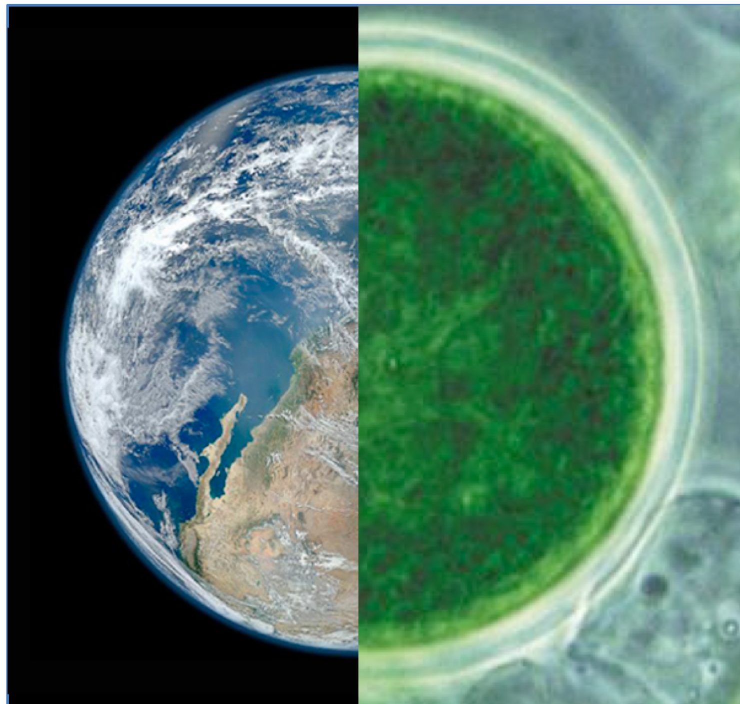
Co-evolution of life and environment on the early Earth



Benjamin Charnay[1]**,** Boris Sauterey[2], Régis Ferrière[2], Franck Lefèvre[3] et Stéphane Mazevet[4]

[1]LESIA, Observatoire de Paris
[2]ENS Paris
[3]LATMOS, Paris
[4]LUTh, Observatoire de Paris

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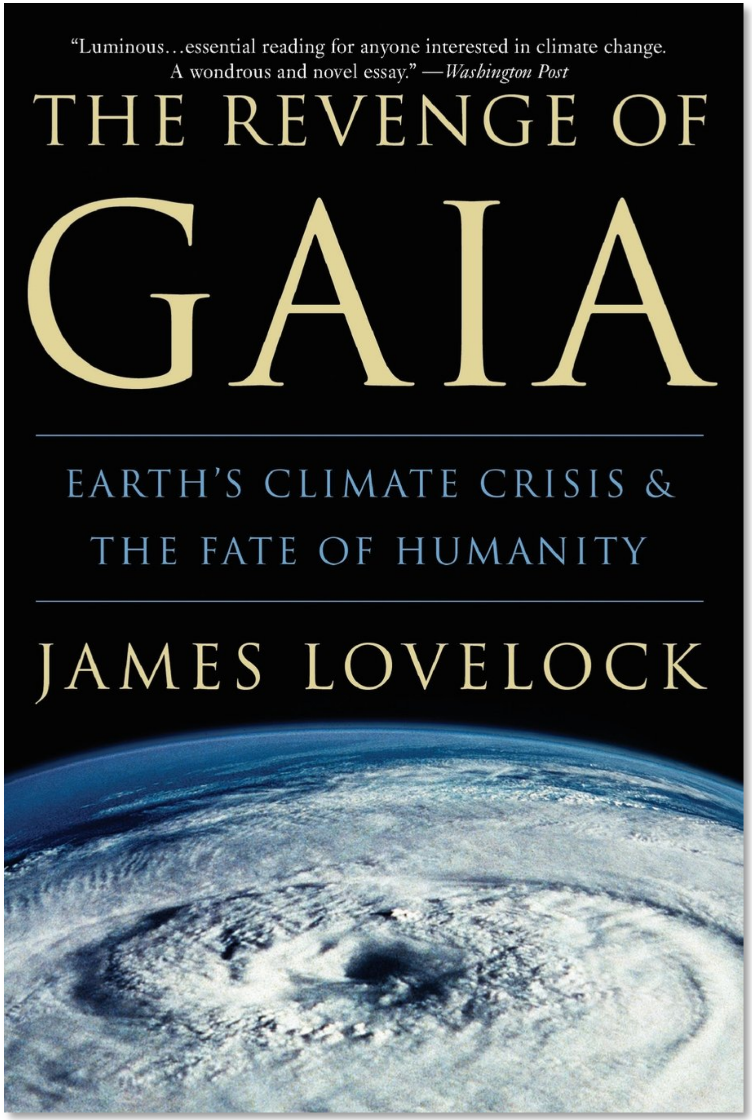
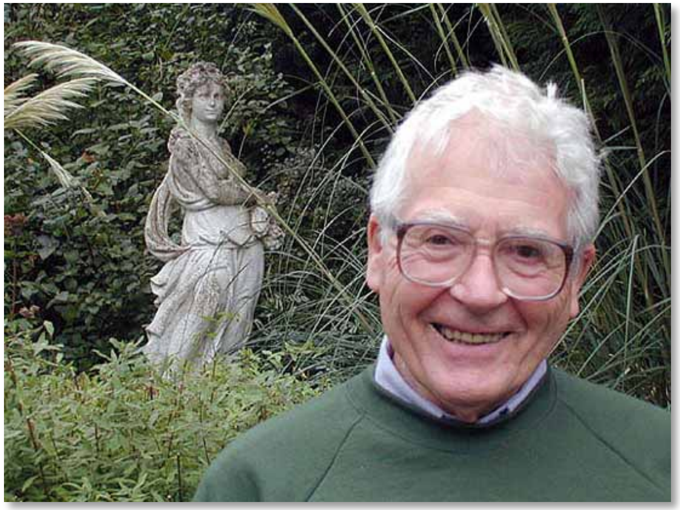


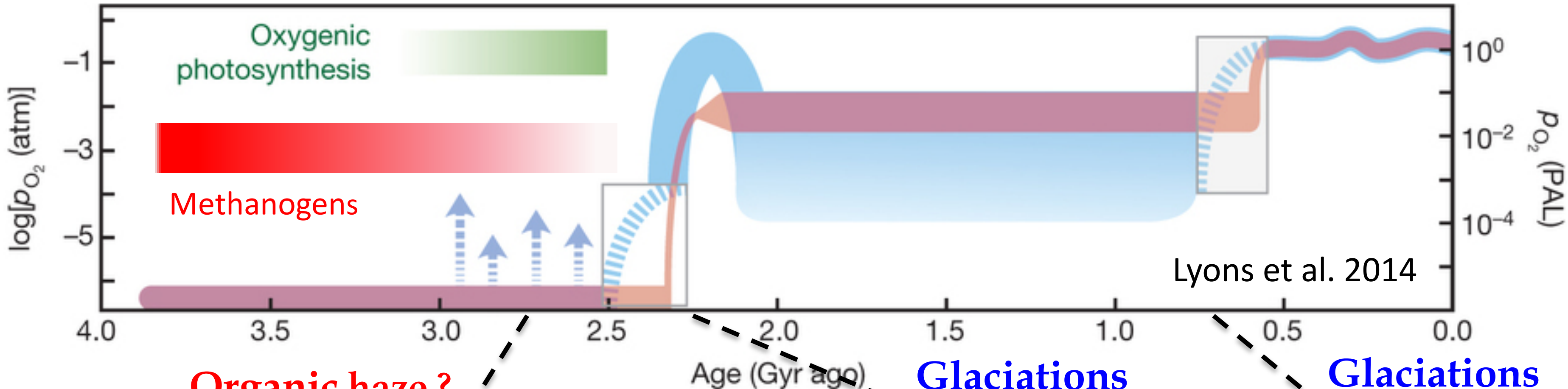


Gaia hypothesis:

"A complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet."

