From GHG emissions to Radiative Forcing: attribution following the causal-chain

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Acknowledgements:
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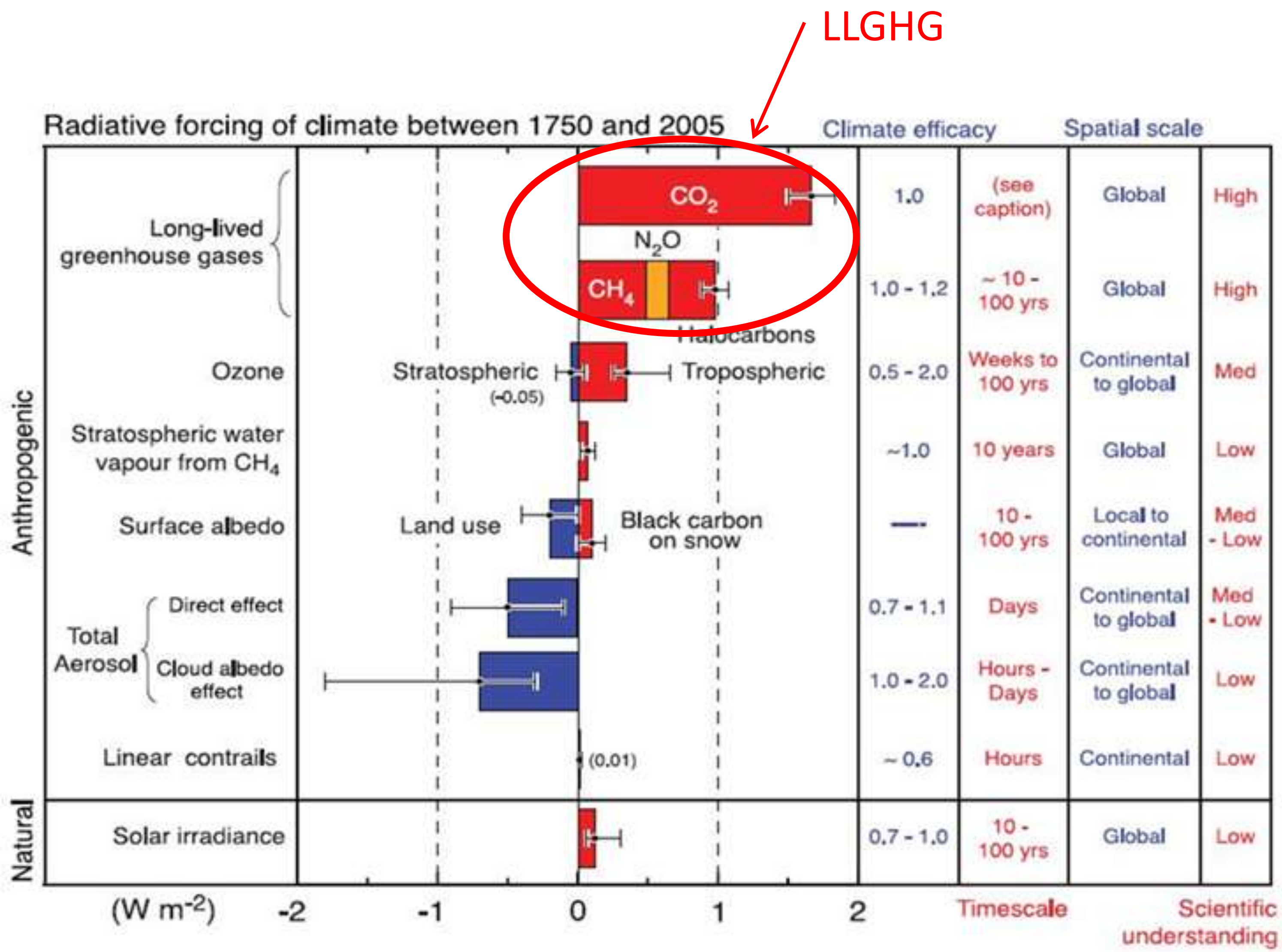
Long-Lived GreenHouse Gases



[Forster et al., AR4, 2007]

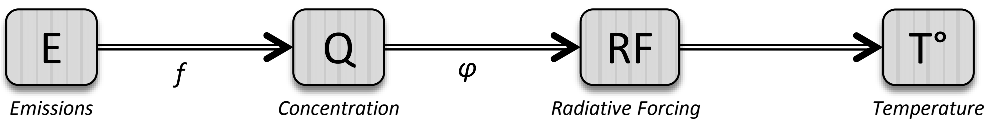
The Causal-Chain

- GHG Causality
- Illustrations
- Attribution
- Linearization

1. The Causal-Chain

1.1. GHG Causality

GHG ‘usual’ causal-chain



Mathematical formulations

• From emissions to concentration:

