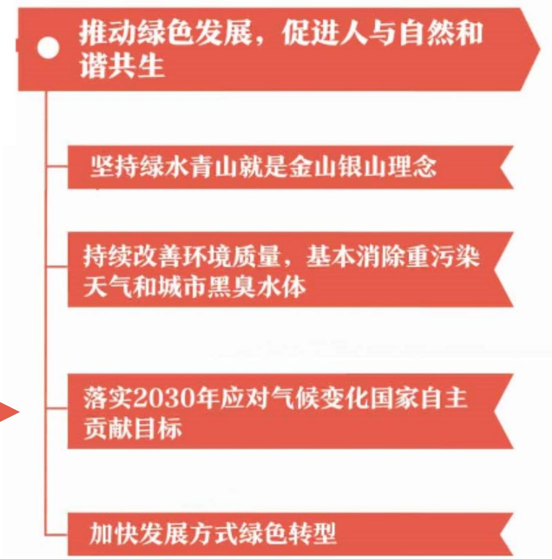
UNITED NATIONS
PARIS CLIMATE AGREEMENT
SIGNING CEREMONY
22 APRIL 2016

中国的承诺

二氧化碳排放力争于2030年前达到峰值

努力争取2060年前实现碳中和

“十四五”时期 环境领域主要目标



- 推动绿色发展，促进人与自然和谐共生
  - 坚持绿水青山就是金山银山理念
  - 持续改善环境质量，基本消除重污染天气和城市黑臭水体
  - 落实2030年应对气候变化国家自主贡献目标
  - 加快发展方式绿色转型

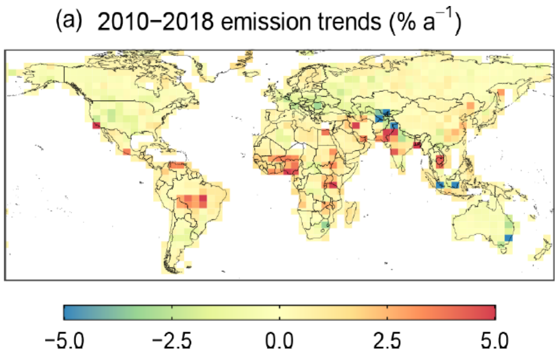
《2021两会政府工作报告》

首次提出控制甲烷等非二氧化碳温室气体

甲烷排放的监测：从全球到点源

全球/国家

考察全球浓度变化的驱动因素
考察自然源和汇的反馈

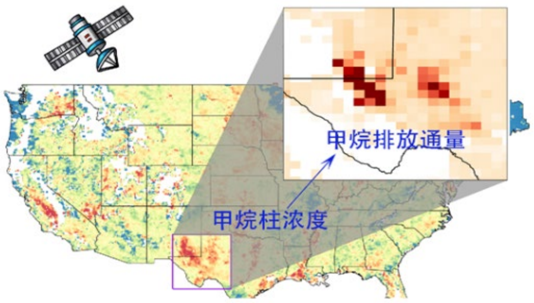

(a) 2010–2018 emission trends (% a⁻¹)
-5.0
-2.5
0.0
2.5
5.0

全球2010-2018年甲烷收支

GOSAT 卫星

区域

支持区域政策制定
理解控制区域排放源的因素

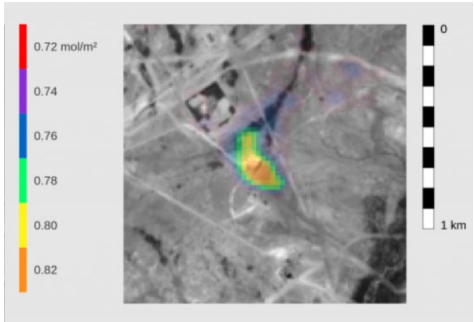

甲烷排放通量
甲烷柱浓度

重点油气生产区域高分辨率反演

TROPOMI 卫星

点源/设施

发现异常排放点源
采取维修、监管措施


0.72 mol/m²
0.74
0.76
0.78
0.80
0.82
0
1 km

~10 m 分辨率

油气生产设施super emitter

高分五号

不同时空尺度之间信息的整合

卫星观测数据的分析：从浓度到排放

Emission monitoring vs concentration monitoring

Spectral signal

Retrieval

Radiative transfer

Concentration

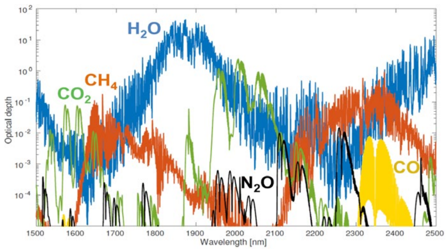
Inversion

CTM

★

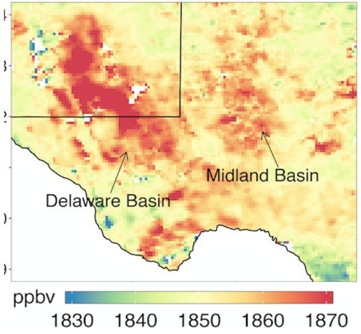
Emissions

SWIR absorption spectrum

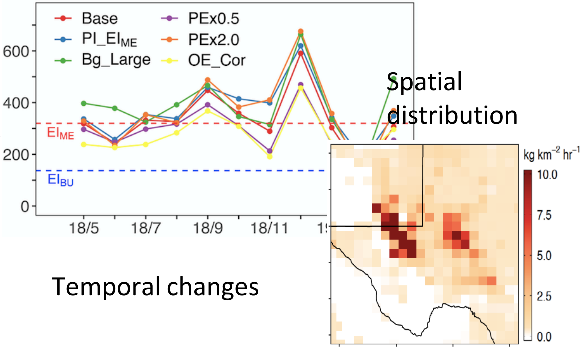


Wavelength [µm]