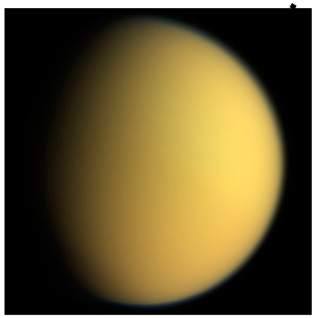
Co-evolution of Earth's atmosphere and life

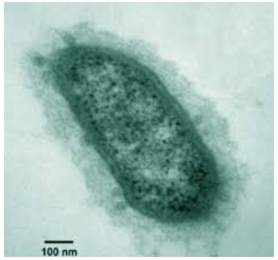
Evolution of O_2 in Earth's atmosphere



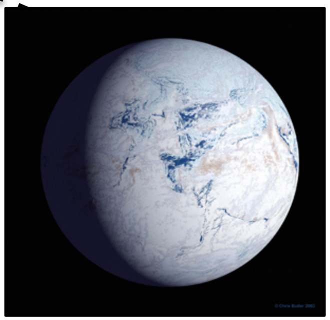
Organic haze ?

(Zerkle et al. 2012)





Glaciations



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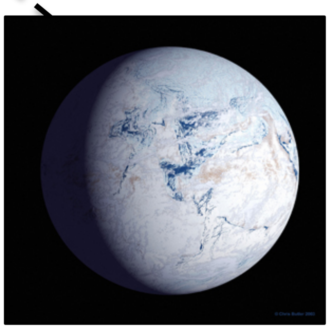
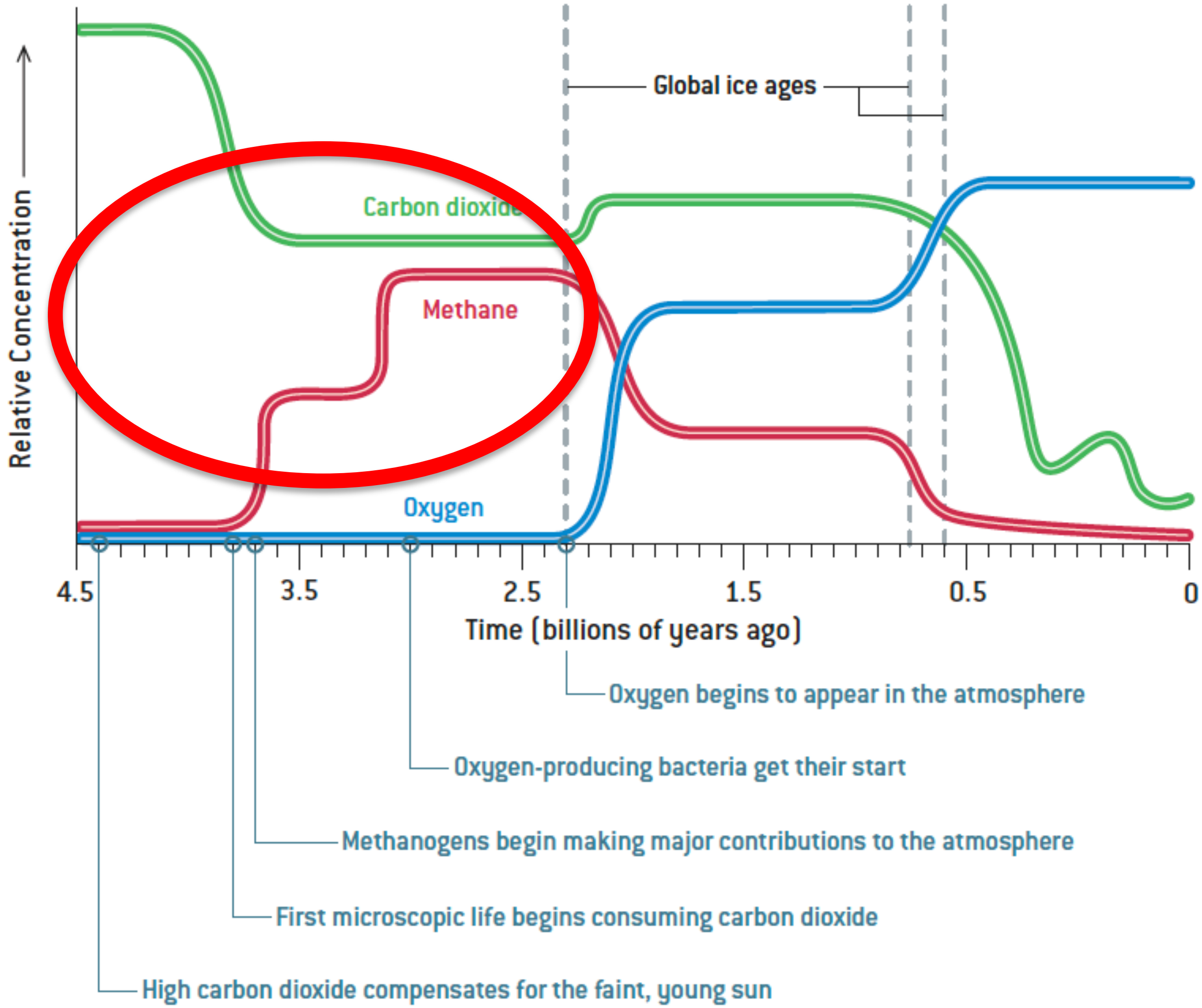


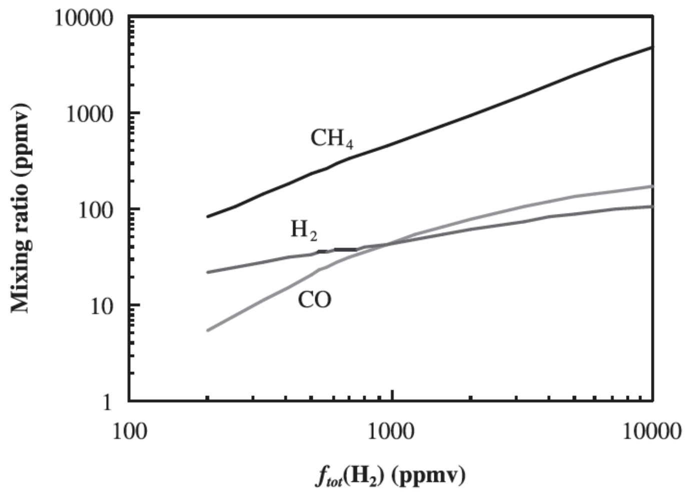
Co-evolution of Earth's atmosphere and life

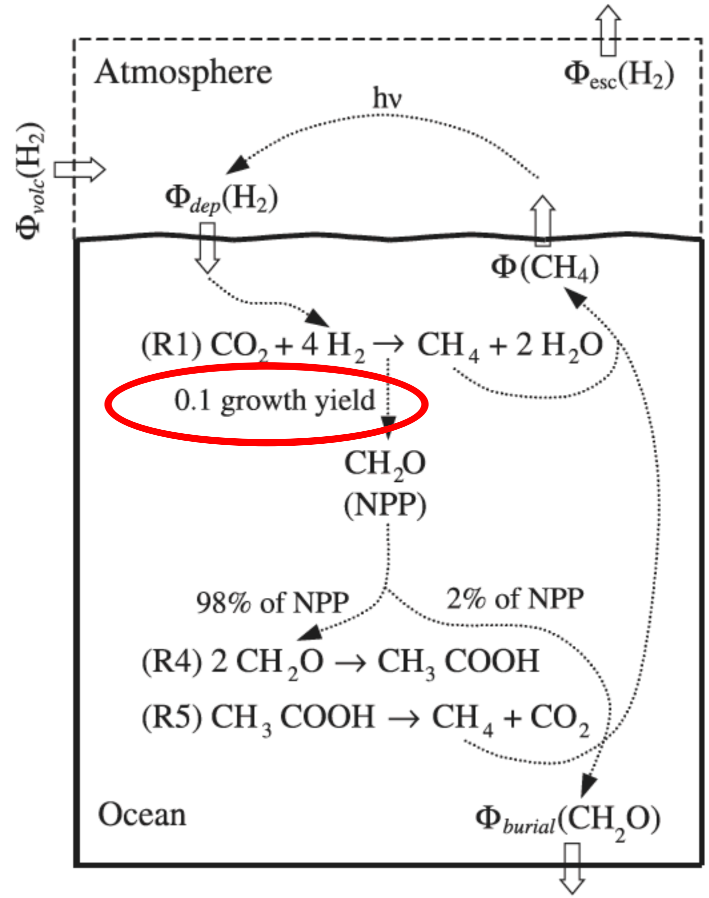


Kasting et al. 2004

Co-evolution of Earth's atmosphere and life

Previous study by Karecha et al. 2005:
- Estimation of CH_4 production and NPP for different early ecosystems
- Calculation based on pure thermodynamics
- Fixed fraction of NPP and fixed ΔG