$$Q(t) = \int_0^t E(t') - S(t')dt'$$

$$= \int_0^t E(t') - S\big(Q(t')\big)dt'$$

$$= \int_0^t E(t') - S\big(E(0,\dots,t')\big)dt'$$

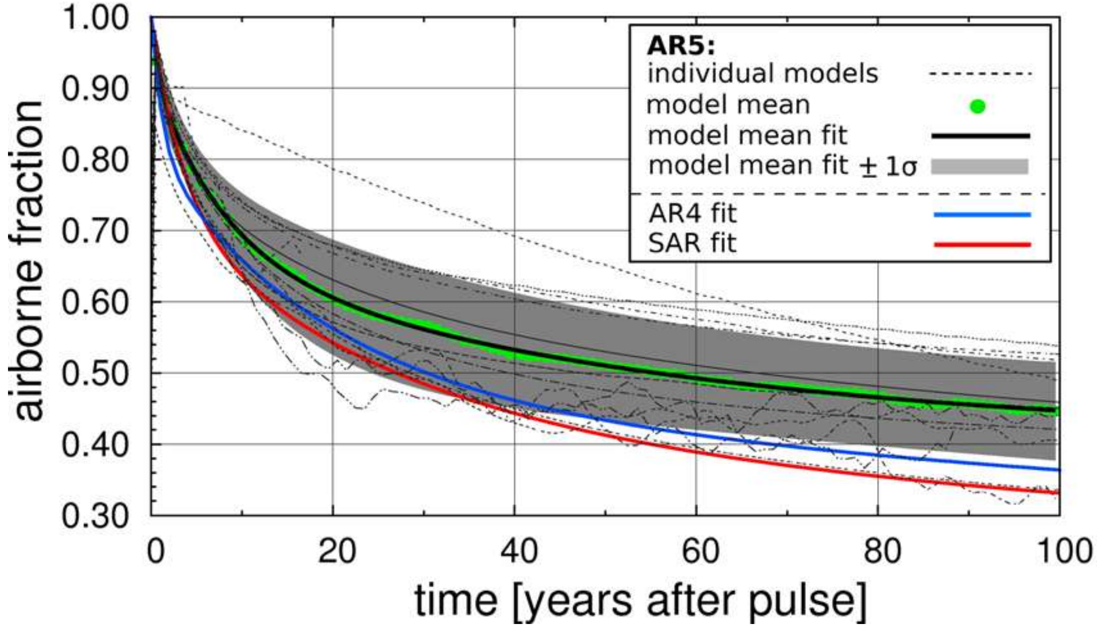
$$Q(t) = f\big(E(0,\dots,t')\big)$$

• From concentration to radiative forcing: $RF(t) = \varphi\big(Q(t)\big)$

1. The Causal-Chain

1.2. Illustrations

- f in simplest models: Impulse Response Functions



Typical IRF for CO2:

$$irf(t) = a_0 + \sum_{i=1}^{N} a_i e^{-t/\tau_i}$$

Leads to:

$$Q(t) = \int_0^t irf(t-t')E(t')dt'$$

- φ by IPCC: fit on 3D radiative models

$RF(t) \propto (Q(t) - Q_0)$ for ‘low’ concentrations (SF6, CFCs, HFCs)

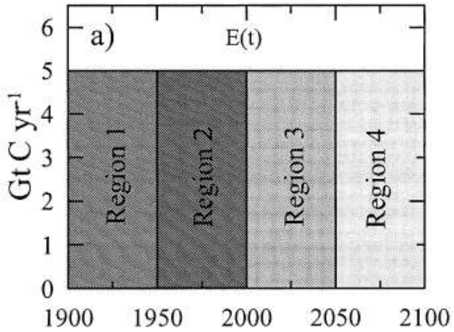
$RF(t) \propto \left(\sqrt{Q(t)} - \sqrt{Q_0}\right)$ for ‘moderate’ concentrations (CH4, N2O)

$RF(t) \propto \ln\left({}^{Q}/_{Q_0}\right)$ for ‘high’ concentrations (CO2)

1. The Causal-Chain

1.3. Attribution (of Q)

Considering regional emissions: $E_{all}(t) = \sum_i E_i(t)$

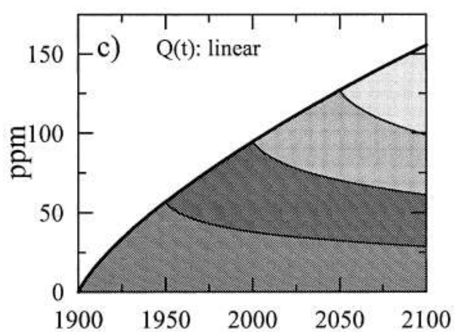


We have: $Q_{all}(t) = f\left(E_{all}(0,\ldots,t)\right)$

But we want $Q_i(t)$ and then $RF_i(t)$.

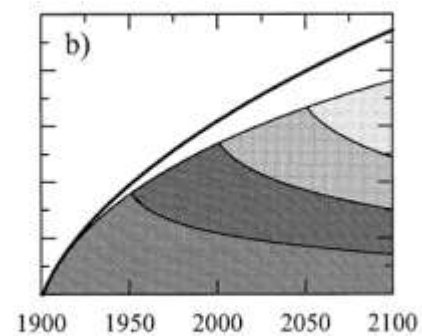
If f is linear:

$$\sum_i Q_i(t) = \sum_i f\left(E_i(0,\ldots,t)\right) = f\left(\sum_i E_i(0,\ldots,t)\right) = Q_{all}(t)$$



If f is not linear:

$$\sum_i Q_i(t) = \sum_i f\left(E_i(0,\ldots,t)\right) \neq f\left(\sum_i E_i(0,\ldots,t)\right) = Q_{all}(t)$$



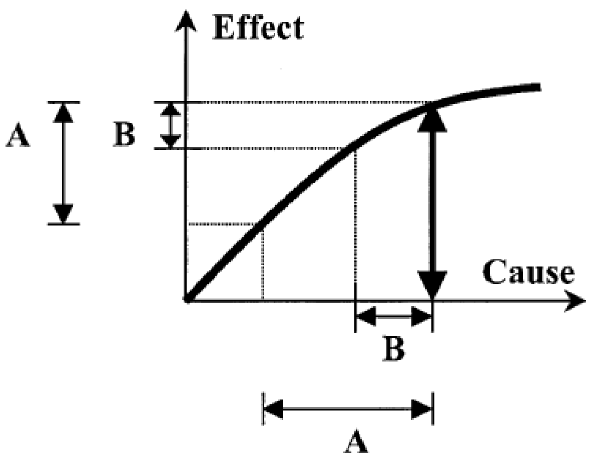
[Trudinger et al., 2005]