XCH4 column mixing ratio


Delaware Basin
Midland Basin
ppbv
1830
1840
1850
1860
1870

Emission estimates



Spatial distribution

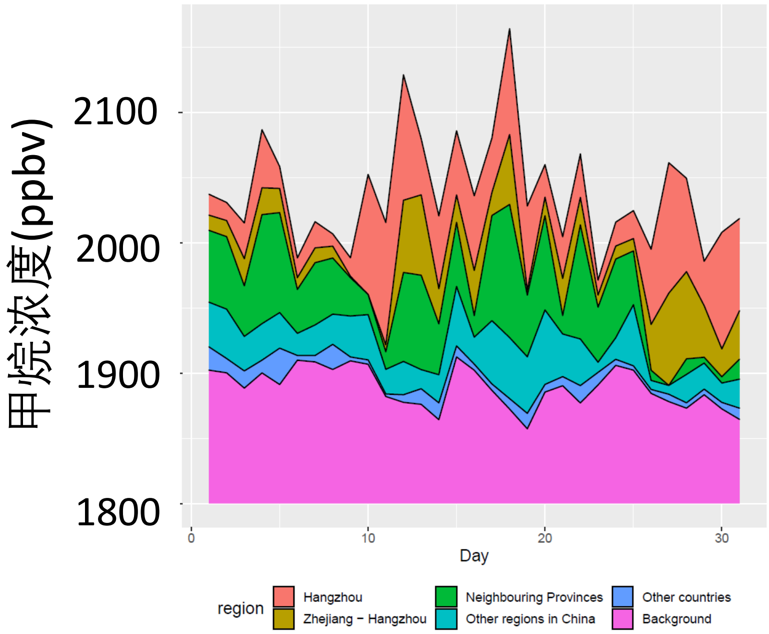
Temporal changes

区域浓度观测与排放之间复杂的关系

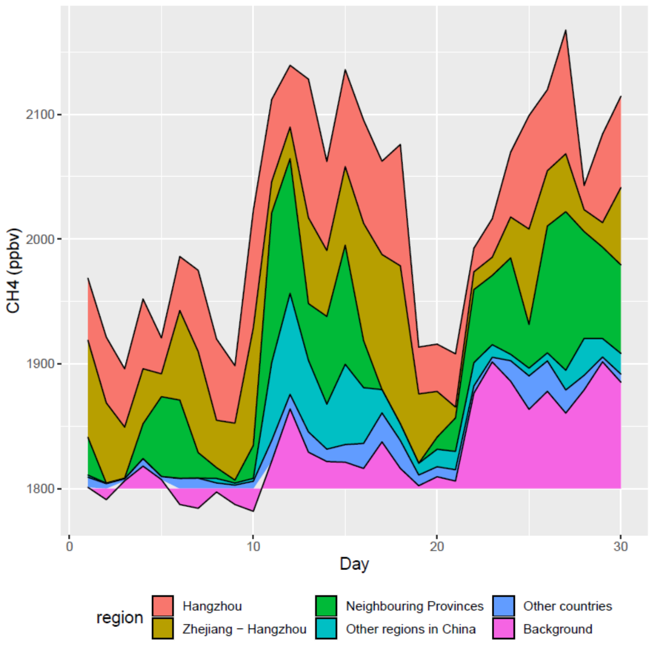
杭州
本地
排放

全球
背景

2010年3月

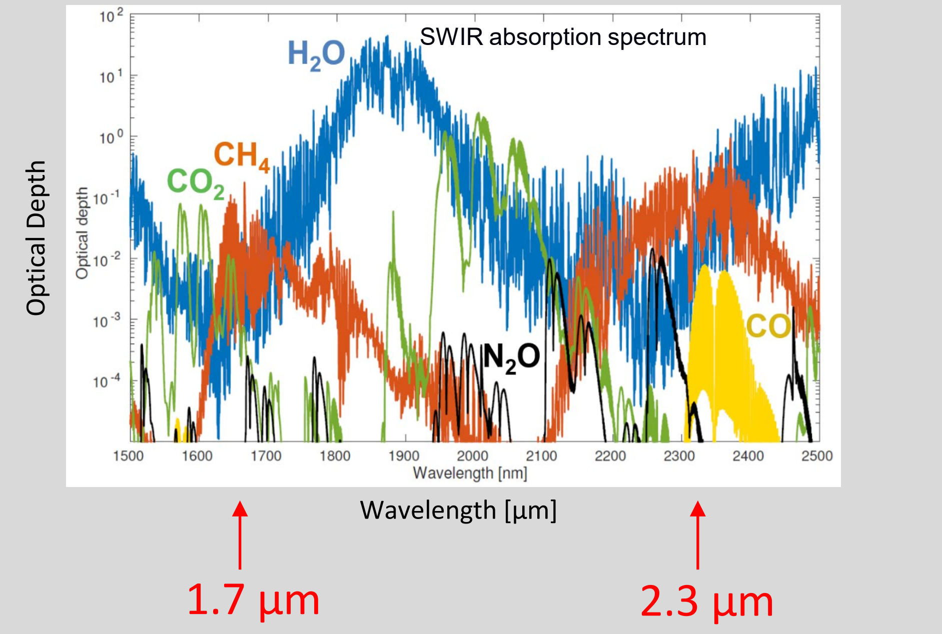


2010年9月

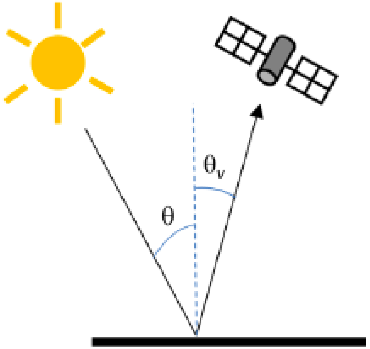


甲烷卫星观测

Absorption spectrum

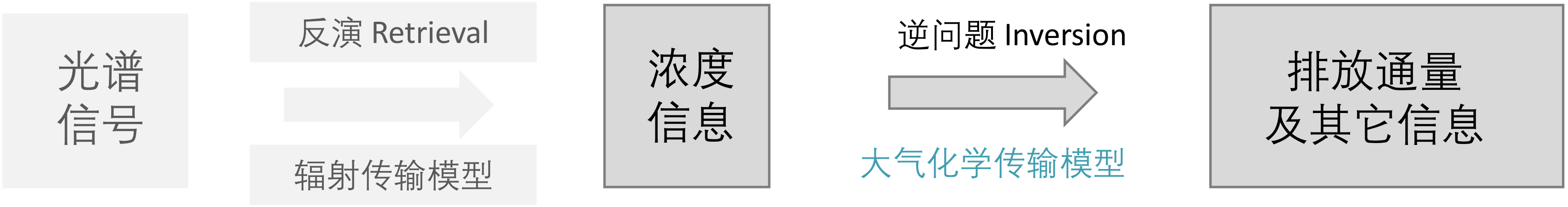


Solar backscatter


θ_v
θ

Absorption along the light path

卫星遥感观测反演的技术路线



光谱信号

反演 Retrieval

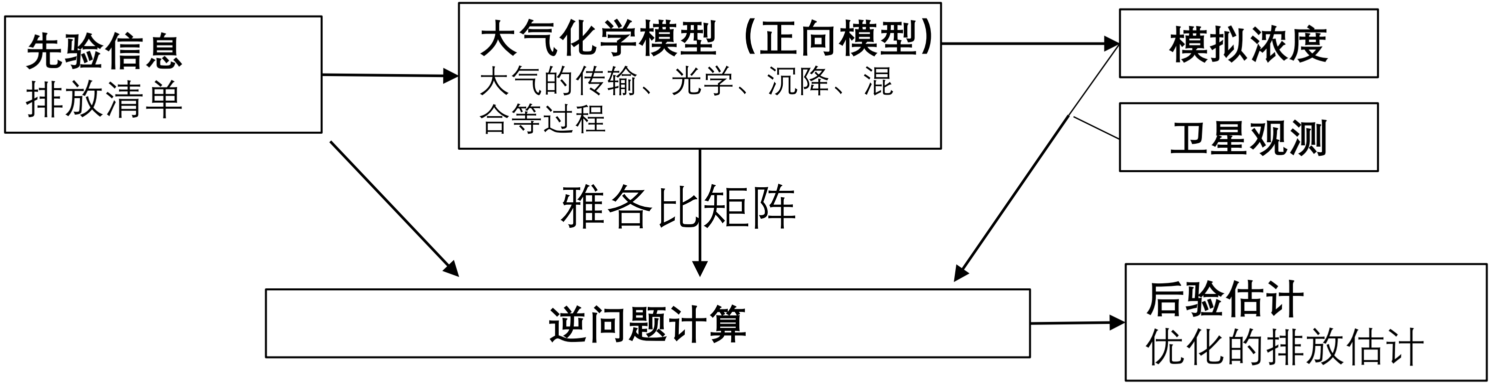
辐射传输模型

浓度信息

逆问题 Inversion

大气化学传输模型

排放通量及其它信息



先验信息
排放清单

大气化学模型（正向模型）
大气的传输、光学、沉降、混合等过程

模拟浓度

卫星观测

雅各比矩阵

逆问题计算

后验估计
优化的排放估计

$$J(\boldsymbol{x}) = (\boldsymbol{x} - \underline{\boldsymbol{x}_a})^{T}\mathbf{S}_a^{-1}(\boldsymbol{x} - \boldsymbol{x}_a) + \gamma(\underline{\boldsymbol{y}} - \mathbf{K}\boldsymbol{x})^{T}\mathbf{S}_O^{-1}(\boldsymbol{y} - \underline{\mathbf{K}\boldsymbol{x}})$$

先验信息

↓ 先验信息的不确定度

卫星观测

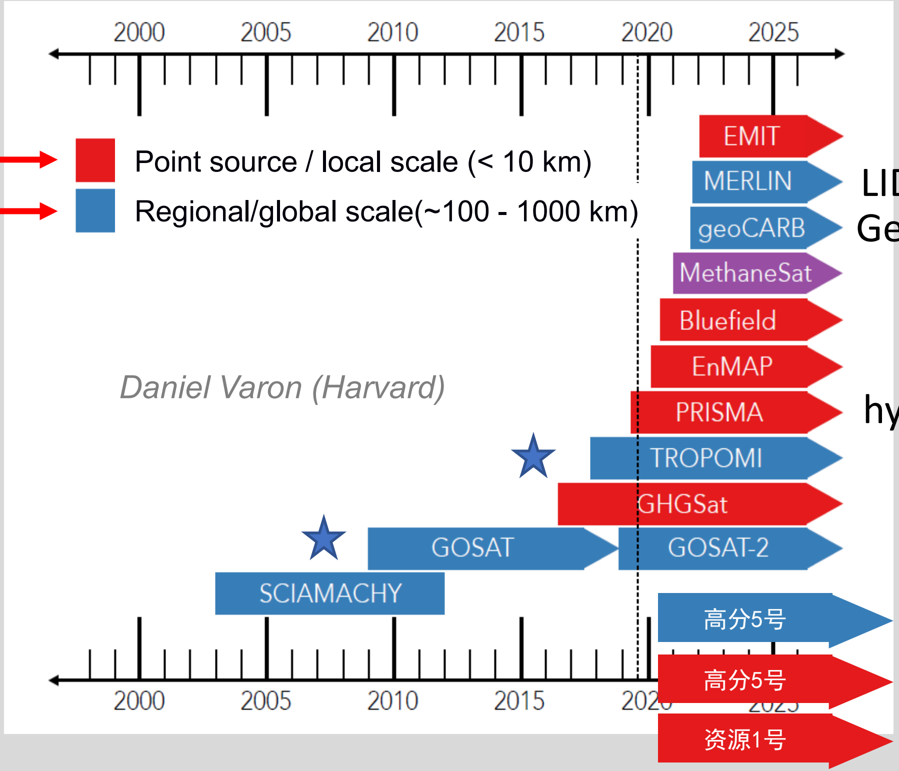
↓ 观测和模型的不确定度

正向模型：观测对排放的敏感度

发展迅速的卫星观测能力

Low precision
high spatial resolution

High precision
low spatial resolution



Daniel Varon (Harvard)

LIDAR → polar region
Geostationary → higher obs. freq.

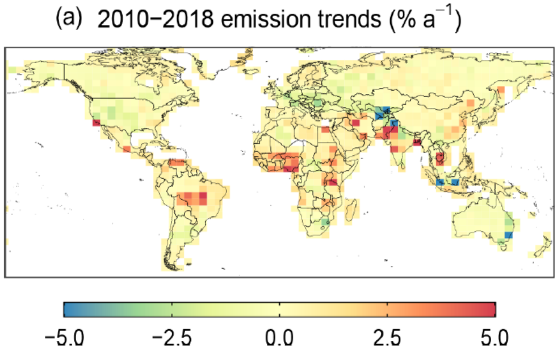
hyperspectral

China’s methane monitoring satellite missions

甲烷排放的监测：从全球到点源

全球/国家

考察全球浓度变化的驱动因素
考察自然源和汇的反馈


(a) 2010–2018 emission trends (% a^{-1})
-5.0
-2.5
0.0
2.5
5.0

全球2010-2018年甲烷收支

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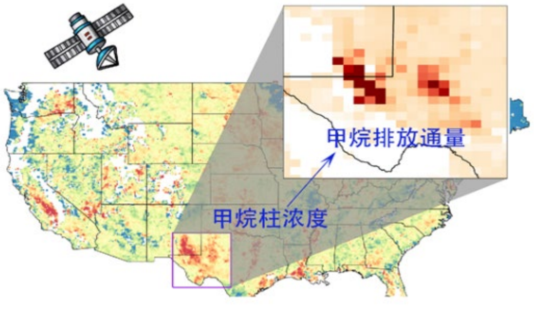
理解控制区域排放源的因素


甲烷排放通量
甲烷柱浓度

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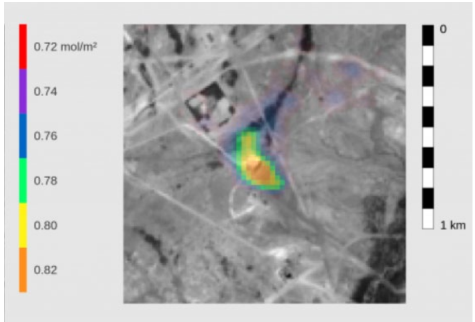
TROPOMI 卫星

点源/设施

发现异常排放点源
采取维修、监管措施


0.72 mol/m²
0.74
0.76
0.78
0.80
0.82
0
1 km

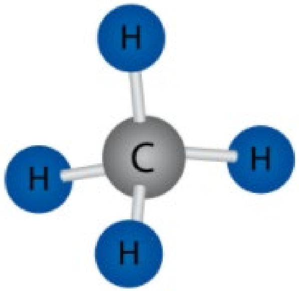
~10 m 分辨率

油气生产设施super emitter

高分五号

不同时空尺度之间信息的整合

提纲



CH_4

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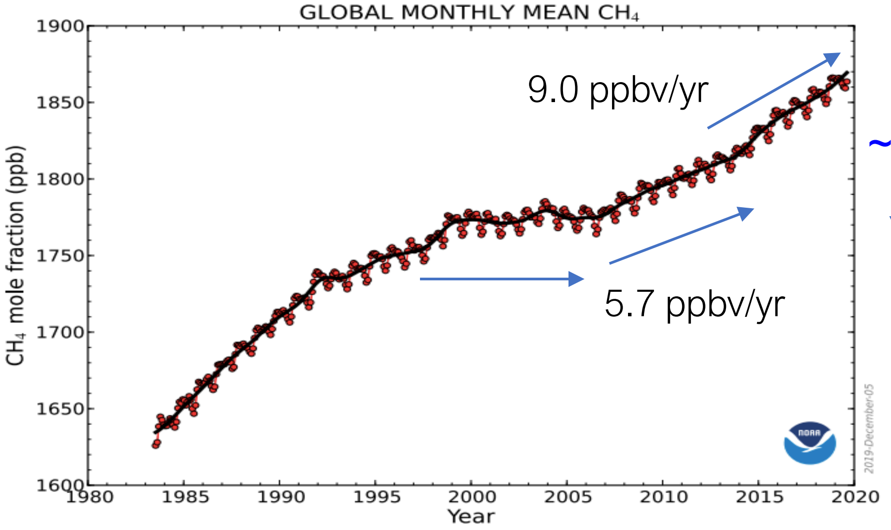
全球大气甲烷浓度变化

CH_4 concentration in last 35 years

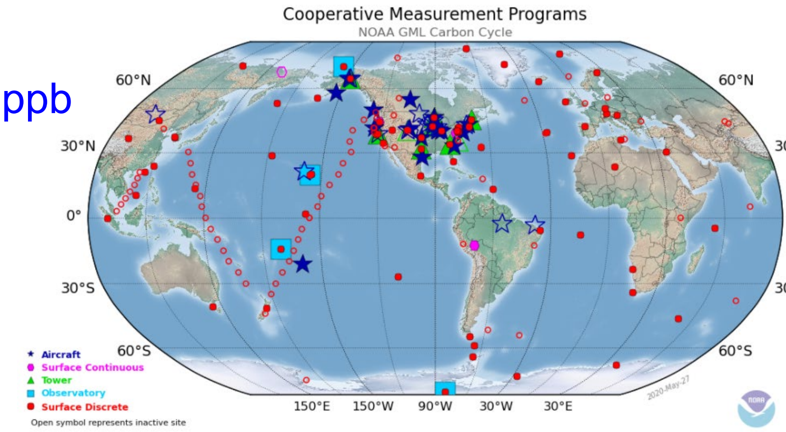


9.0 ppbv/yr

5.7 ppbv/yr

~ 75 ppb

Surface measurement network


Cooperative Measurement Programs
NOAA GML Carbon Cycle
60°N
30°N
0°
30°S
60°S
150°E
150°W
90°W
30°W
30°E
★ Aircraft
● Surface Continuous
▲ Tower
■ Observatory
● Surface Discrete
Open symbol represents inactive site
2020-May-27
NOAA