$$\Delta G = \Delta G^0 + RT\ln Q$$

$$\Delta G = -30 \text{ KJ/mol (1 mol of ATP)}$$

$$Q = \frac{[CH_4]^*_{aq}\, a(H_2O)^2}{[CO_2]^*_{aq}([H_2]^*_{aq})^4}$$

Co-evolution of Earth's atmosphere and life

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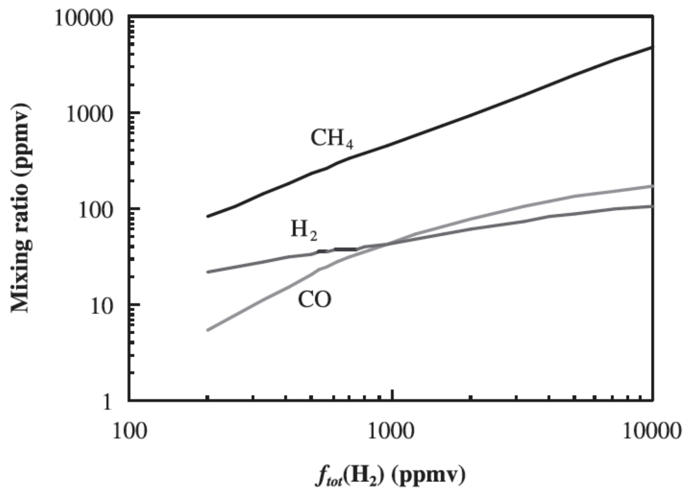
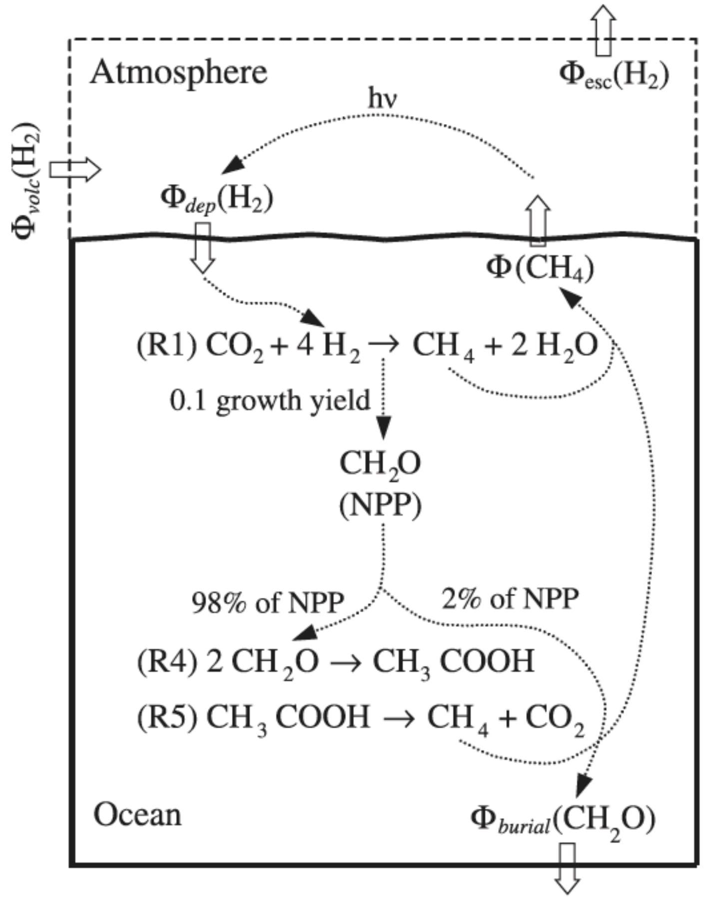
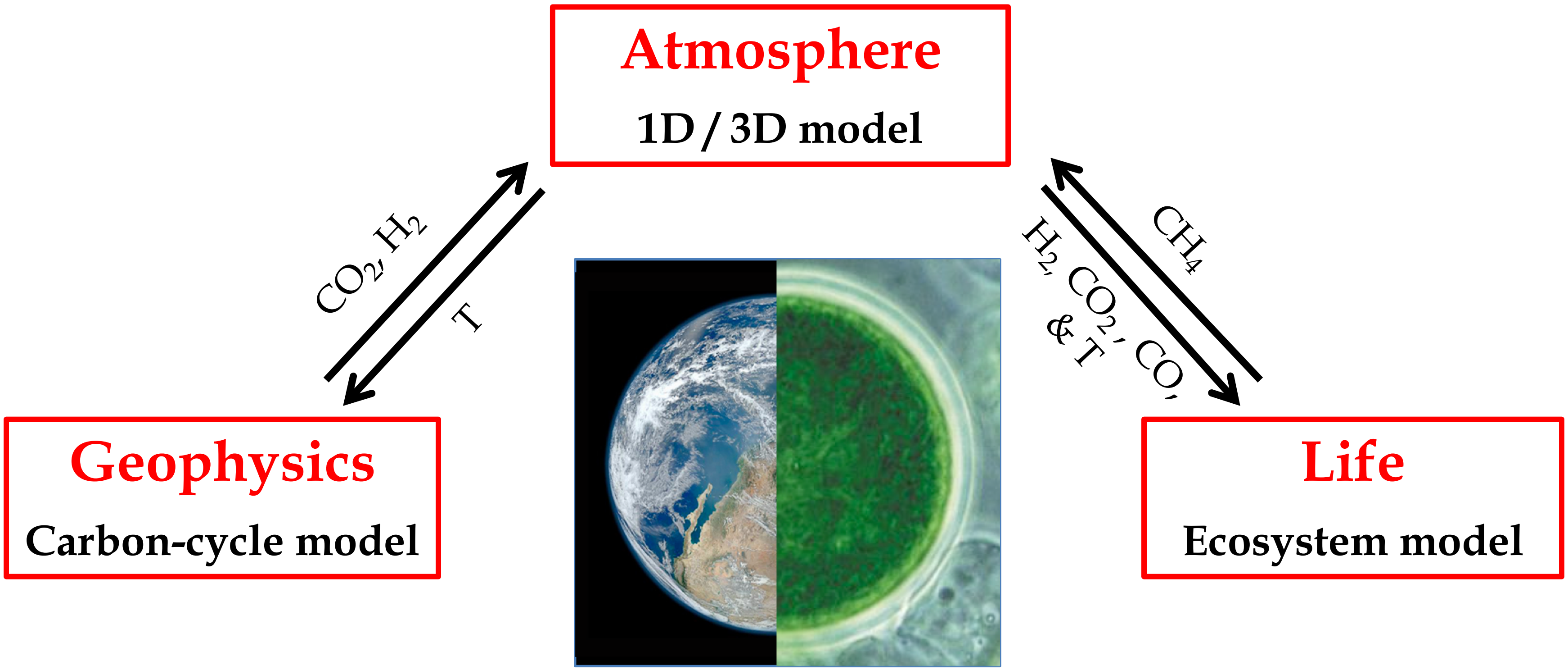