1. The Causal-Chain

1.4. Linearization (1)

We define attribution coefficients: $Q_i(t) = \xi_i^* \, Q_{all}(t)$

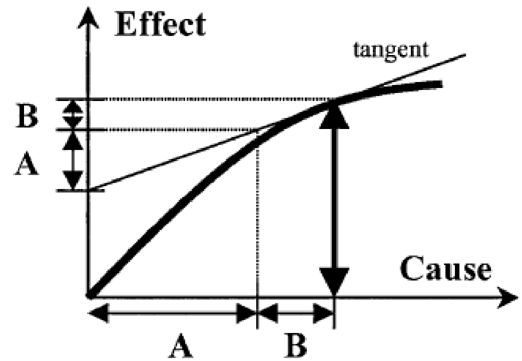
Normalized Residual method:



$$\xi_i = f\big(E_{all}(0,\dots,t)\big) - f\big(E_{all}(0,\dots,t) - E_i(0,\dots,t)\big)$$

$$\xi_i^* = \frac{\xi_i}{\sum_i \xi_i}$$

Normalized Marginal method:



$$\xi_i = \frac{\partial f}{\partial E}\Big|_{E_{all}(0,\dots,t)} E_i(0,\dots,t)$$

$$\xi_i^* = \frac{\xi_i}{\sum_i \xi_i}$$

[Trudinger et al., 2005]

1. The Causal-Chain

1.4. Linearization (2)

Normalized Residual method:

- For *China* vs. *Rest of the World*, it requires only 3 simulations.
- If we know a model is 'almost' linear, we can skip one simulation…
- NR is the 'second best' method according to UNFCCC. The first one is NM.
- To be used with complex models (e.g. aerosols / atm. chemistry)

Normalized Marginal method:

- It is necessary to define a derivative of a model!
- We can either approximate by:

$$\frac{f\left(E_{all}(0,\ldots,t)\right)-f\left(E_{all}(0,\ldots,t)-\alpha E_i(0,\ldots,t)\right)}{\alpha E_i(0,\ldots,t)} \xrightarrow[\alpha\to 0]{} \left.\frac{\partial f}{\partial E}\right|_{E_{all}(0,\ldots,t)}$$

- or create some sort of 'adjoint' model with formal derivative forms included deep within the code.
- To be used with simple models (e.g. LLGHG)

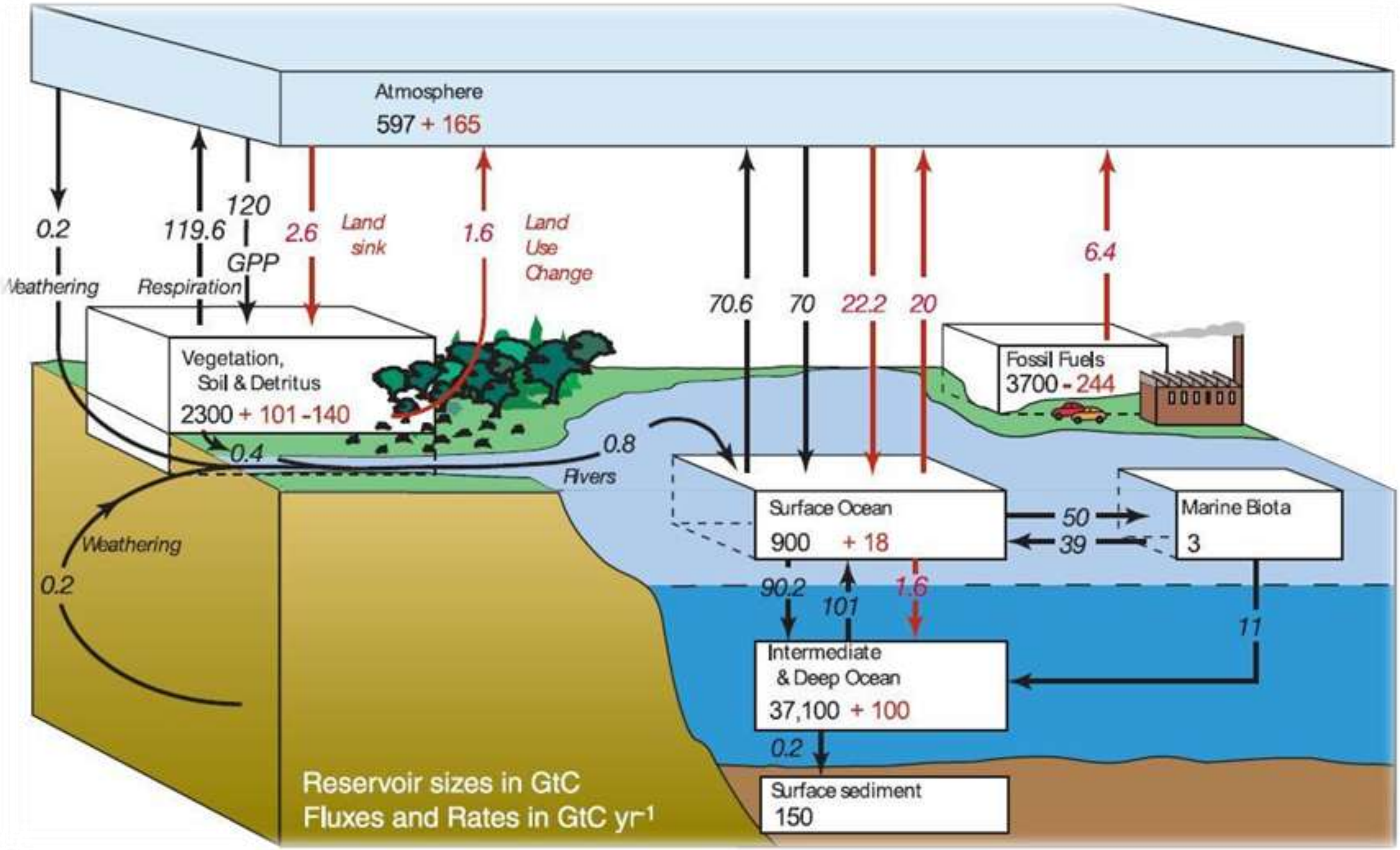
[Trudinger et al., 2005]

Preliminary Results

- CO_2
- CH_4
- N_2O

2. Preliminary Results

2.1. CO2 cycle



[Denman et al., AR4, 2007]