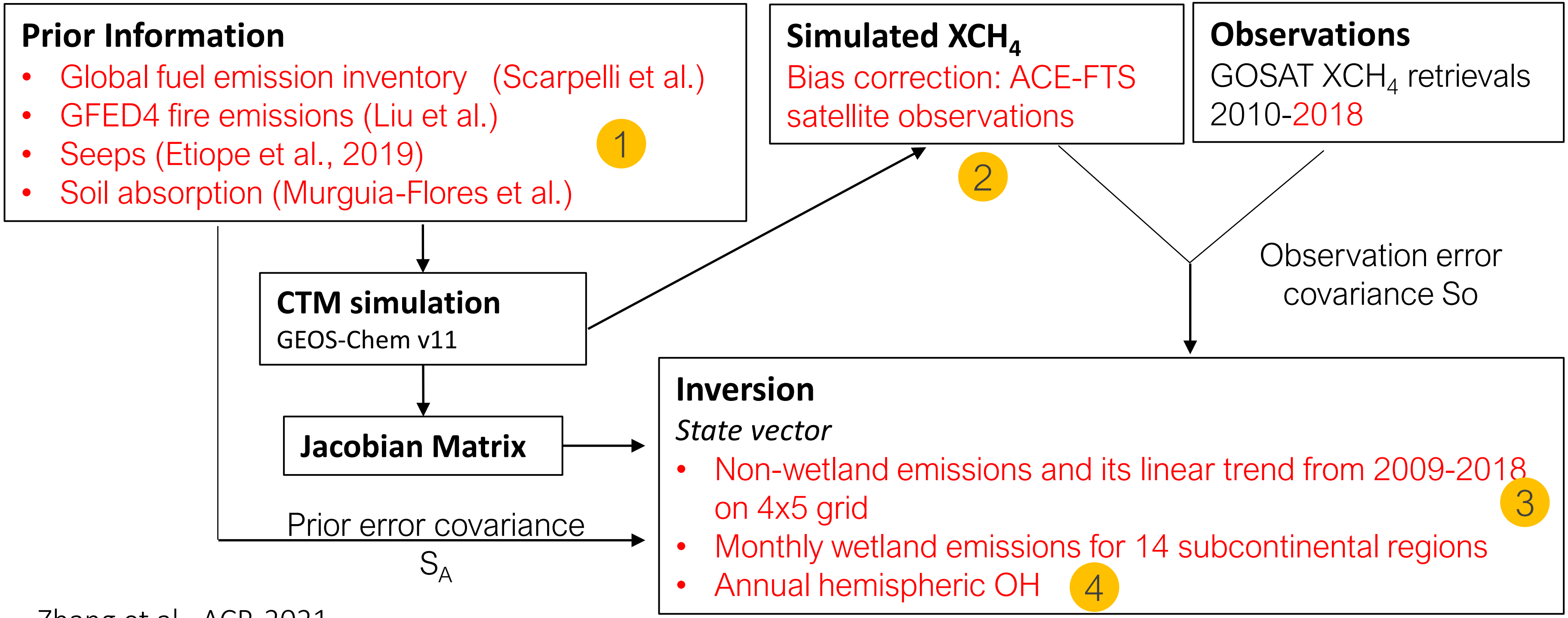
卫星数据的反演分析

① Best available prior information

② Improved stratospheric bias correction

③ Better treatment for wetland emissions

④ Annual hemispheric OH



Prior Information
- Global fuel emission inventory (Scarpelli et al.)
- GFED4 fire emissions (Liu et al.)
- Seeps (Etiope et al., 2019)
- Soil absorption (Murguia-Flores et al.)

①

Simulated XCH_4

Bias correction: ACE-FTS satellite observations

②

Observations

GOSAT XCH_4 retrievals 2010-2018

Observation error covariance So

CTM simulation

GEOS-Chem v11

Jacobian Matrix

Prior error covariance S_A

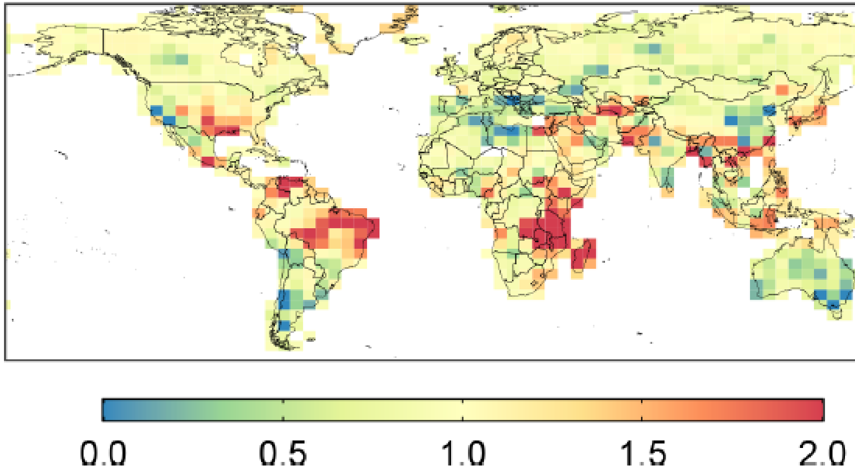
Inversion

State vector
- Non-wetland emissions and its linear trend from 2009-2018 on 4x5 grid ③
- Monthly wetland emissions for 14 subcontinental regions
- Annual hemispheric OH ④

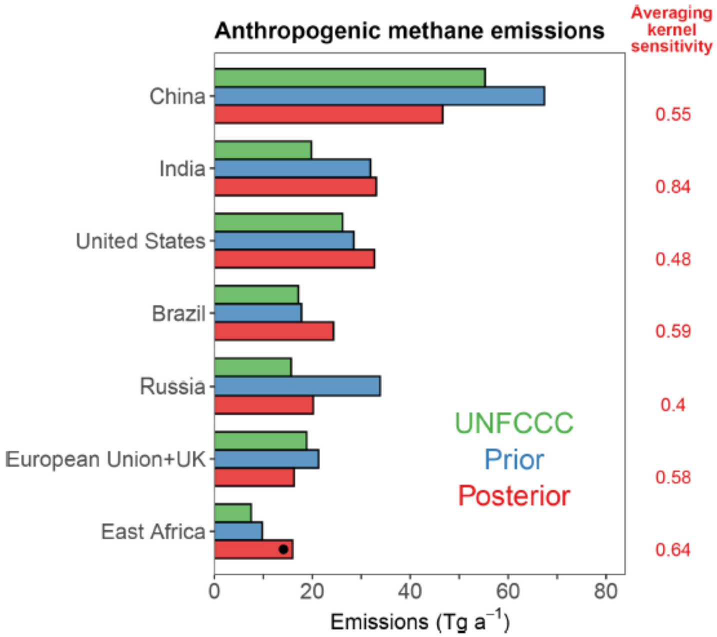
Zhang et al., ACP, 2021

全球2010-2018 GOSAT反演：人为源排放

(a) Posterior/prior emission ratios

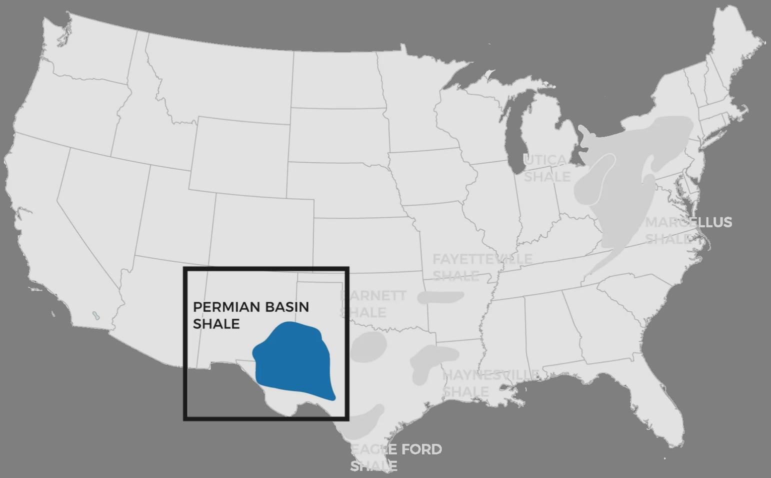

0.0
0.5
1.0
1.5
2.0

验证国家清单



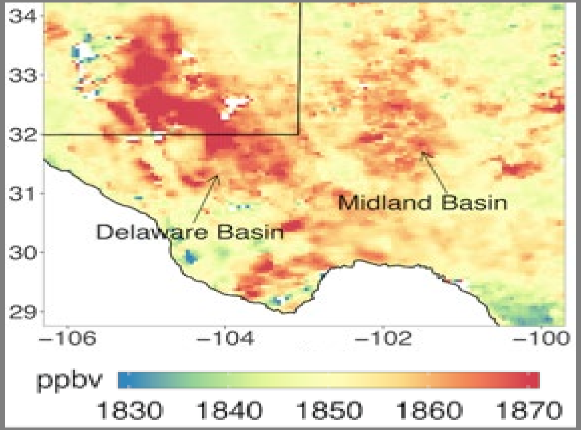
Zhang et al., ACP, 2021

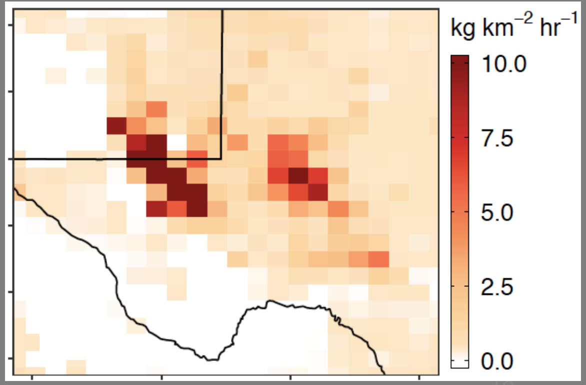
U.S.'s Permian Basin *(Zhang et al., Science Advances, 2020)*
美国最大的油气生产盆地