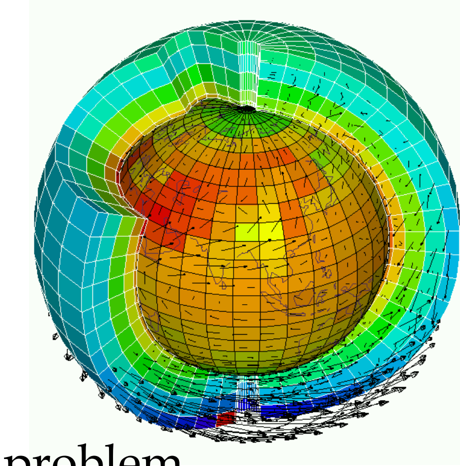
Goal of our study

Revisiting Karecha's study with state-of-the art models:
- Estimating CH_4 emission, greenhouse effect and NPP for different ecosystems
- Analysing feedbacks between early ecosystems and the environment

Co-evolution of Earth’s atmosphere and life

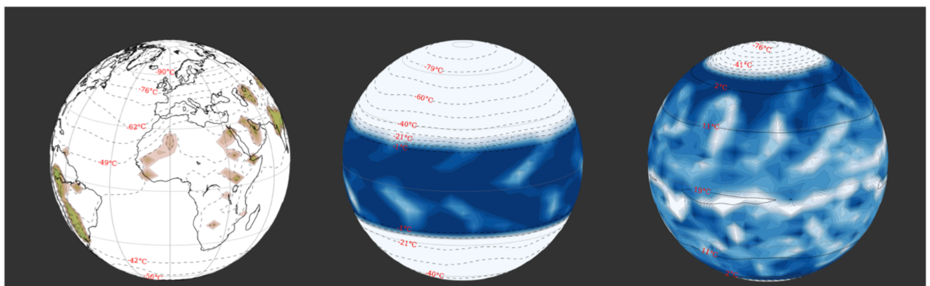


Atmospheric model:



- Climate states simulated with the **Generic LMD GCM**

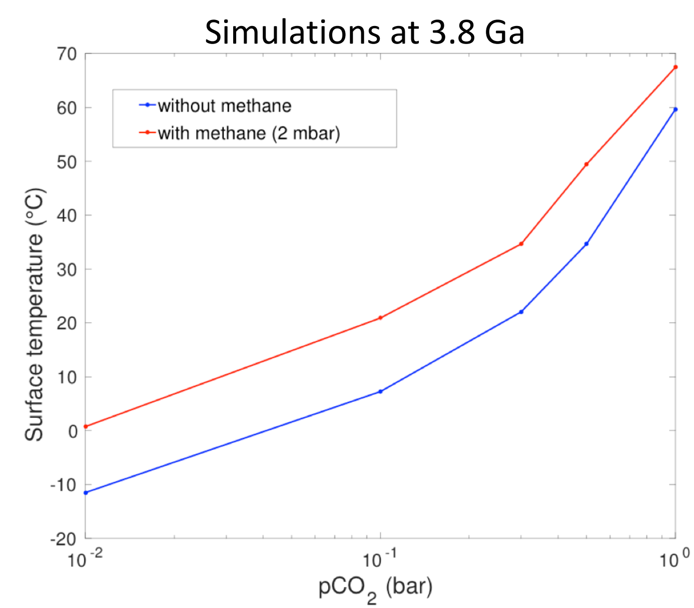
➢ Archean/Hadean climates and solutions to the faint young Sun problem (Charnay et al. 2013, 2018)



With present-day continents and atmosphere

Before continents emerged, doubling CO2

Before continents emerged, with a CO2- and CH4-rich atmosphere



- Atmospheric composition: N_2, CO_2, CH_4 & H_2O
- Surface pressure = 1 bar
- No land

→ parameterization $T_{surf} = f(pCO_2, pCH_4, t)$

Atmospheric model:

- Photochemistry in 1D with the photochemical core from Lefèvre et al. 2003

- Hydrocarbure chemistry (18 species, 82 reactions)
- Nitrogen chemistry (15 species, 42 reactions): Production of NOx by lightning
- Boundary conditions: - fixed mixing ratio (CO_2, H_2, CH_4)
  - fixed surface flux (CO, diffusion limited in the ocean)
  - H escape to space

Key reactions:

(1) $CO_2 + H_2 + h\nu \rightarrow CO + H_2O$

(2) $CO_2 + CH_4 + h\nu \rightarrow 2CO + 2H_2$

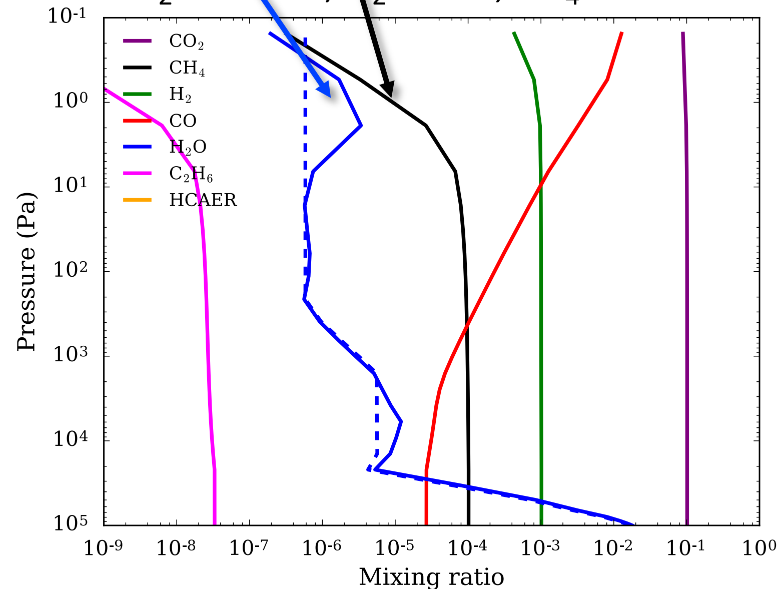
Atmospheric model:

Key reactions:

(1) $CO_2 + H_2 + h\nu \rightarrow CO + H_2O$

(2) $CO_2 + CH_4 + h\nu \rightarrow 2CO + 2H_2$

CO_2=100 mb, H_2=1 mb, CH_4=0.1 mb

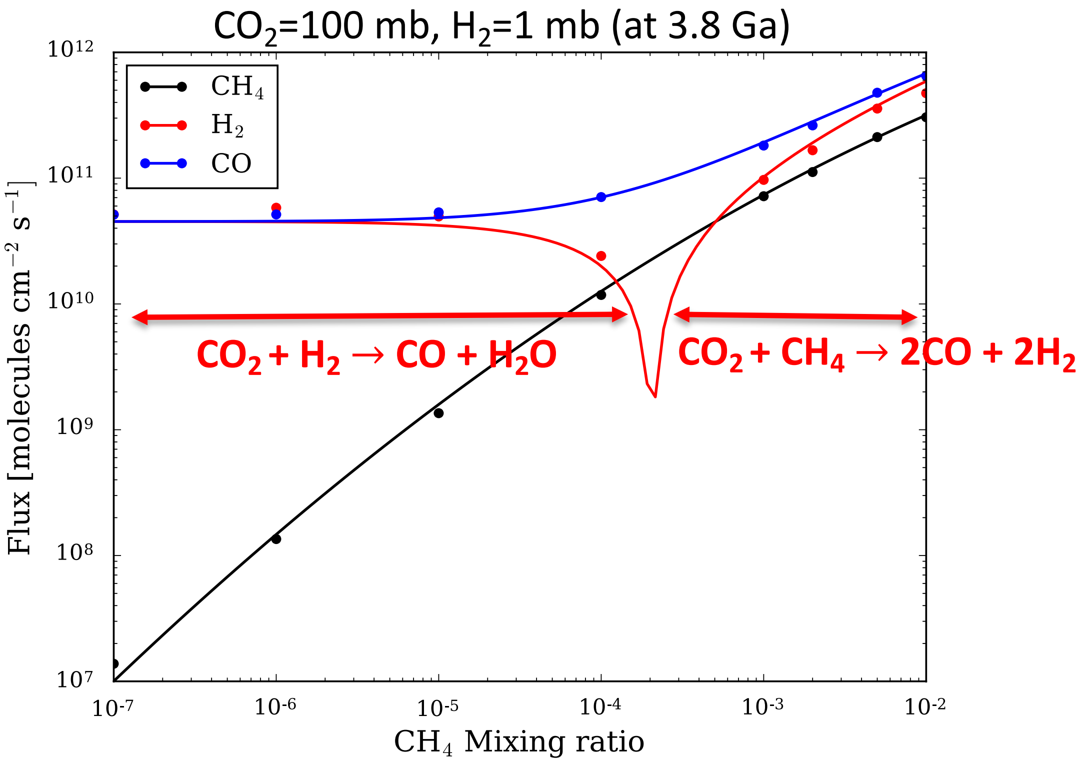


High CO production from CO_2 and CH_4 photolysis

Atmospheric model:

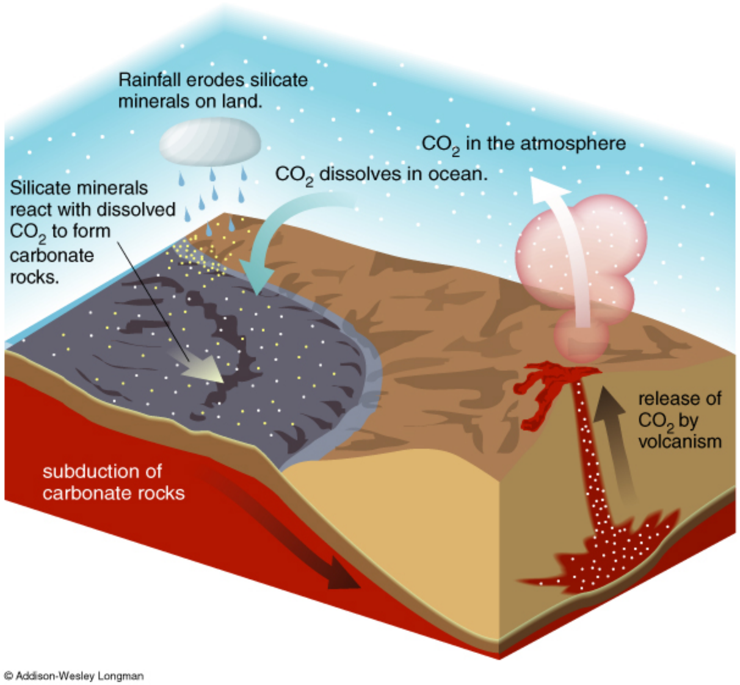
Computation of an atmospheric with different mixing ratio of CO_2, H_2 and CH_4 (CO assumed to be efficiently consumed by acetogens)

→ parameterization for surface fluxes of CO_2, H_2, CH_4 and CO at equilibrium



High CO production from CO_2 and CH_4 photolysis

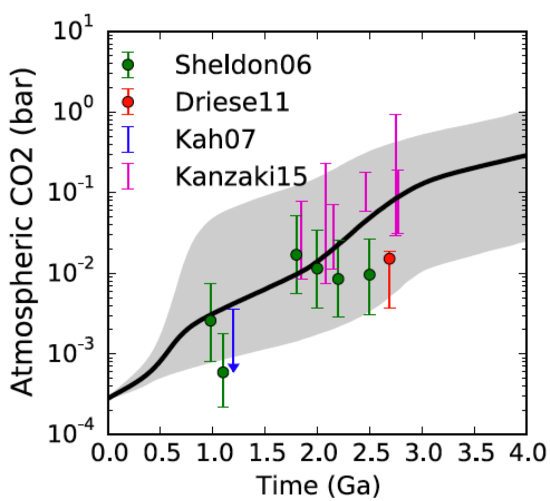
Carbon cycle model

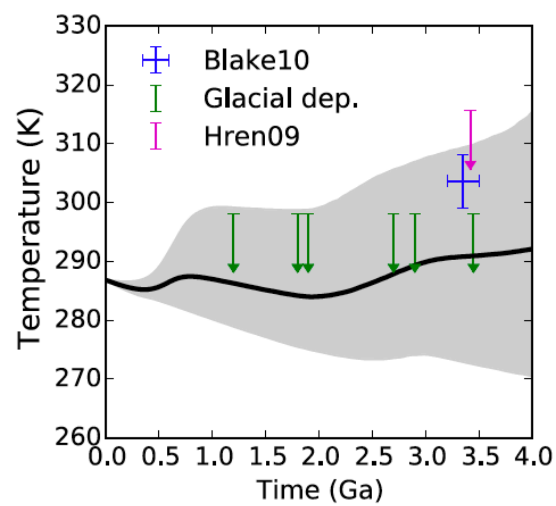


Model from Krissansen-Totton et al. 2018

CO_2 sources:
- Arc volcanoes
- Mid-oceanic ridges

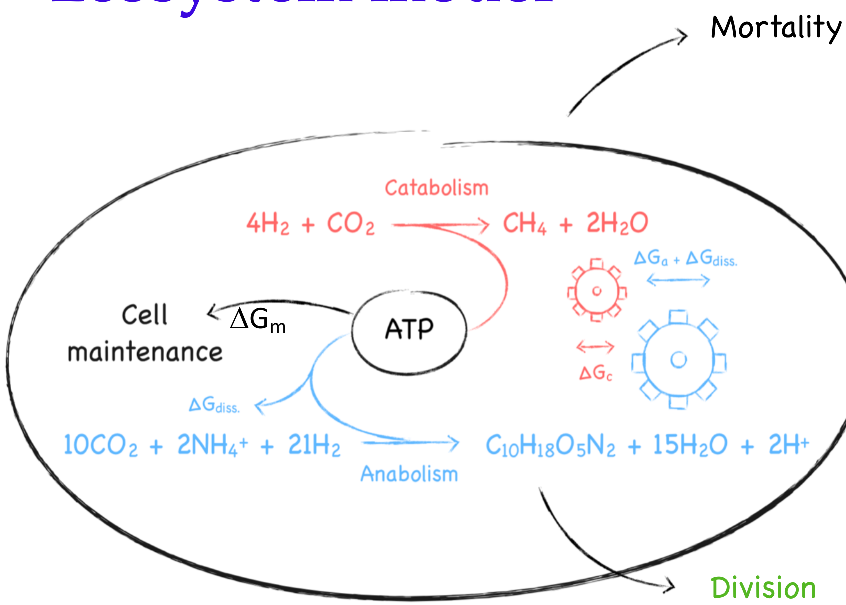
CO_2 sinks:
- Silicate weathering
- Seafloor weathering





Krissansen-Totton et al. 2018

Ecosystem model



Cellular dynamics :

- Catabolism
- Anabolism
- Cellular division
- Mortality

$$\frac{dN}{dt} = N.\left(r(B) - m(q_{cat})\right)$$

$$\frac{dB}{dt} = q_{ana} - r(B)\frac{B + Q_c}{2}$$

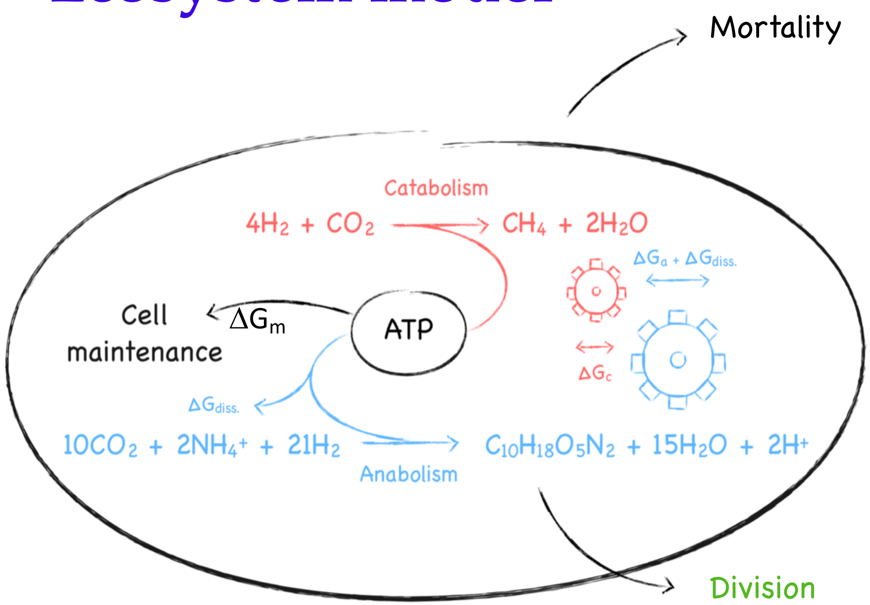
$$\frac{dX_i}{dt} = F(X_i)_{bio}{}^{oc\text{-}atm} + N.\left(qcat.\gamma_{Xi}{}^{cat} + q_{ana}.\gamma_{Xi}{}^{ana}\right) + m.\gamma_{Xi}{}^{rec}.N(B + Q_c)$$