2. Preliminary Results

2.2. CO2 budget

1.1 ± 0.7 GtC/yr
Land-Use Change

+

7.7 ± 0.5 GtC/yr
Fossil Fuels

4.1 ± 0.1 GtC/yr
Atmosphere
47%

2,7 GtC/yr
Land
27%

2.3 ± 0.4 GtC/yr
Oceans
26%

Sinks

2. Preliminary Results

2.3. CO2 attribution (1)

Budget equation: $$\frac{dCO2_{atm}}{dt} = \mathrm{E(t)} - \mathrm{S_{ocean}(t)} - \mathrm{S_{land}(t)}$$

With: $$\mathrm{S_{ocean}(t)} = f_o(\mathrm{CO2(t)}; \mathrm{T°(t)}, \mathrm{N(t)}, \ldots)$$
$$\mathrm{S_{land}(t)} = f_l(\mathrm{CO2(t)}; \mathrm{T°(t)}, \mathrm{N(t)}, \ldots)$$

Shall we (can we) account for 'secondary drivers'?

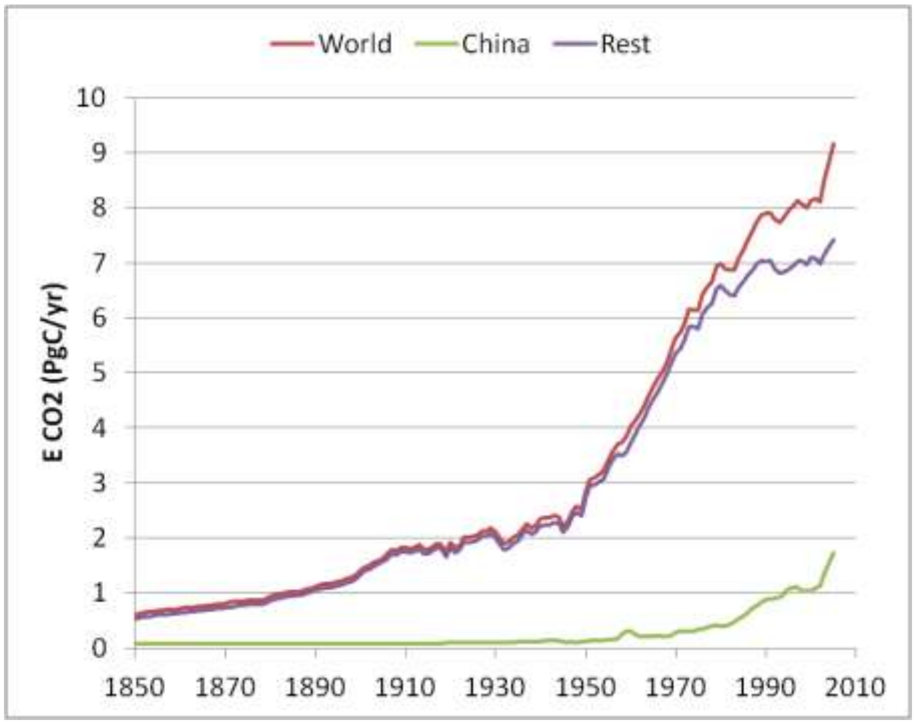
Attribution with OSCAR:

- a regionalized box model, which land module is calibrated on ORCHIDEE, with a bookkeeping land-use model, with coupled climate responses functions

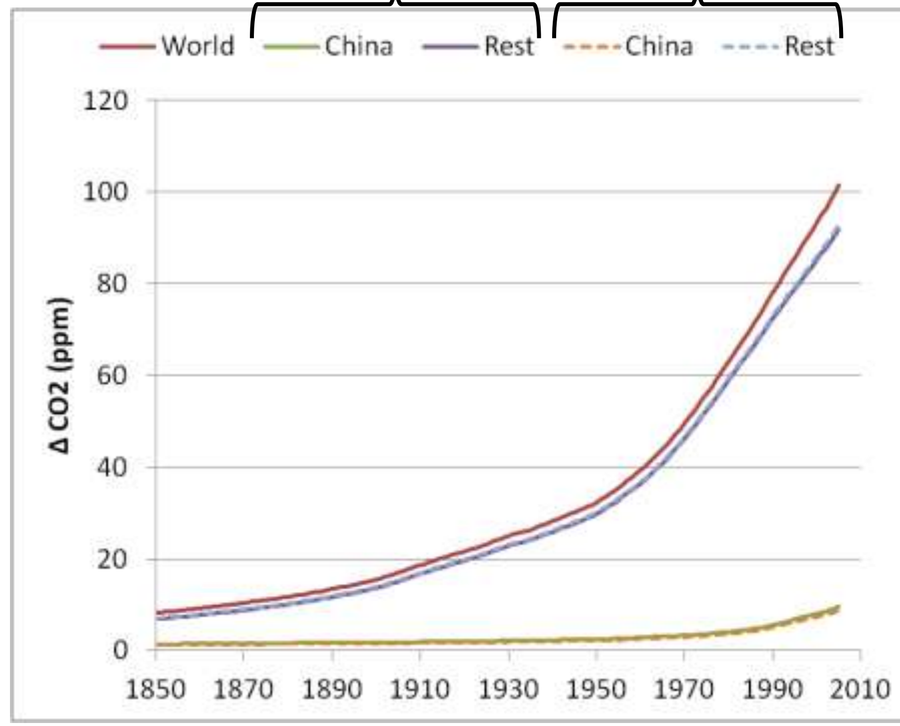
- where: $$\mathrm{S_{ocean}(t)} = \tilde{f}_o\left(\mathrm{CO2(t)}; \mathrm{T°(t)}\right)$$
$$\mathrm{S_{land}(t)} = \tilde{f}_l\left(\mathrm{CO2(t)}; \mathrm{T°(t)}\right)$$

2. Preliminary Results

2.3. CO2 attribution (2)



w/ T° feedback
w/o T° feedback



China's contribution to ΔCO2 in 2005: 10ppm over 101 (≈10%)