UTICA SHALE
MARCELLUS SHALE
FAYETTEVILLE SHALE
BARNETT SHALE
PERMIAN BASIN SHALE
HAYNESVILLE SHALE
EAGLE FORD SHALE

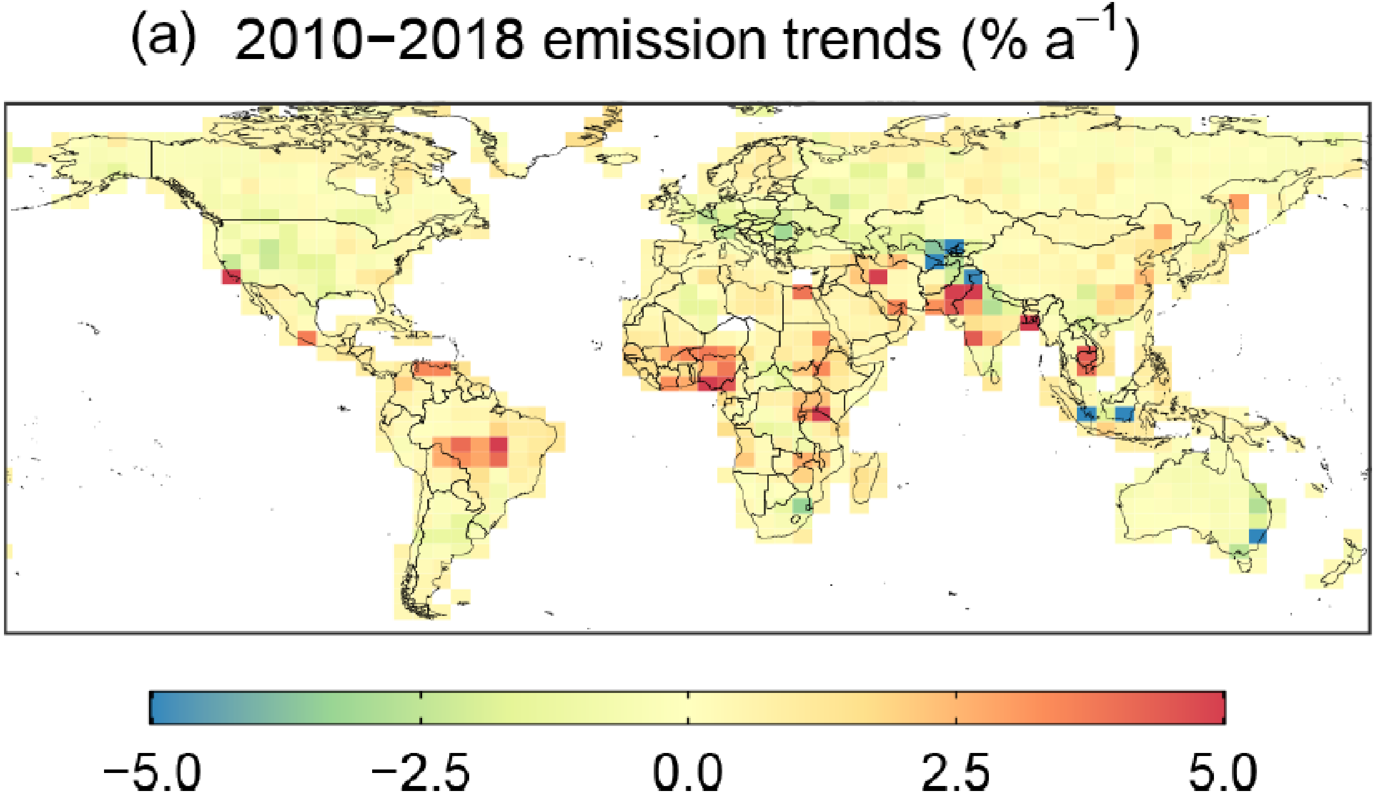
TROPOMI
甲烷柱浓度

甲烷排放
通量分布

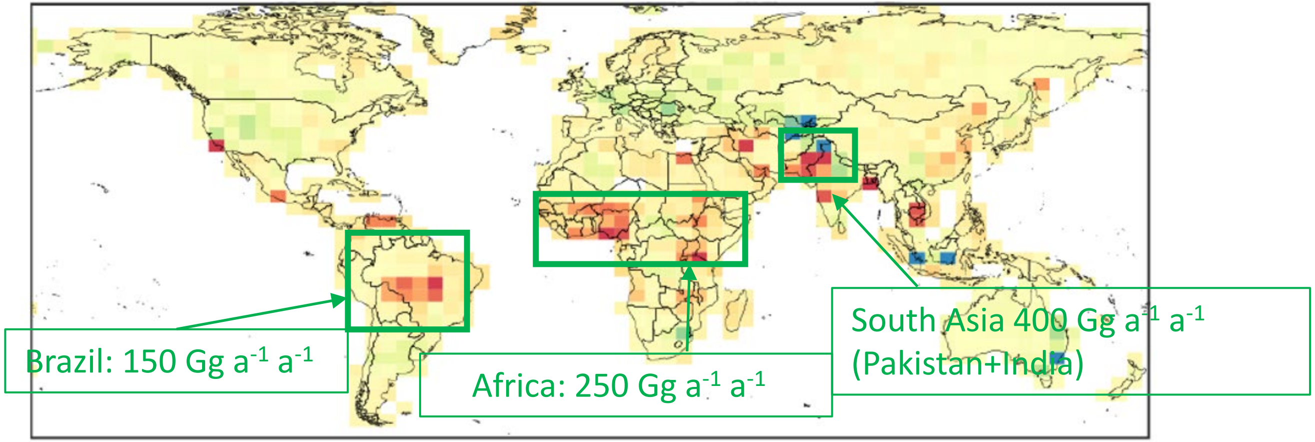

34
33
32
31
30
29
−106
−104
−102
−100
Delaware Basin
Midland Basin
ppbv
1830
1840
1850
1860
1870


kg km^{-2} hr^{-1}
10.0
7.5
5.0
2.5
0.0

全球2010-2018 GOSAT反演：人为源排放趋势


(a) 2010-2018 emission trends (% a^{-1})
-5.0
-2.5
0.0
2.5
5.0

发展中地区的农业畜牧源增长缺少重视和深入研究



Brazil: 150 Gg a^{-1} a^{-1}

Africa: 250 Gg a^{-1} a^{-1}

South Asia 400 Gg a^{-1} a^{-1}
(Pakistan+India)

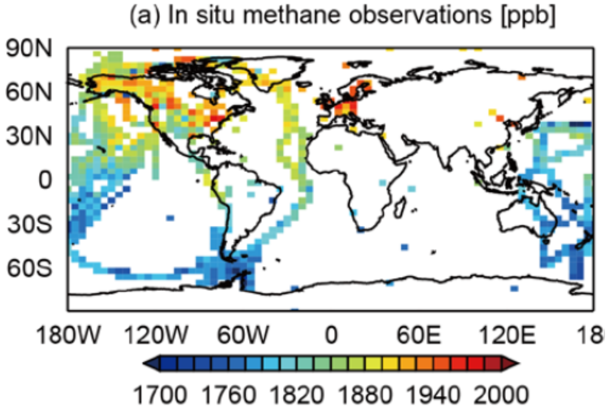
Top 5 counties with fastest growing cattle population

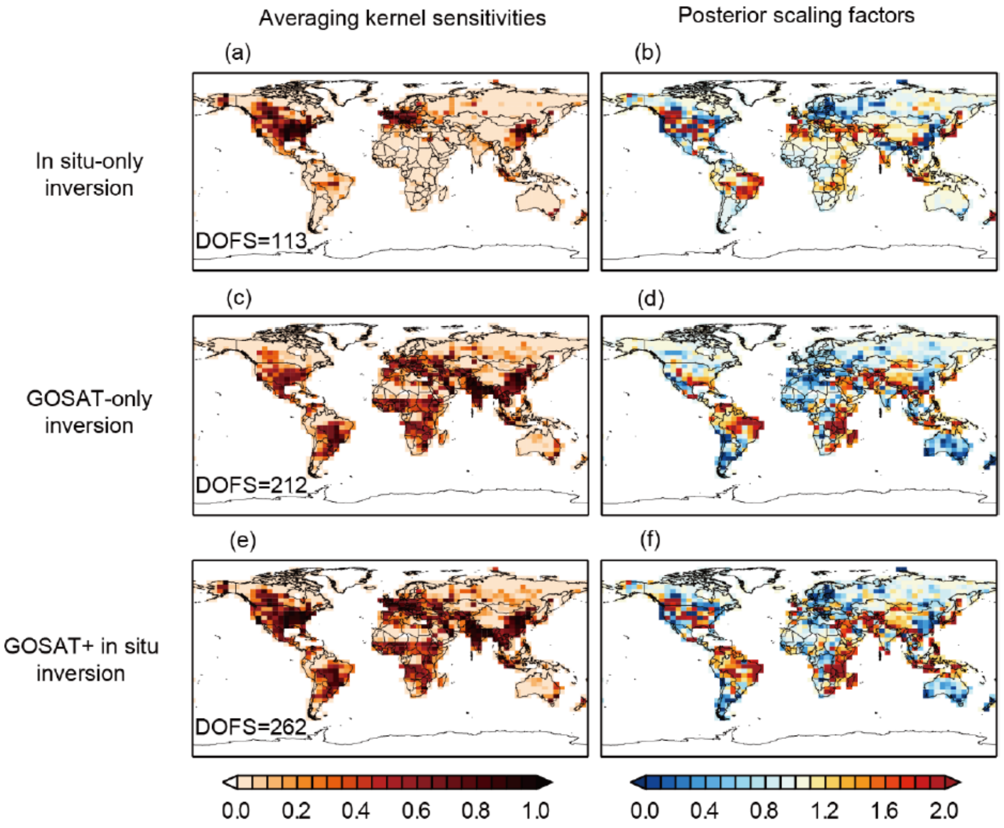
UNFAO

Country	Trend (million head per year)
Pakistan	1.4
Ethiopia	1.2
Tanzania	1.1
Brazil	0.9
Argentina	0.7

卫星和地面甲烷观测互相补充

地面和飞机观测

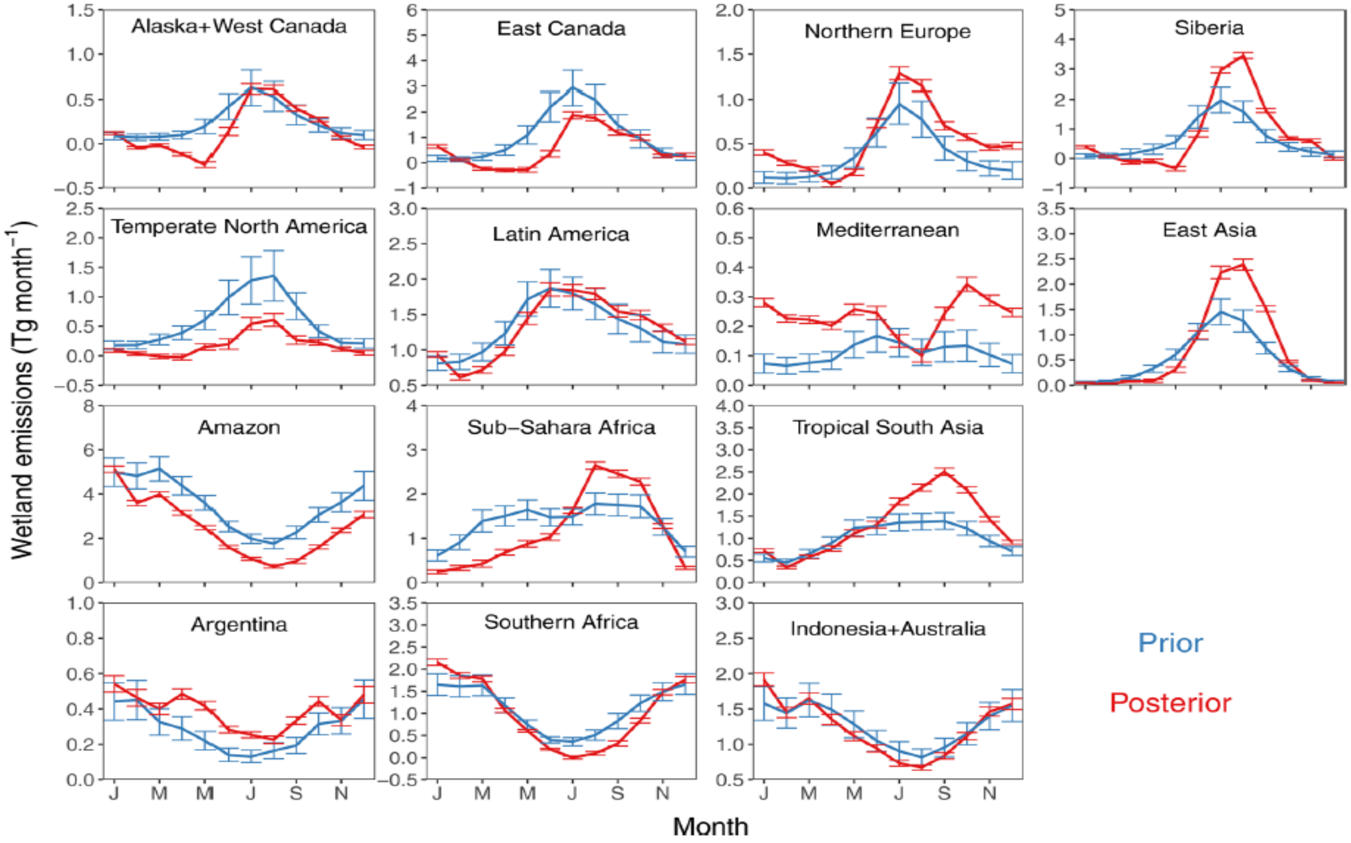

(a) In situ methane observations [ppb]
90N
60N
30N
0
30S
60S
180W
120W
60W
0
60E
120E
18
1700
1760
1820
1880
1940
2000