N = cell concentration
B = biomass per cell
X_i = mixing ratio of specie i

Population dynamics:

- Gas exchange with environment
- Influence of temperature

Ecosystem model



Cellular dynamics :

- Catabolism
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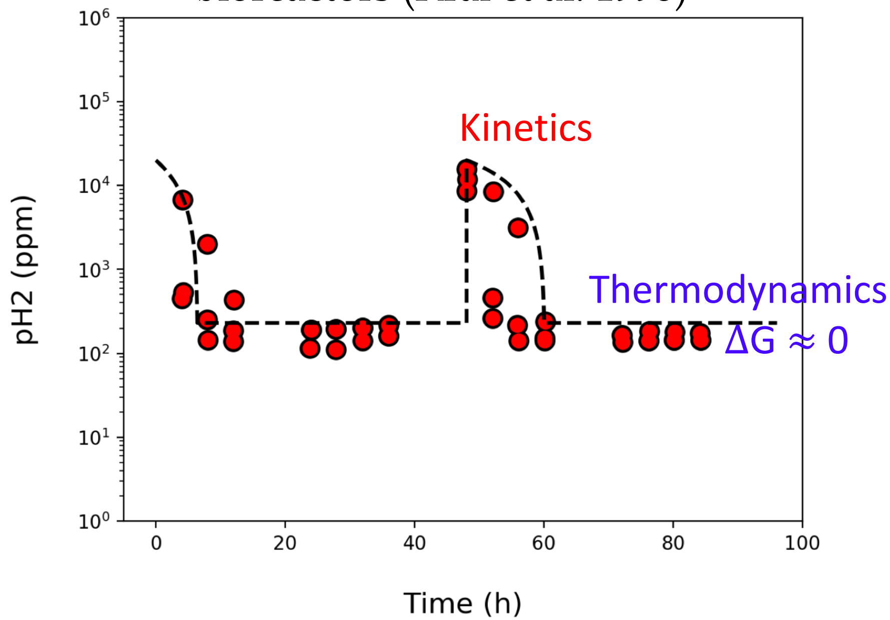
Population dynamics:

- Gas exchange with environment
- Influence of temperature

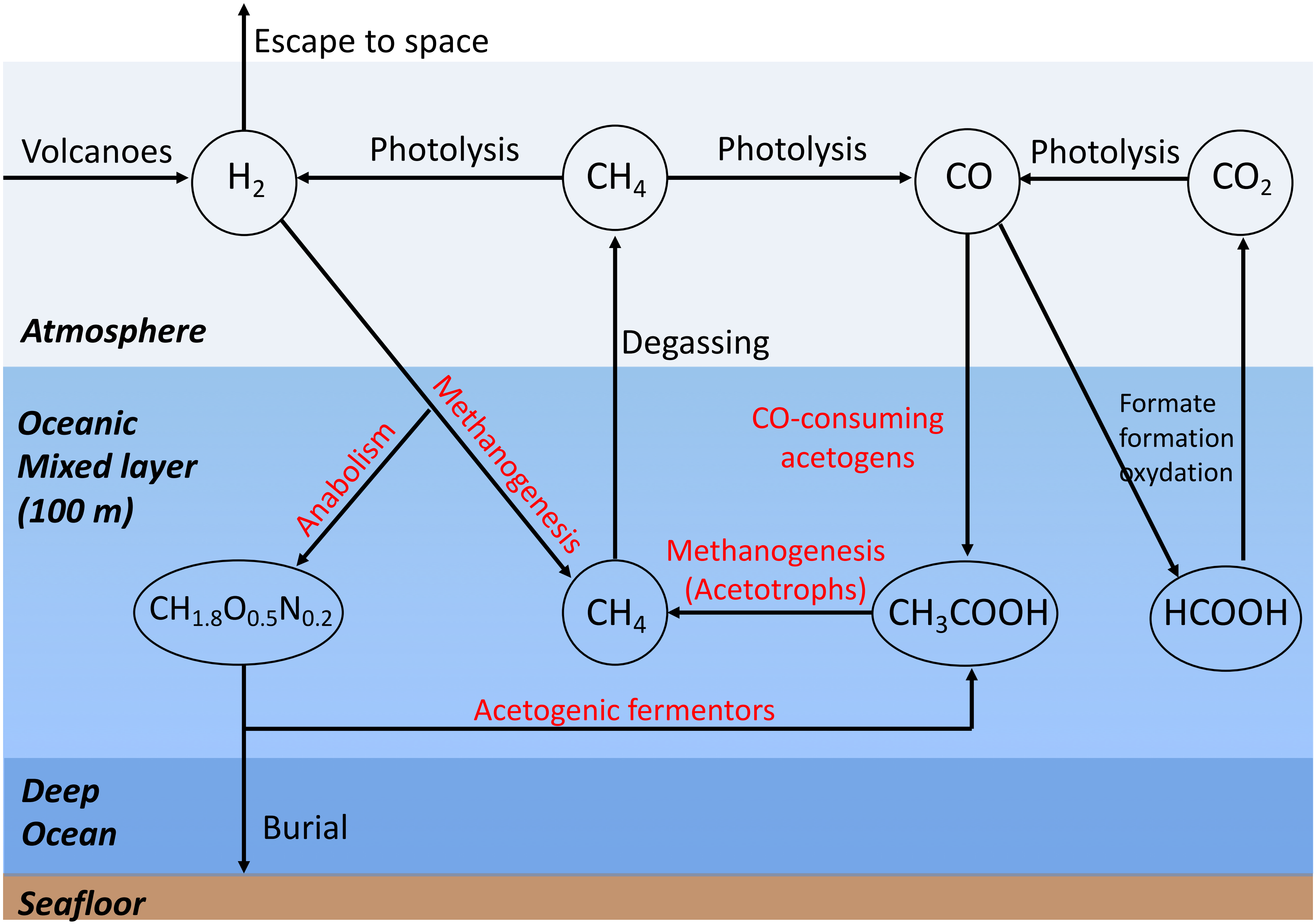
Validation with data of methanogens in bioreactors (Kral et al. 1998)



List of metabolisms

Reaction	ΔG_0	ΔH_0
Catabolic reactions:		
Methanogenesis: $0.25 \cdot CO_2 + H_2 \rightarrow 0.25 \cdot CH_4 + 0.5 \cdot H_2O$	-32.575	-63.175
Acetogenesis: $2 \cdot CO + H_2O \rightarrow CO_2 + 0.5 \cdot CH_3COOH$	-77.850	-129.850
Acetotrophy: $CH_3COOH \rightarrow CO_2 + CH_4$	-55.0	16.2
Acetogenic fermentors: $CH_{1.8}O_{0.5}N_{0.2} + 5/6H_2O + 0.2 \cdot H^+ \rightarrow 1/3CH_3COOH + 1/3CO_2 + 2.3/3H_2 + 0.2 \cdot NH_4^+$	-12.71	10.066
Anabolic reactions:		
$CO_2 + 0.2 \cdot NH_4^+ + 2.1H_2 \rightarrow CH_{1.8}O_{0.5}N_{0.2} + 1.5 \cdot H_2O + 0.2H^+$	-12.390	-99.700
$CO_2 + 0.1 \cdot N_2 + 2.1H_2 \rightarrow CH_{1.8}O_{0.5}N_{0.2} + 1.5 \cdot H_2O$	28.25	128