2. Preliminary Results

2.4. Details of regional budgets

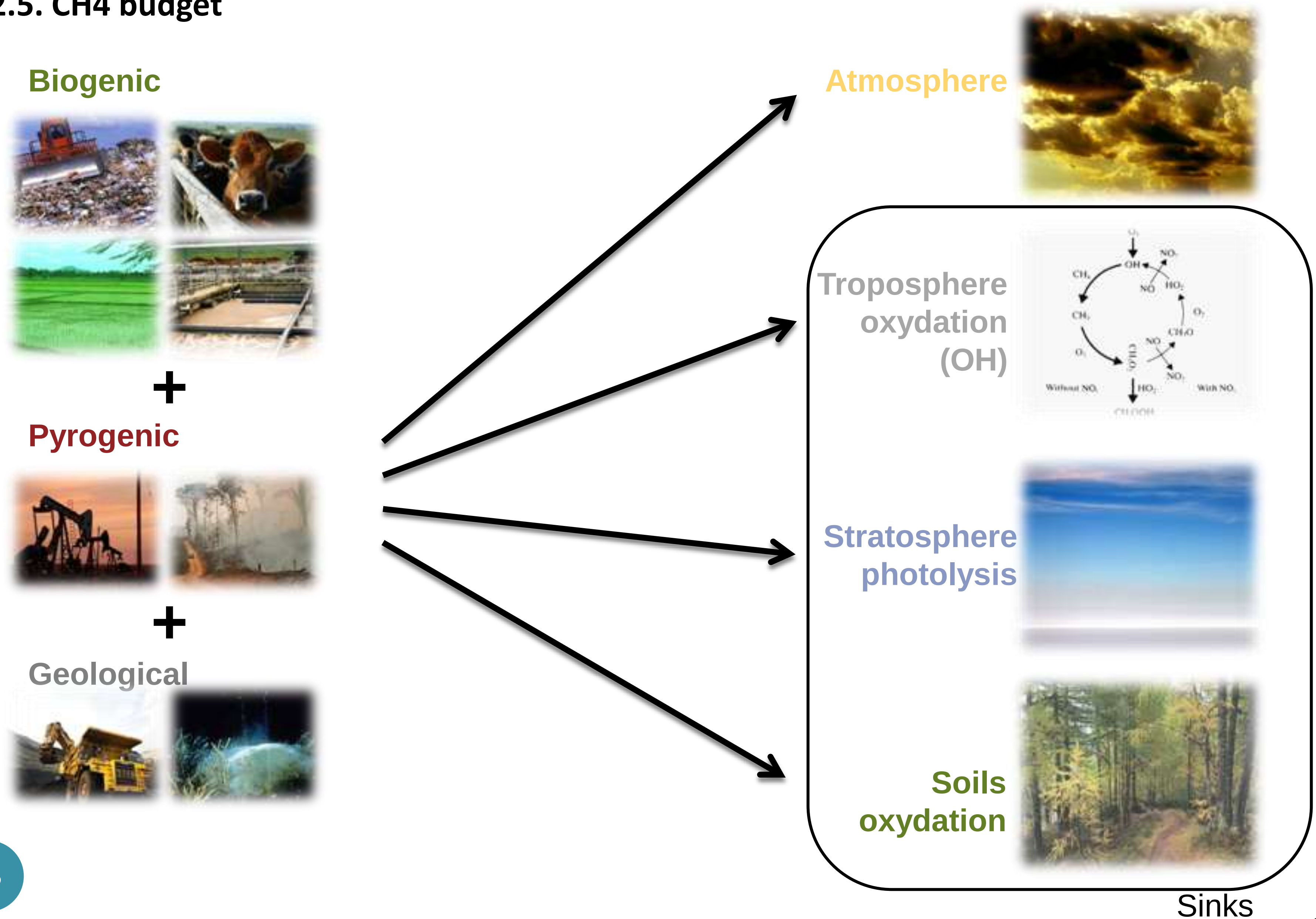
Cross-Attribution Table, cumulated from 1700 to 2005 (in GtC):

C removal over ↓ / due to →		N. America	S.&C. America	Europe	N. Africa & M.-East	Trop. Africa	FSU	China	S.&S.E. Asia	Pacific Dvp.	n/a*
Terrestrial Biosphere	N. America	-5.9	-2.5	-5.0	-0.5	-0.8	-3.1	-1.9	-2.5	-0.8	-0.2
	S.&C. America	-15.6	-6.8	-12.9	-1.3	-2.3	-8.2	-4.9	-6.5	-2.3	-0.7
	Europe	-0.7	-0.3	-0.6	-0.1	-0.1	-0.3	-0.2	-0.3	-0.1	0.0
	N. Africa & M.-East	-0.2	-0.1	-0.2	-0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0
	Trop. Africa	-0.3	-6.9	-3.1	-5.7	-0.6	-1.0	-3.6	-2.2	-2.9	-0.3
	FSU	-5.9	-2.4	-5.0	-0.4	-0.8	-3.1	-1.9	-2.4	-0.8	-0.2
	China	-1.7	-0.7	-1.5	-0.1	-0.2	-0.9	-0.6	-0.7	-0.2	-0.1
	S.&S.E. Asia	-4.3	-1.8	-3.6	-0.3	-0.6	-2.2	-1.4	-1.8	-0.6	-0.2
	Pacific Dvp.	-1.8	-0.8	-1.5	-0.2	-0.3	-1.0	-0.6	-0.8	-0.3	-0.1
Oceans**		-41.9	-17.3	-35.7	-3.4	-5.9	-22.1	-14.5	-17.4	-5.9	-1.7

[Gasser et al., in prep.]

2. Preliminary Results

2.5. CH4 budget



2. Preliminary Results

2.6. CH4 attribution (1)

Budget equation: $$\frac{dCH4_{atm}}{dt} = \mathrm{E(t)} - \mathrm{S_{oh}(t)} - \mathrm{S_{strato}(t)} - \mathrm{S_{soils}(t)}$$

With: $$\mathrm{S_{oh}(t)} = f_{oh}(\mathrm{CH4(t); O3P(t), T°(t)})$$
$$\mathrm{S_{strato}(t)} = f_{st}(\mathrm{CH4(t)})$$
$$\mathrm{S_{soils}(t)} = f_{sl}(\mathrm{CH4(t)})$$

'Secondary drivers'...