Averaging kernel sensitivities
Posterior scaling factors
(a)
(b)
In situ-only inversion
DOFS=113
(c)
(d)
GOSAT-only inversion
DOFS=212
(e)
(f)
GOSAT+ in situ inversion
DOFS=262
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.4
0.8
1.2
1.6
2.0

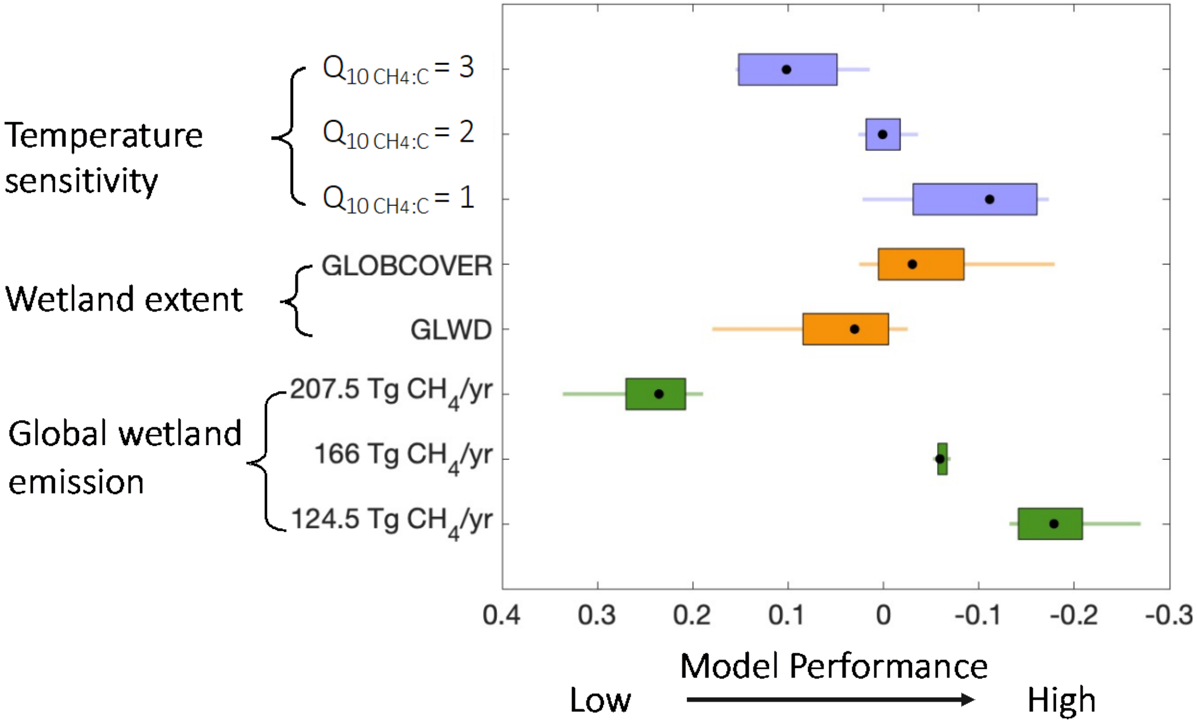
卫星提供的信息对表征
南半球排放尤为重要

Lu et al, ACP, 2021

湿地排放


Alaska+West Canada
East Canada
Northern Europe
Siberia
Temperate North America
Latin America
Mediterranean
East Asia
Amazon
Sub−Sahara Africa
Tropical South Asia
Argentina
Southern Africa
Indonesia+Australia
Wetland emissions (Tg month^{-1})
Month
J
M
M
J
S
N
Prior
Posterior

湿地排放：评估湿地甲烷生物地球模型

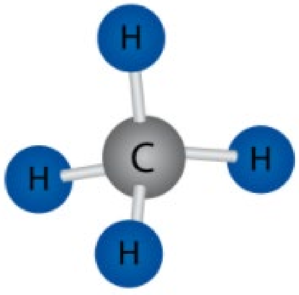


热带湿地排放受降水控制

寒带湿地排放受温度控制

Ma et al., AGU Advances, 2021

提纲



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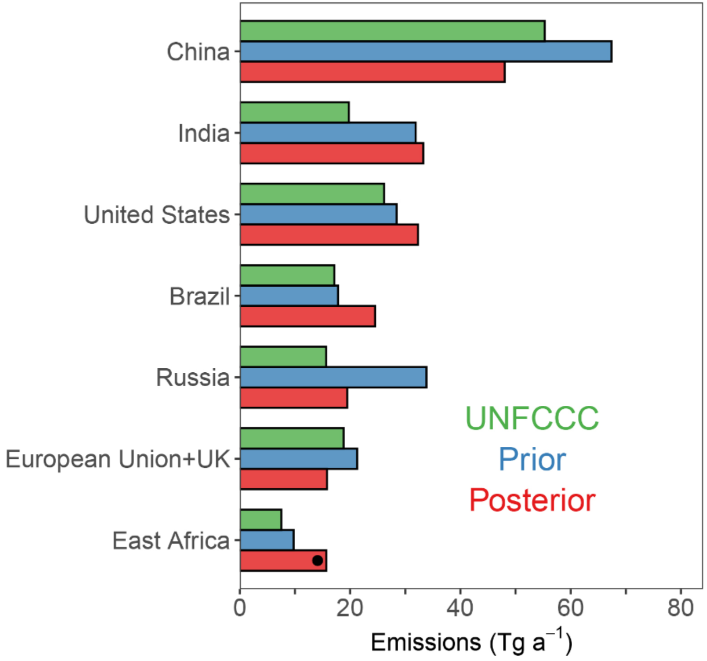
4. 观测系统模拟实验(OSSE)

中国甲烷排放

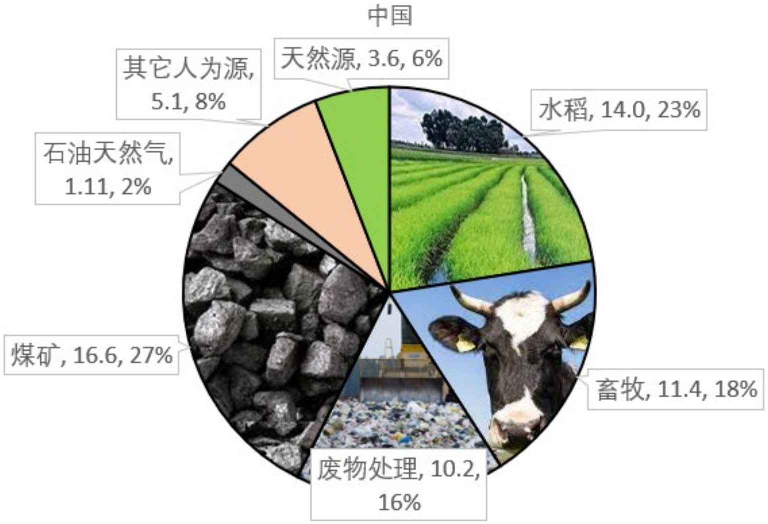
人为源排放(百万吨/年)



Zhang et al. (2021)