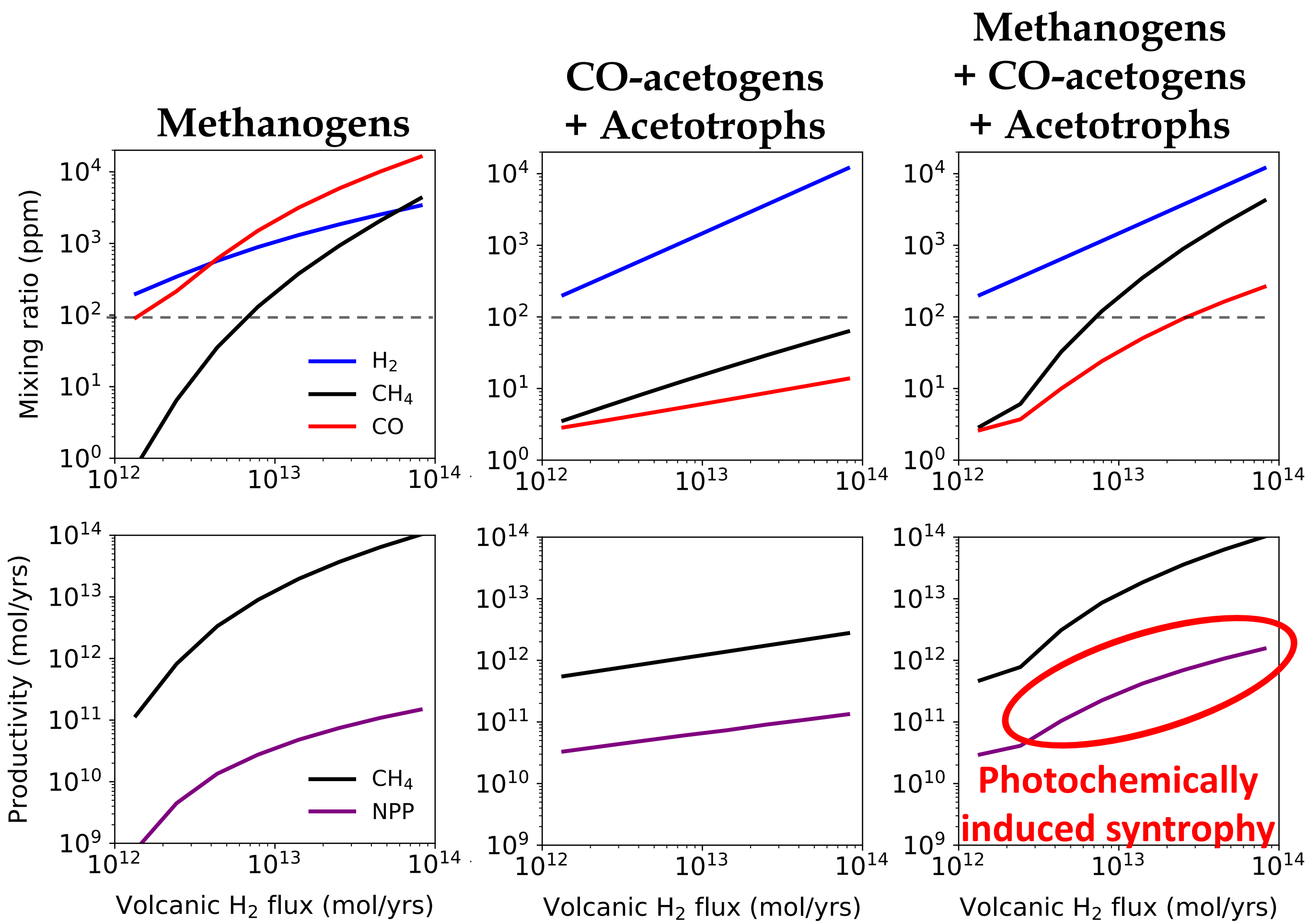
Diagram of the primitive biosphere



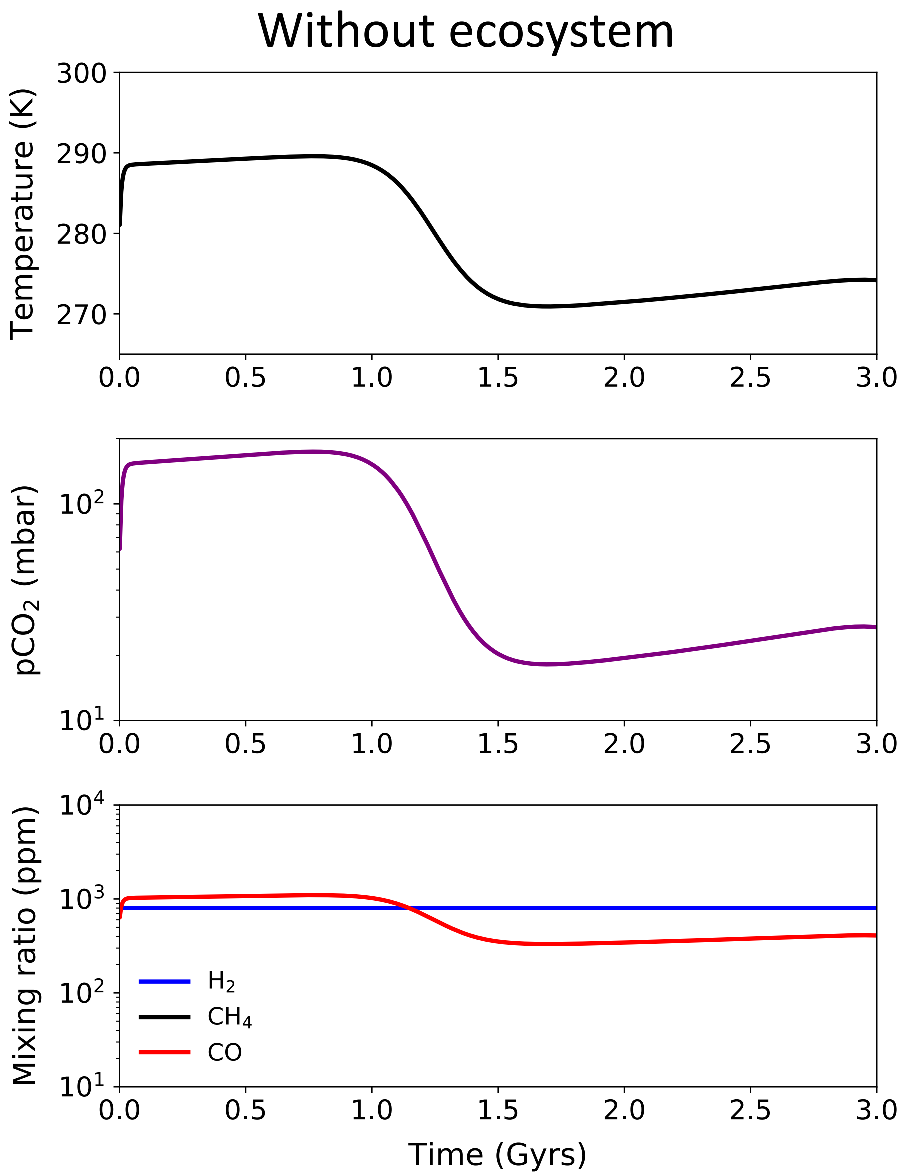
Results for ecosystems + atmosphere

Simulations at 3.8 Ga with :