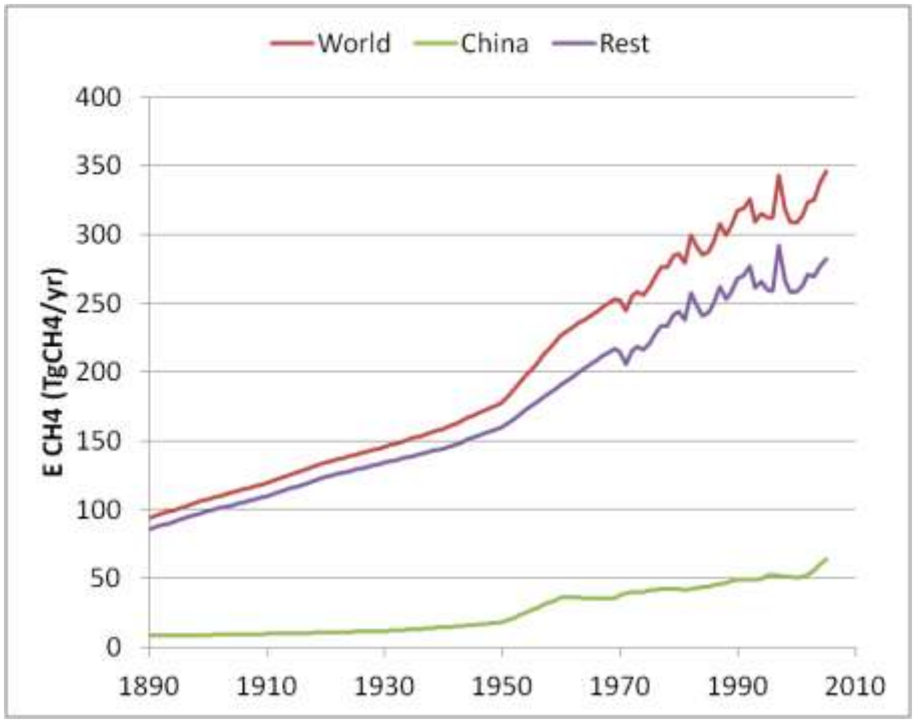
(Quick) attribution based on MAGICC:

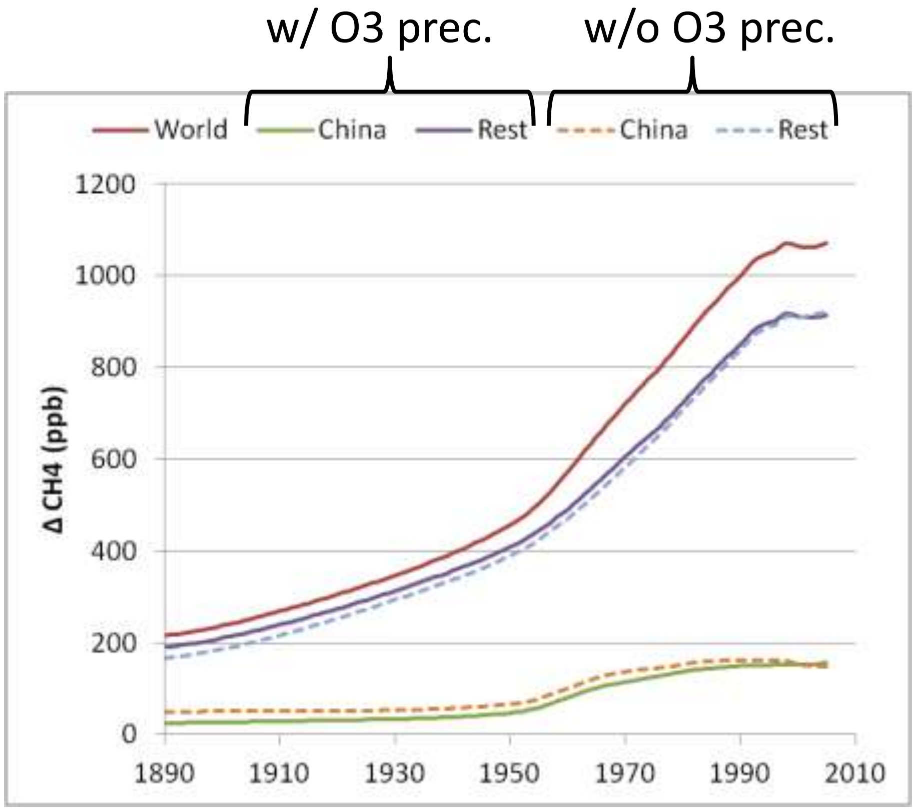
- a global box model

- simple global atmospheric chemistry equilibrium equations, based on OxComp model intercomparison (O3P are NOx, VOC, CO)