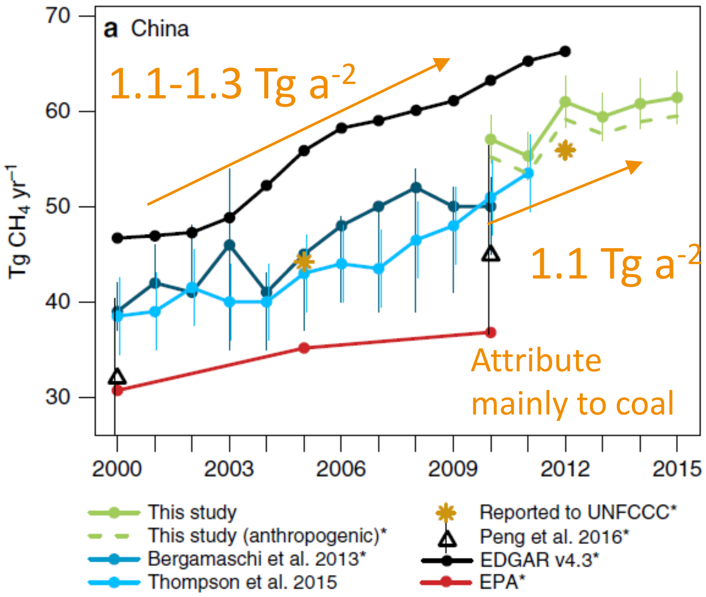
GWP=30

CH_4	CO_2
1800 Tg a^{-1} CO_{2e}	9000 Tg a^{-1} CO_2



近年来中国甲烷排放趋势

Satellite inversion



1.1-1.3 Tg a^{-2}

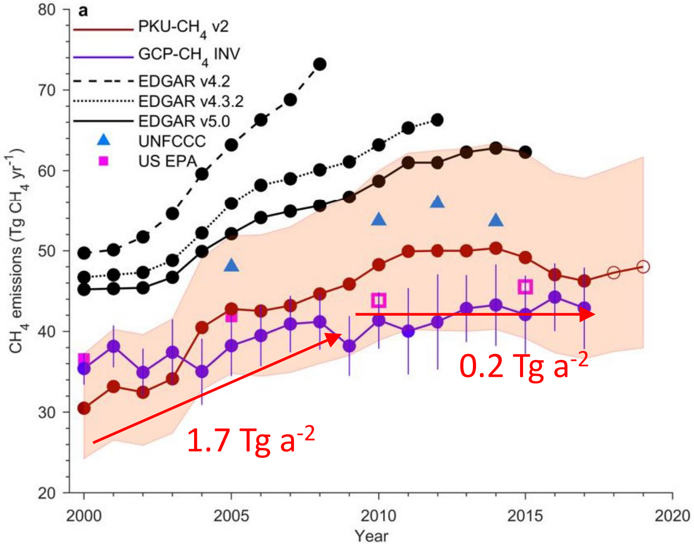
1.1 Tg a^{-2}

Attribute mainly to coal

Miller et al., 2019

Coarse resolution
Inaccurate prior sectoral distribution

Bottom-up inventory



0.2 Tg a^{-2}

1.7 Tg a^{-2}

Liu et al., 2021

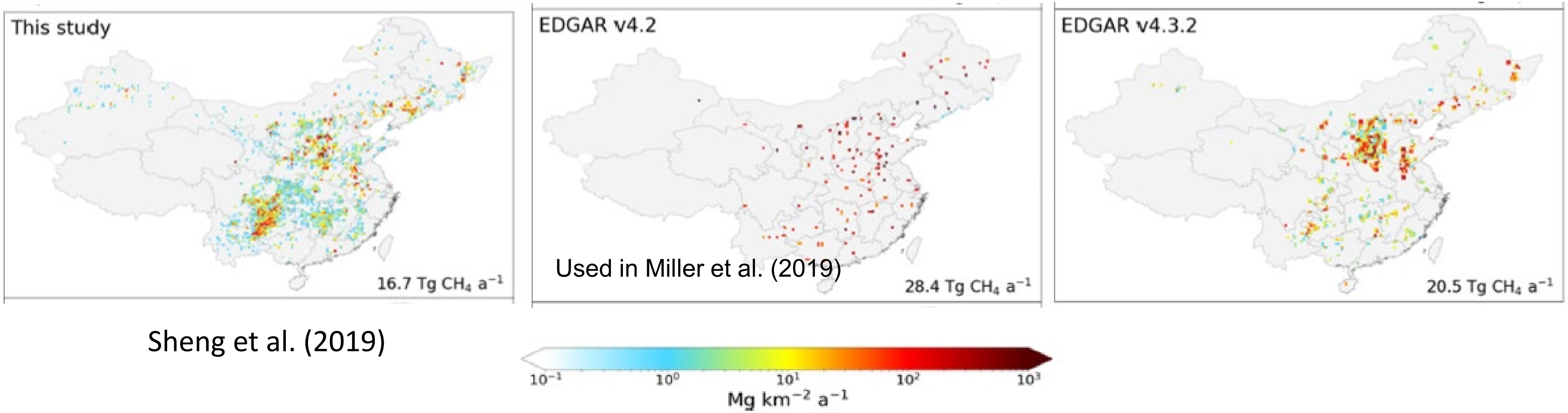
Provincial-level activity data

Changes may not be accounted for in the bottom-up inventories

部门排放清单的不确定性

Affect inference of methane fluxes as well as sector attribution

Distribution of coal mine emissions from different bottom-up inventories


This study
16.7 Tg CH₄ a⁻¹
EDGAR v4.2
28.4 Tg CH₄ a⁻¹
EDGAR v4.3.2
20.5 Tg CH₄ a⁻¹
10⁻¹
10⁰
10¹
10²
10³
Mg km⁻² a⁻¹

Used in Miller et al. (2019)

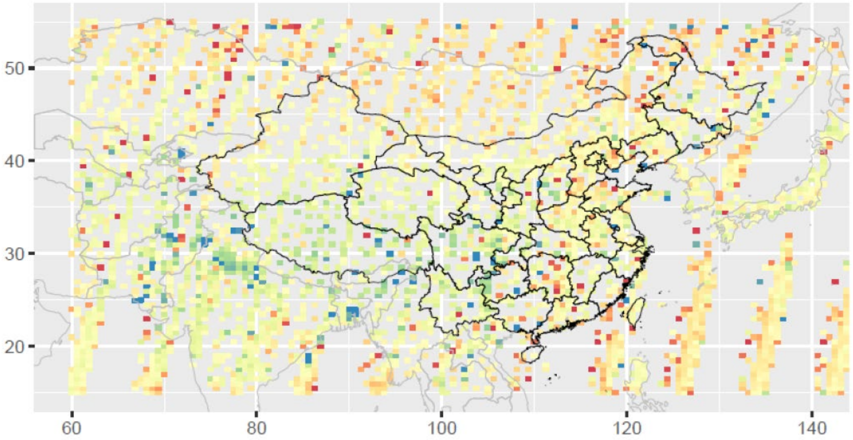
Sheng et al. (2019)

Sheng et al. (2021) derived a trend (0.4 Tg a^{-2}) smaller than Miller et al. (2019) (1.1 Tg a^{-2})

中国甲烷排放反演

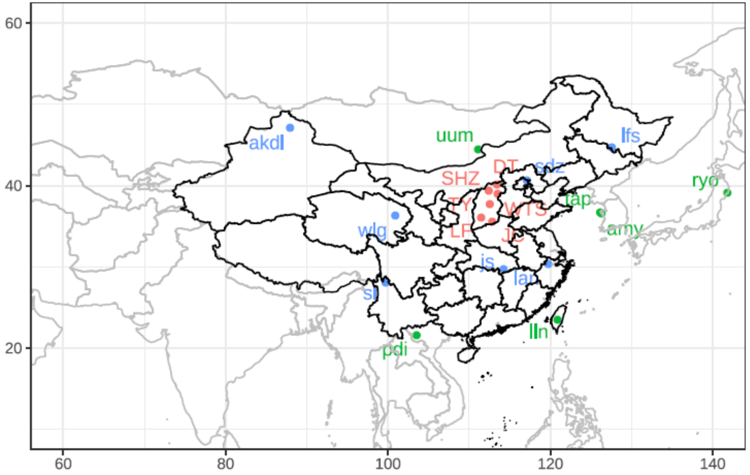
高分辨率区域反演　　地面长期观测站点网络

GOSAT卫星观测



50
40
30
20
60
80
100
120
140

地面站点2010-2017



60
40
20
60
80
100
120
140
akdl
uum
lfs
DT
sdz
SHZ
ryo
TY
WTS
tap
wlg
LF
JC
amy
js
lan
sl
lln
pdi

Zhang et al. in prep

中国甲烷排放反演

Bottom-up estimates

Multiple anthropogenic emission inventories are used as prior for (sensitivity) inversions to explore uncertainties

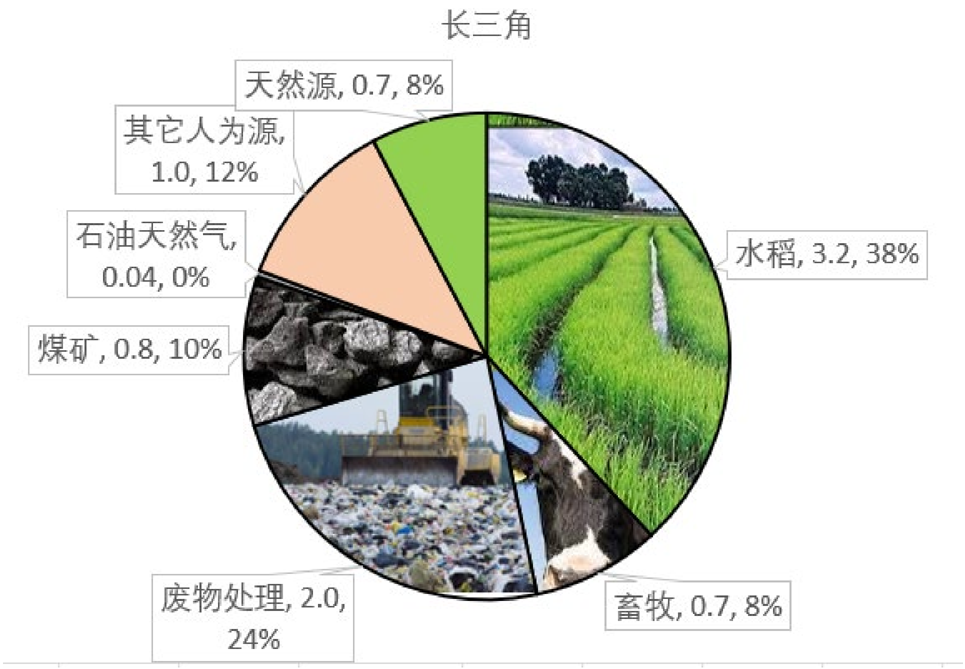
Name	Anthropogenic emissions	Emissions (Tg a^{-1})	Trend (Tg a^{-2})
E1	EDGAR v4.3.2 for 2012, except for coal (Sheng et al., 2019)	59	0
E2	PKU 2010-2017	49	-0.3
E3	EDGAR v5.0 2010-2015	60	+0.4
E4	CEDS v2021-04-21	51	+0.2

Natural emissions are not perturbed in the ensemble

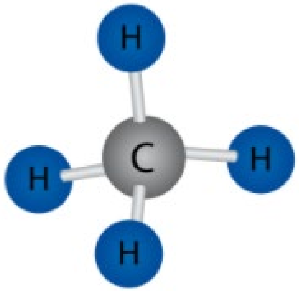
Natural Emissions	Wetland	WETCHARTs
	Biomass burning	GFED4
	Geological seeps	Maasakkers et al.
	Termites	Fung et al.

a Urban natural gas supply & consumption from China Energy Year Book
b Rice spatial distribution from G. Zhang et al. (2020), area for early, middle, and late rice from China Agriculture Year Book, emission factors from Yan et al. (2003)
c Area information from China Fishery Year Book; Emission factors from Yuan et al. (2019)

长三角地区甲烷排放源分布



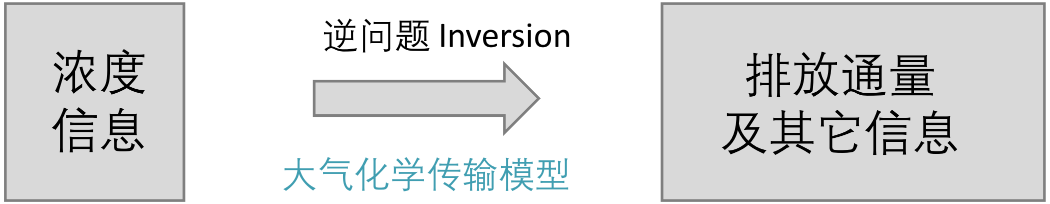
提纲



CH_4

1. 温室气体甲烷
2. 全球大气甲烷收支
3. 中国甲烷排放：分布和趋势
4. 观测系统模拟实验(OSSE)