2. Preliminary Results

2.6. CH4 attribution (2)

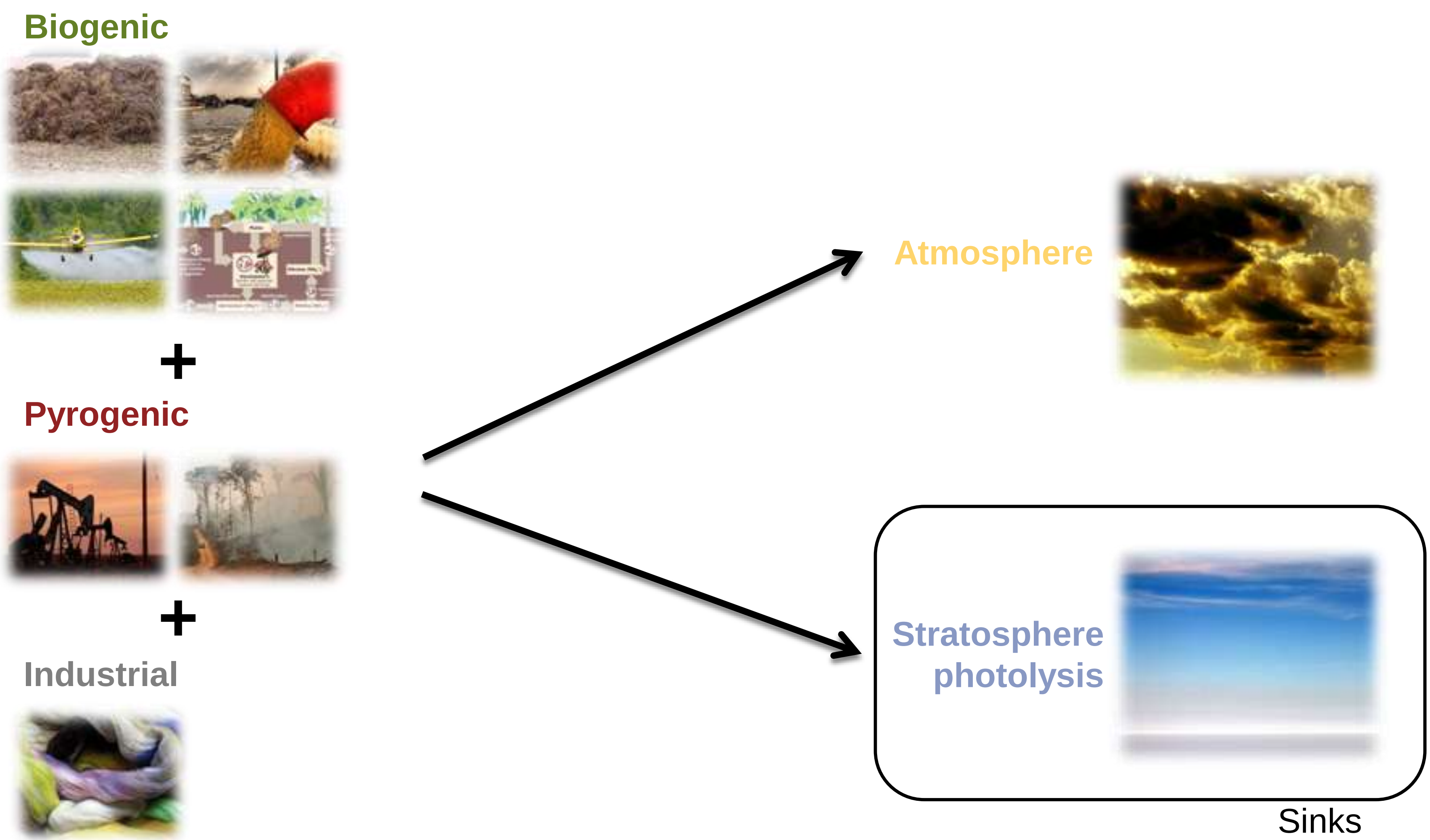




China's contribution to ΔCH4 in 2005: 158ppm over 1072 (≈15%)

2. Preliminary Results

2.7. N2O budget



2. Preliminary Results

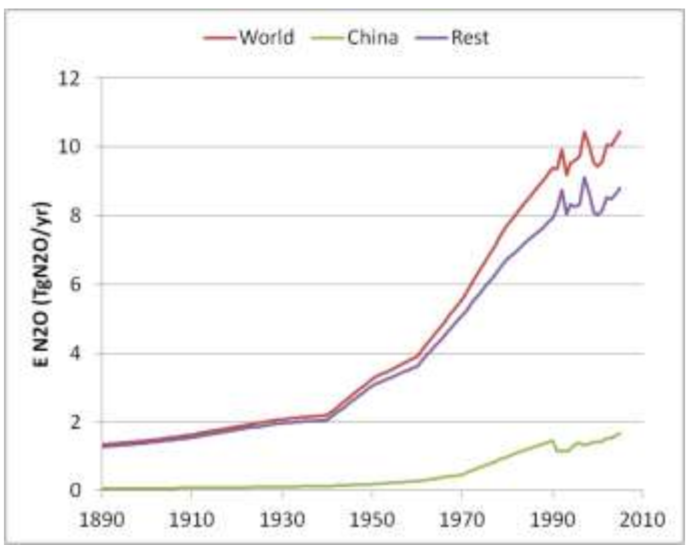
2.8. N2O attribution

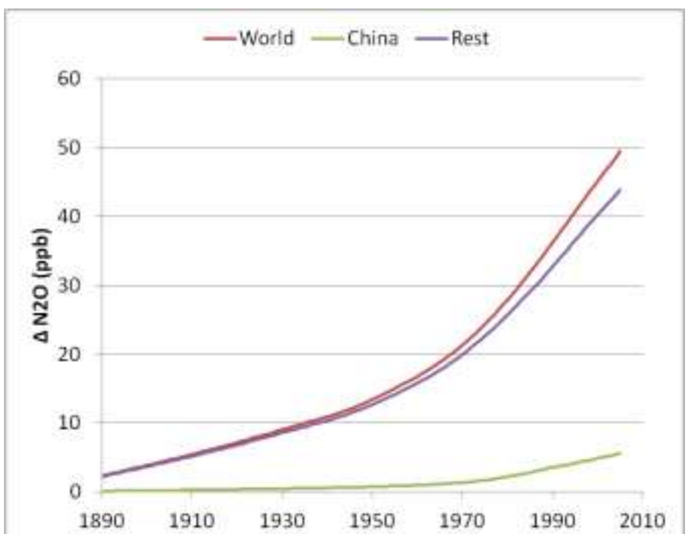
Budget equation: $\frac{dN2O_{atm}}{dt} = \mathrm{E(t)} - \mathrm{S_{strato}(t)}$

With: $\mathrm{S_{strato}(t)} = f_{st}\left(\mathrm{N2O(t)}\right)$ ☐ ← 'Secondary' drivers?

(Quick) illustration with an IRF (τ=114yr):

$$\frac{dN2O_{atm}}{dt} = \mathrm{E(t)} - \mathrm{N2O_{atm}(t)/\tau} \quad \Rightarrow \quad N2O_{atm}(t) = \int_0^t E(t')\exp\left(-\frac{t-t'}{\tau}\right)dt'$$



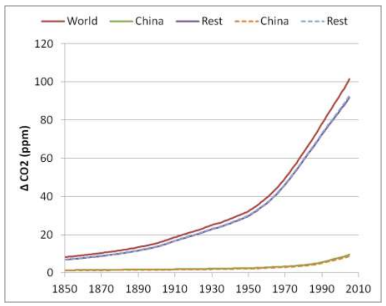


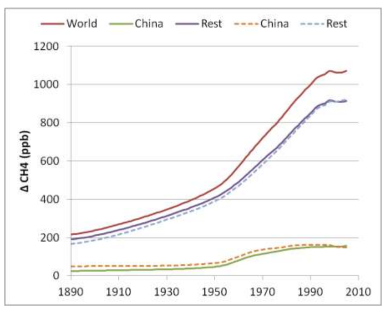
(≈11%)

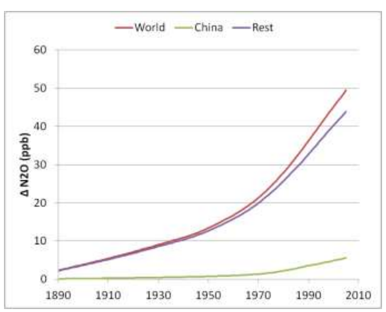
2. Preliminary Results

2.9. RF attribution

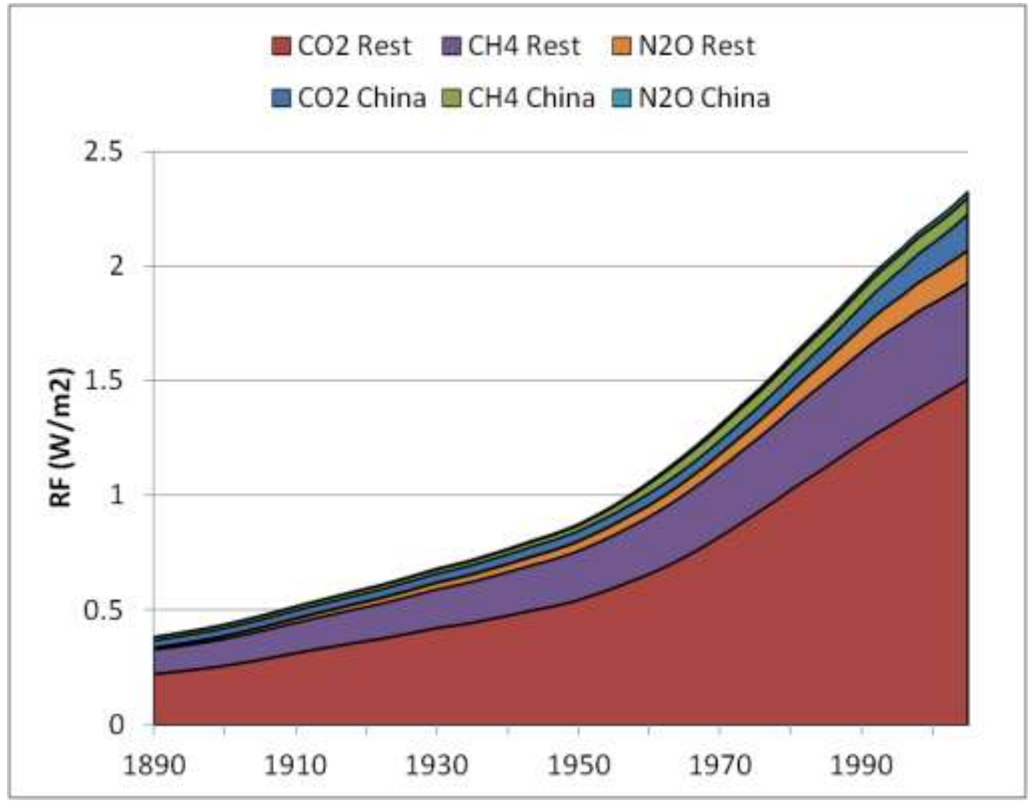
For CO2, CH4 and N2O:







[Ramaswamy et al., TAR, 2001]



China's contribution to RF (CO2,CH4,N2O) in 2005:
0.26 W/m2 over 2.32 (≈11%)

Discussion

A. Linearization Methods

A.1. Attribution coefficients

	ALL SOURCES	SOURCE over CHINA ONLY	SOURCE ALL but CHINA	Delta (ALL-China-All but China)
GLOBAL	RF(W) = -0.12	RF(C) = +0.03	RF(W-C) = -0.12	-0.03
CHINA	-0.29	-0.18 (62%)	-0.06	-0.05

Direct method: $\xi(C) = RF(C)$

$$\xi^*(C) = \frac{RF(C)}{RF(C)+RF(W-C)}$$

Residual method: $\xi(C) = RF(W) - RF(W-C)$

$$\xi^*(C) = \frac{RF(W)-RF(W-C)}{2RF(W)-RF(W-C)-RF(C)}$$

Advised by UNFCCC

A. Linearization Methods

A.2. Direct vs. Residual methods

	ALL SOURCES	SOURCE over CHINA ONLY	SOURCE ALL but CHINA	Delta (ALL-China-All but China)
GLOBAL	RF(W) = -0.12	RF(C) = +0.03	RF(W-C) = -0.12	-0.03
CHINA	-0.29	-0.18 (62%)	-0.06	-0.05

	(W/m2)	World	China	Rest
Direct	**Global**	*-0.12*	*-0.04*	*-0.08*
	China	*-0.29*	*-0.22 (75%)*	*-0.07*
Residual	**Global**	*-0.12*	*0.00*	*-0.12*
	China	*-0.29*	*-0.20 (68%)*	*-0.09*