排放反演技术路线

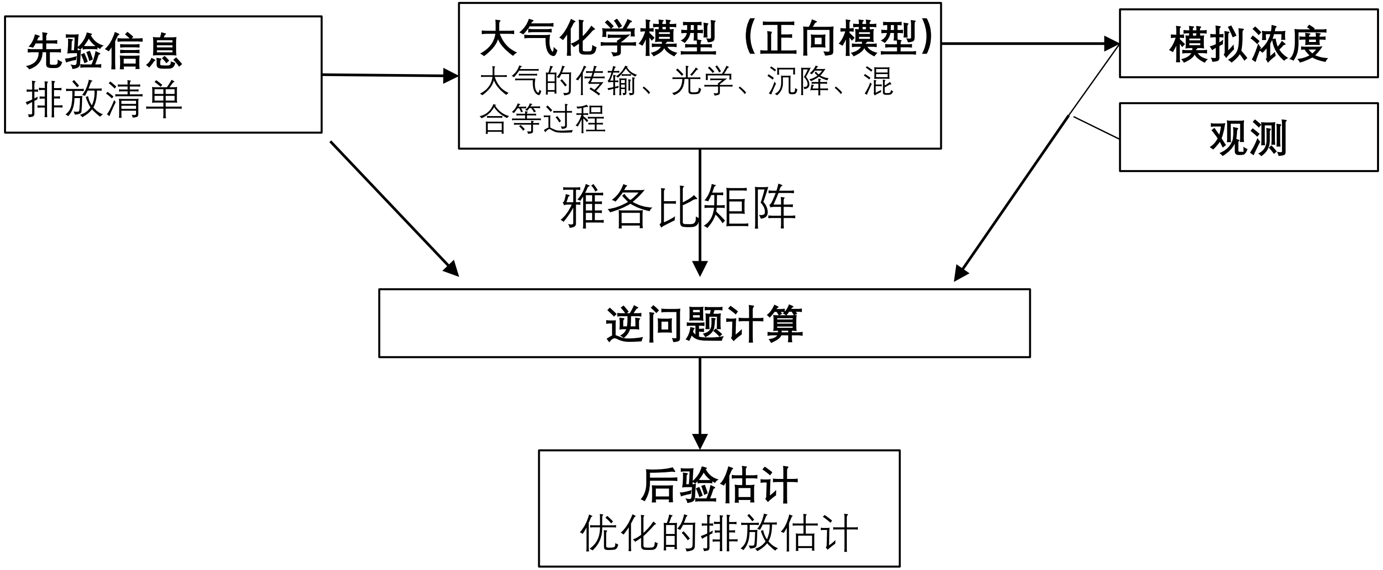


浓度信息

逆问题 Inversion

大气化学传输模型

排放通量及其它信息



先验信息
排放清单

大气化学模型（正向模型）
大气的传输、光学、沉降、混合等过程

模拟浓度

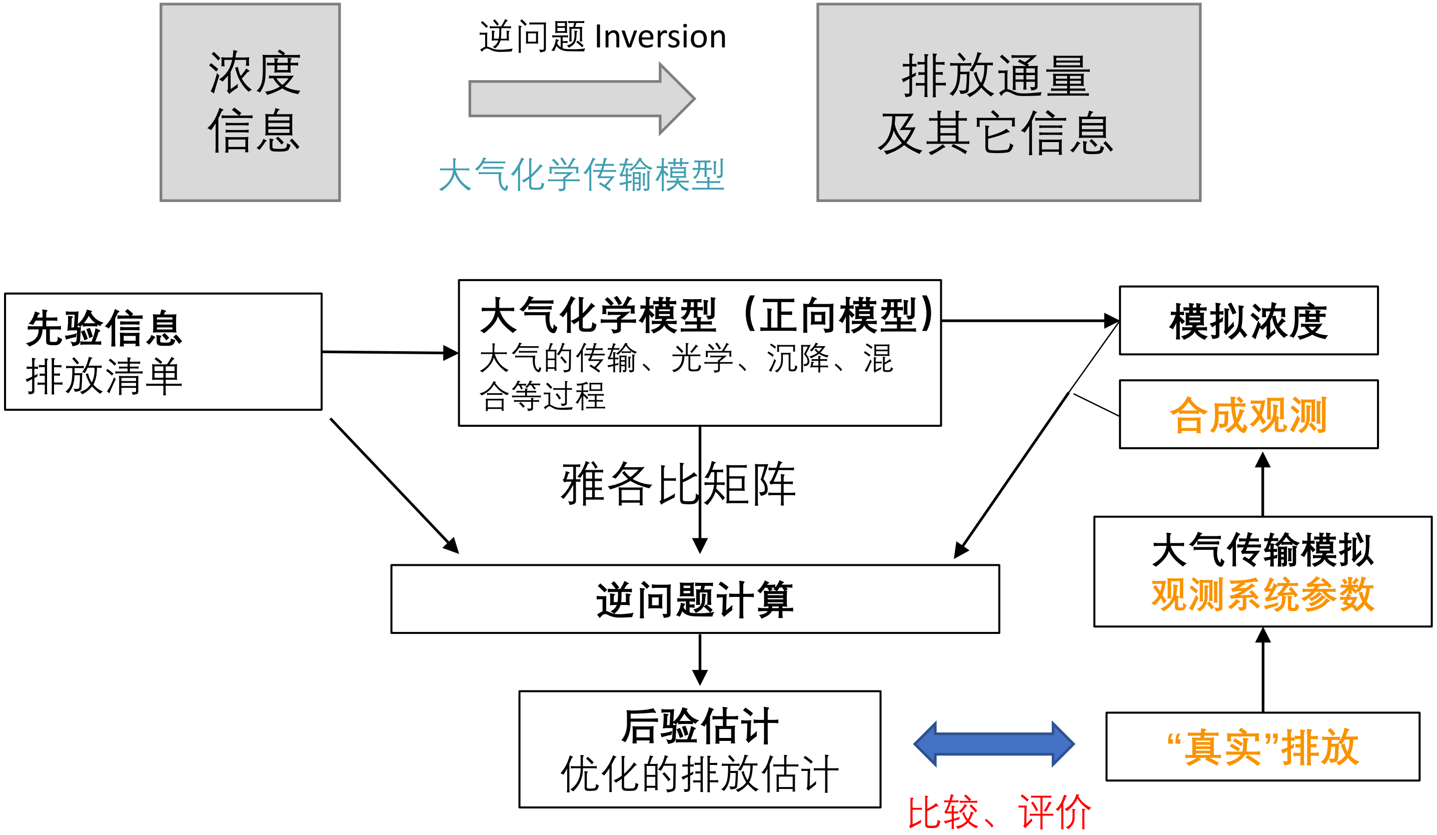
观测

雅各比矩阵

逆问题计算

后验估计
优化的排放估计

观测系统模拟实验（observation system simulation experiment）



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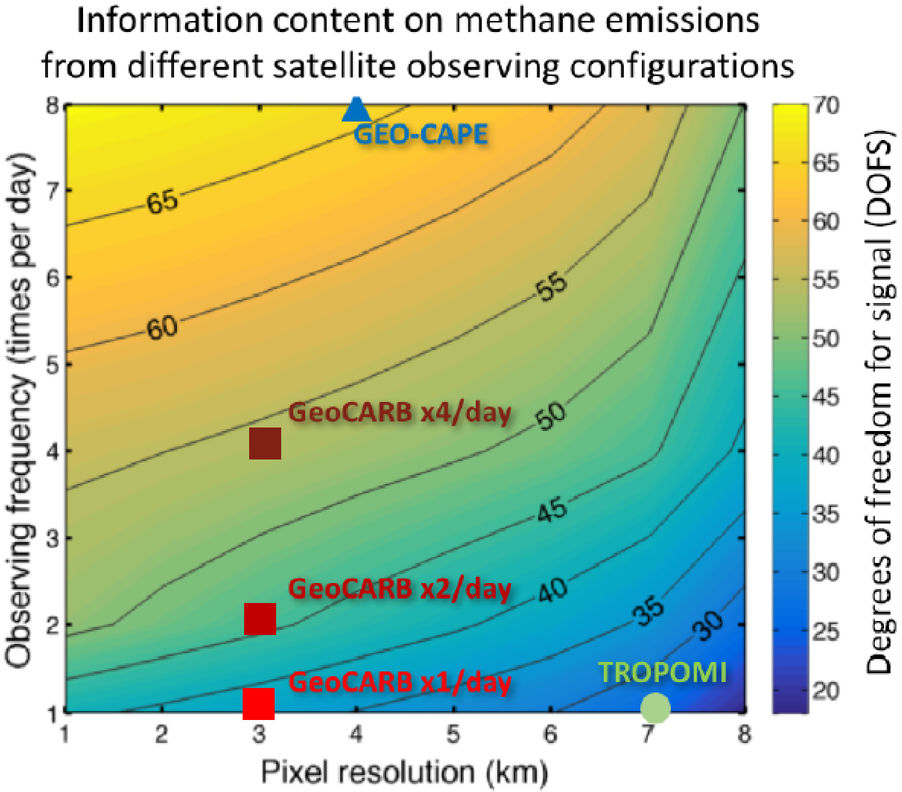
大气传输模拟
观测系统参数

后验估计
优化的排放估计

比较、评价

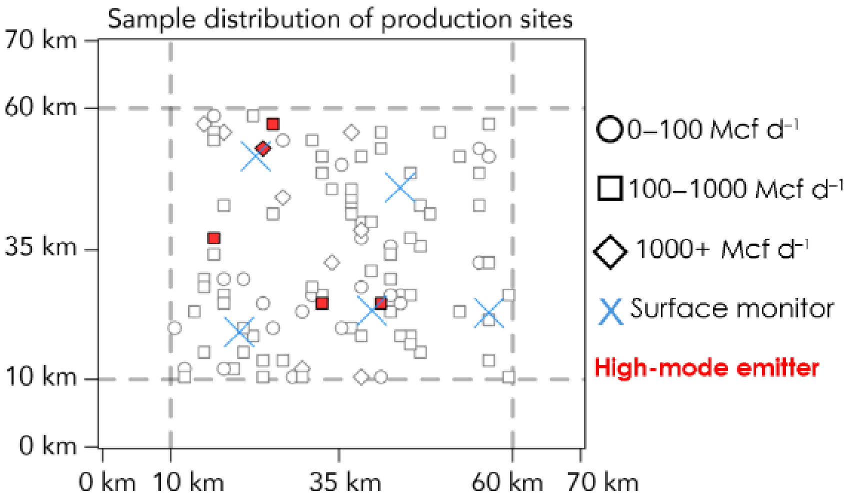
“真实”排放

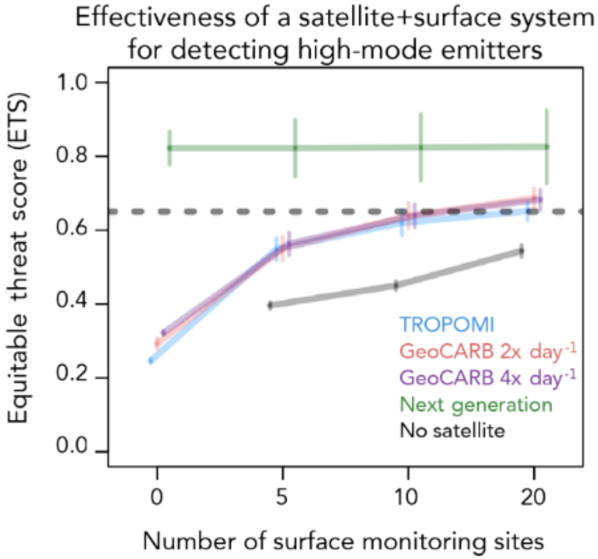
评估不同卫星设计约束排放反演的能力



Sheng et al., AMT, 2018

评估卫星+地面站点观测探测油田甲烷异常泄漏的能力

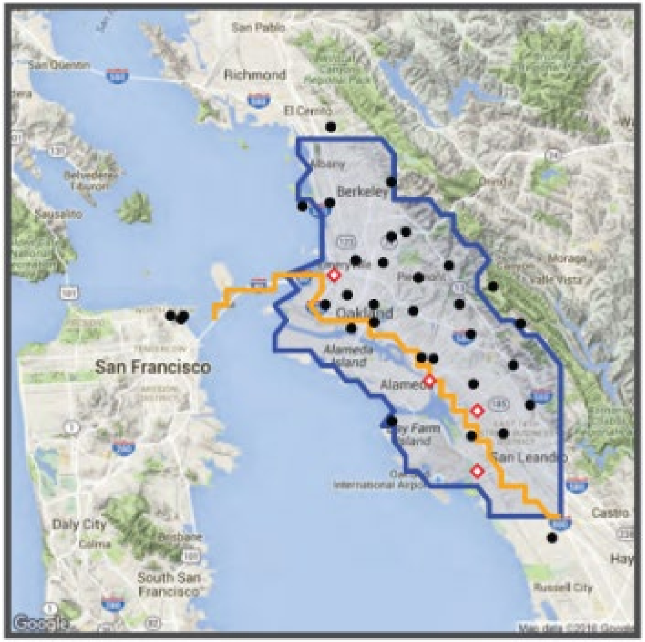

Sample distribution of production sites
70 km
60 km
35 km
10 km
0 km
0 km
10 km
35 km
60 km
70 km
0–100 Mcf d⁻¹
100–1000 Mcf d⁻¹
1000+ Mcf d⁻¹
Surface monitor
High-mode emitter



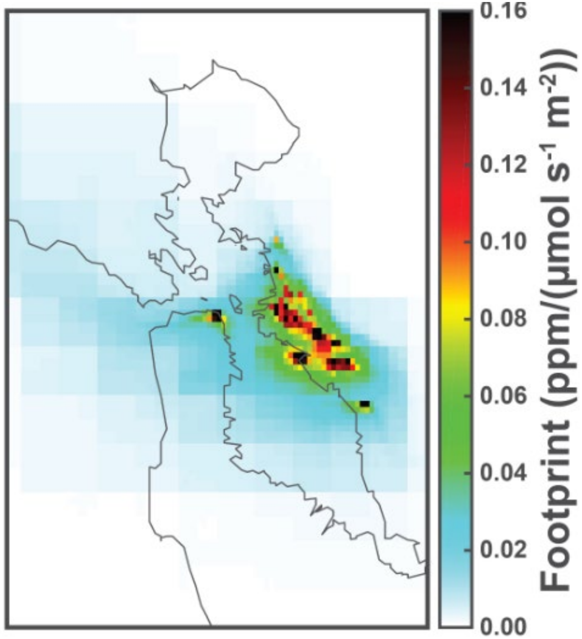
Cusworth et al., ACP, 2018

城市CO2排放监测网络设计

Turner et al., ACP, 2016

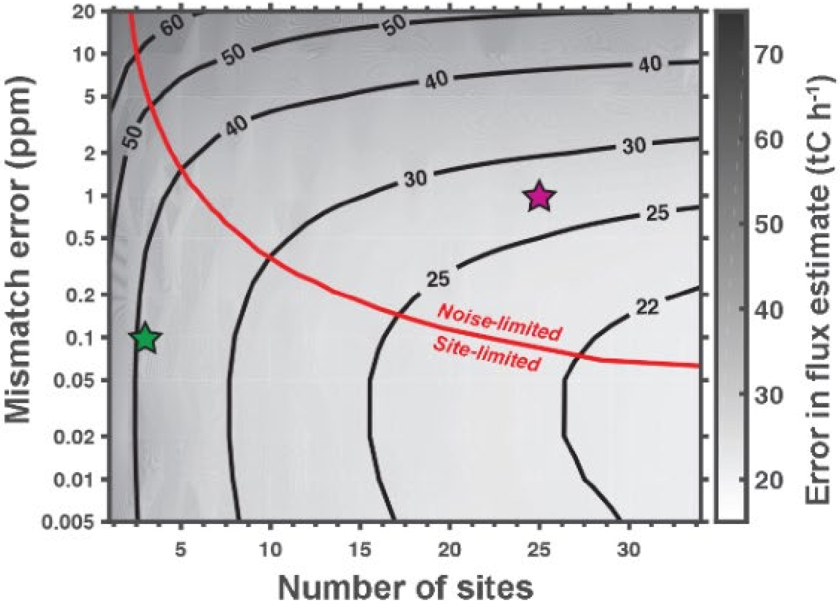


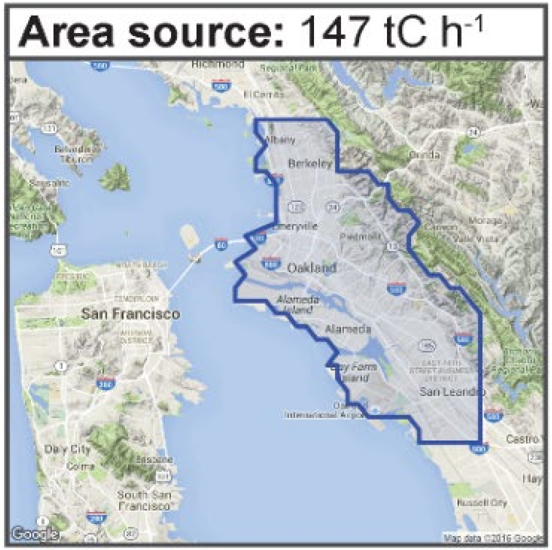
San Pablo
San Quentin
Richmond
El Cerrito
Albany
Berkeley
Belvedere
Tiburon
Sausalito
Orinda
Moraga
Valle Vista
Oakland
Alameda Island
Alameda
Bay Farm Island
San Leandro
International Airport
San Francisco
Daly City
Colma
Brisbane
South San Francisco
Castro
Hay
Russell City
Google
Map data ©2016 Google



城市CO2排放监测网络设计

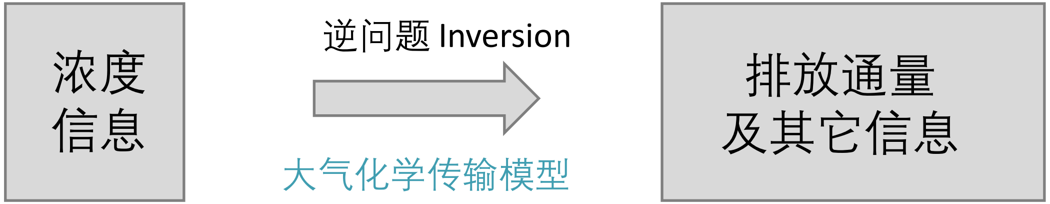
站点密度 vs. 观测/模型误差对反演结果的影响





Area source: 147 tC h^{-1}
Richmond
El Cerrito
Albany
Berkeley
Orinda
Emeryville
Piedmont
Oakland
Alameda Island
Alameda
San Francisco
Bay Farm Island
San Leandro
Castro
Daly City
Colma
Brisbane
South San Francisco
Russell City
Google
Map data ©2016 Google

观测系统模拟实验（observation system simulation experiment）



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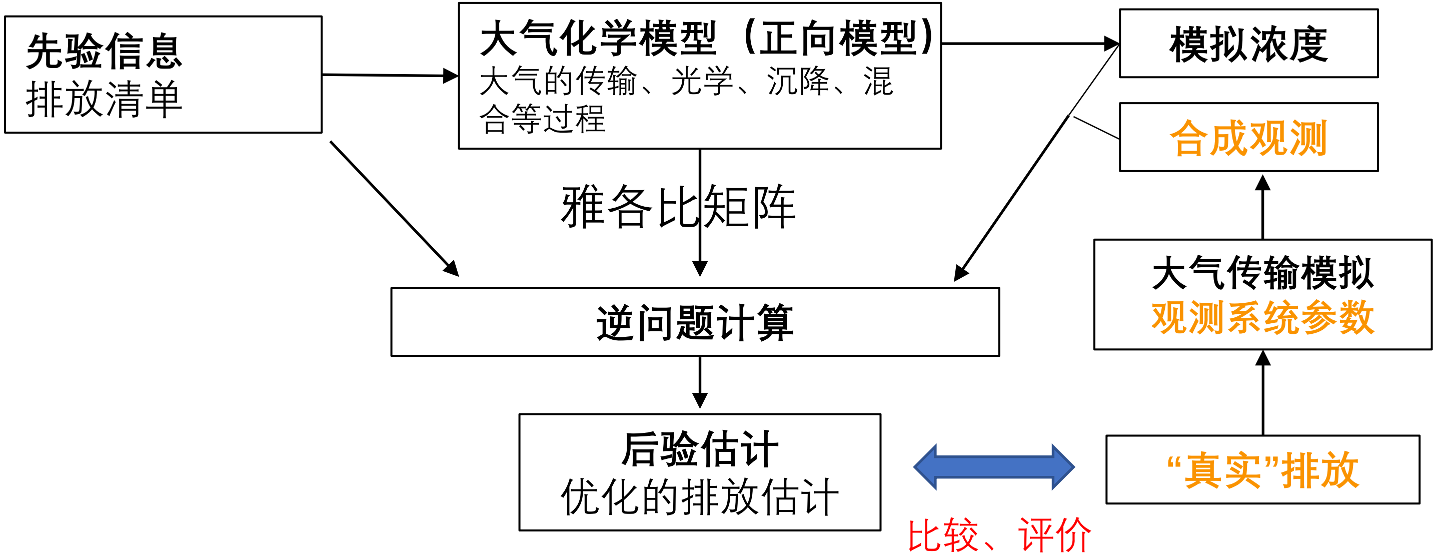

先验信息
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优化的排放估计

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“真实”排放

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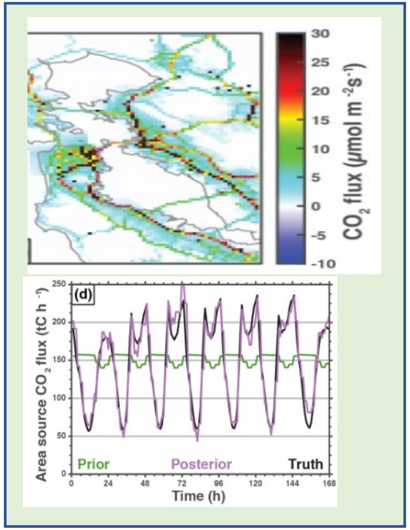

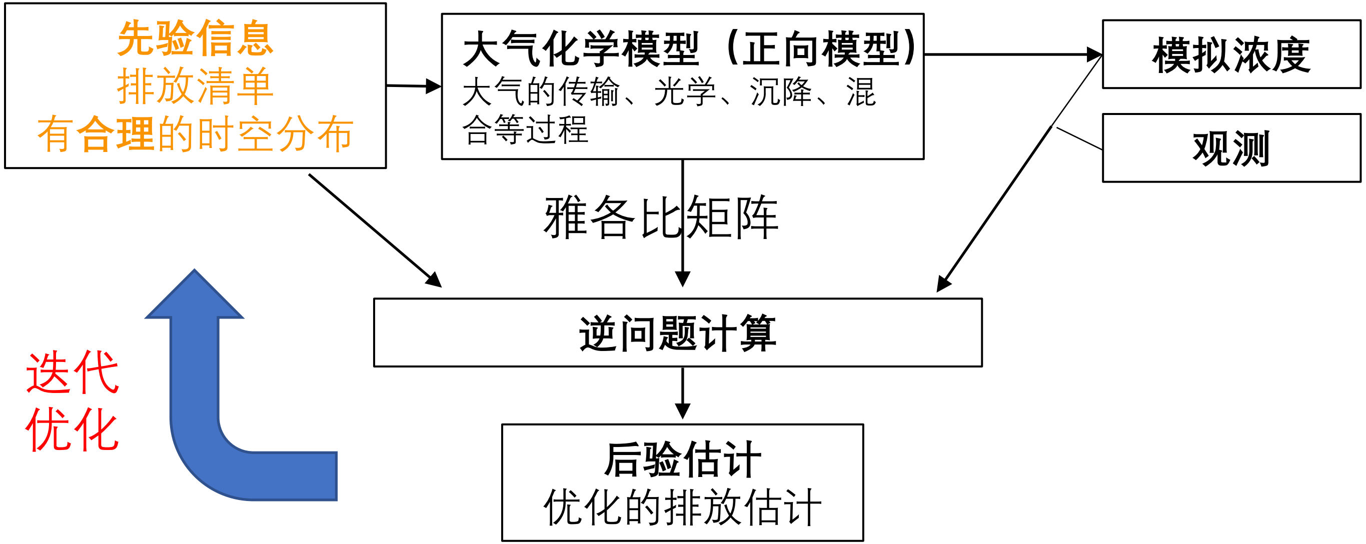

先验信息
排放清单
有**合理**的时空分布

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模拟浓度

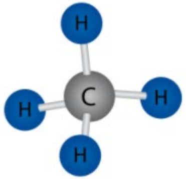
观测

雅各比矩阵

逆问题计算

后验估计
优化的排放估计

迭代
优化



总结

- 甲烷是强势的温室气体，控制甲烷排放是减缓全球变暖的必要措施
- 卫星提供了监测甲烷浓度分布的能力；通过反演分析卫星浓度观测，可得到甲烷排放分布和变化的信息
- 全球来看，畜牧甲烷排放呈显著上升趋势；中国近年来甲烷排放仍有上升趋势——不同区域煤矿排放呈不同趋势，水稻排放增长趋势较明显
- 结合多平台观测数据监测甲烷全球及区域排放是辅助甲烷减排的有力工具