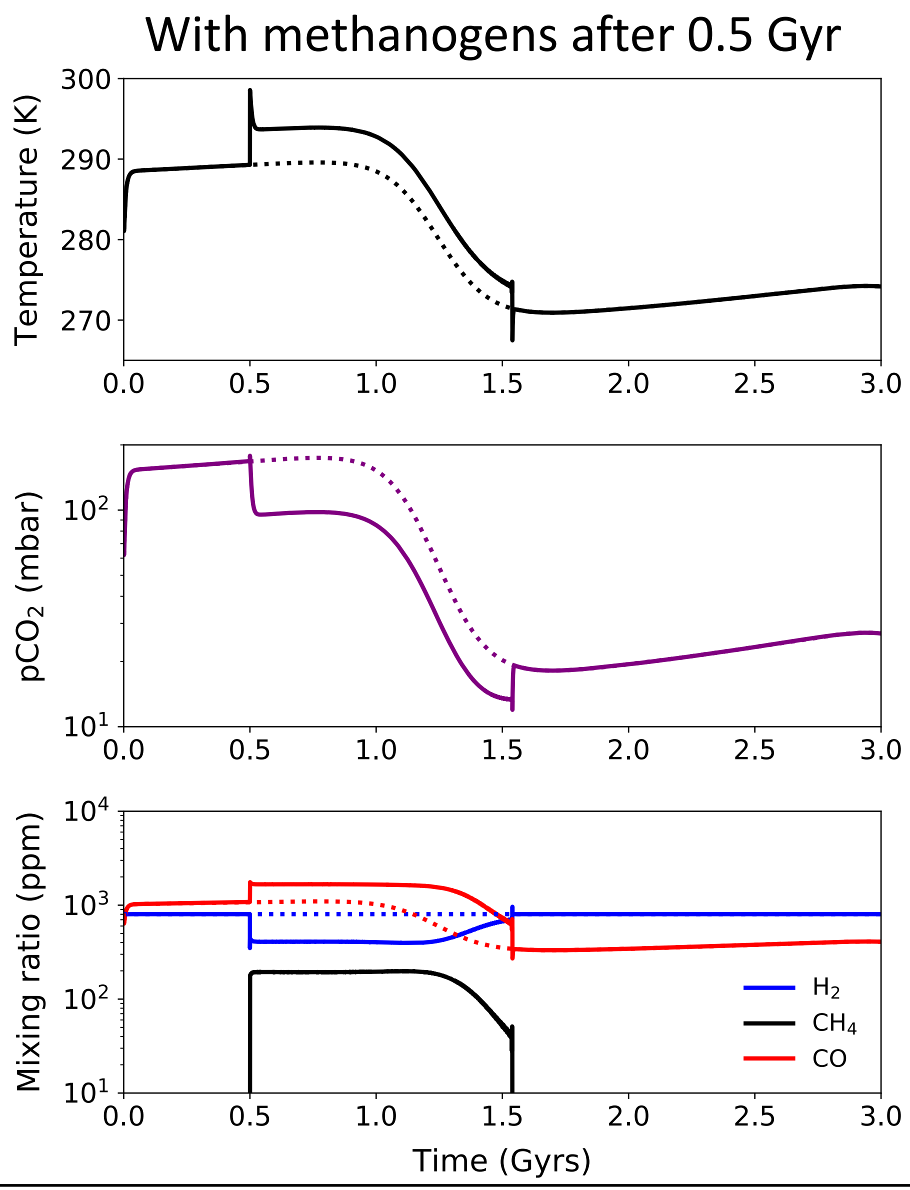
- pCO_2 = 100 mbar, T = 285 K
- $\Phi(H_2)_{volc}$ = 1-80 Tmol / yr
- non-limited by nitrogen (N-fixation or recycling by fermentors)



Results for ecosystems + atmosphere + C cycle



Results for ecosystems + atmosphere + C cycle



Possible implications for the trigerring of Huronian glaciation

Summary

- First dynamic model of early ecosystems coupled to climate and C cycle
- Efficient CH_4 production by methanogens ($[CH_4]$ = 100-1000 ppm) but less than Karecha et al. 2005
- Low NPP by methanogens (~30× lower than Karecha)
- CO-acetogens + acetotrophs enhance NPP by a factor ~10
- Methanogens induce a weak positive feedback on climate and facilitate glaciations

No gaian regulation of the climate by methanogens

Perspectives

- Including anoxygenic and oxygenic photosynthesis
- Computation of chemical disequilibrium and biosignatures

For the Archean, disequilibrium dominated by (Krissansen-Totton et al. 2018):

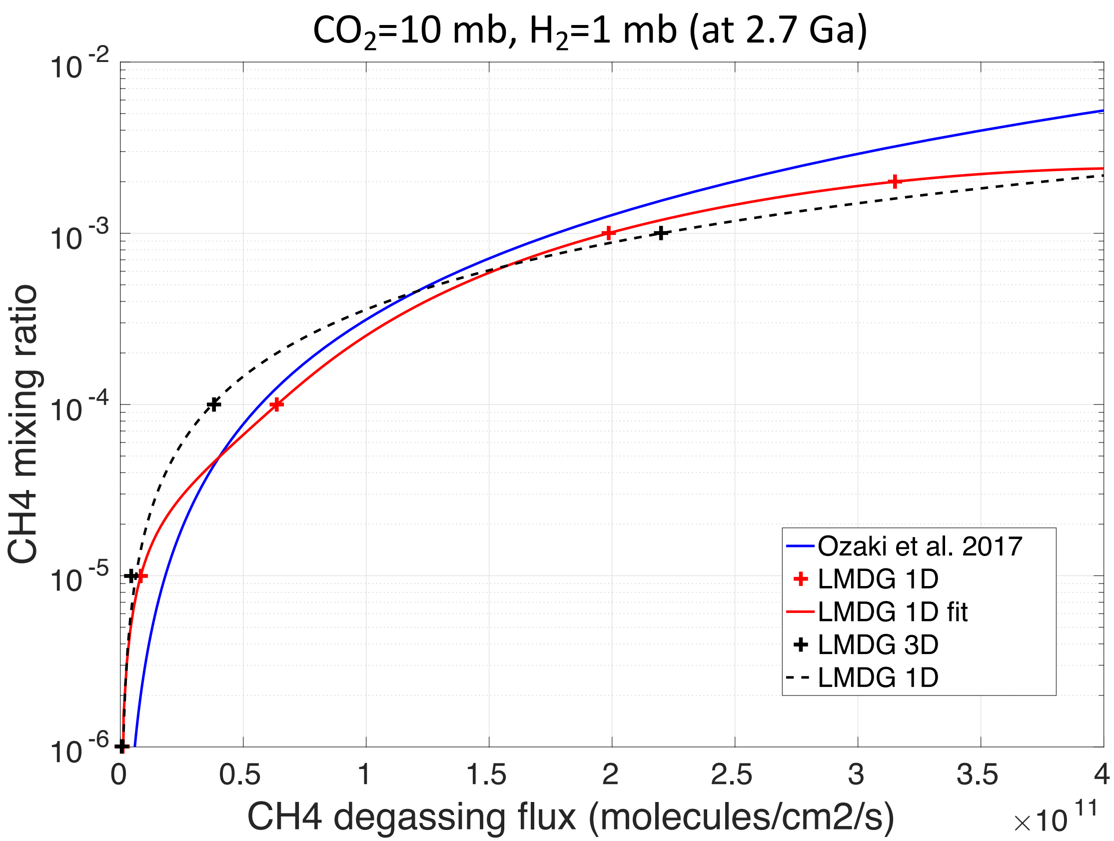
$$5CO_2 + 4N_2 + 3CH_4 + 14H_2O \rightarrow 8NH_4^{\;+} + 8HCO_3^{\;-}$$

For the Proterozoic and modern Earth:

$$5O_2 + 2N_2 + 2H_2O \rightarrow 4H^{\;+} + 4NO_3^{\;-}$$

Atmospheric model:

Comparaison to previous study and 1D VS 3D



1D model adequate

Atmospheric model:

- Nitrogen chemistry (15 species, 42 reactions)
  Production of NOx using lightning frequency from Wong, Charnay et al. 2017

$CO_2 + N_2 \rightarrow CO + 2NO$

At 3.8 Ga with pCO_2=0.1 bar:
NOx flux in the ocean = $1.8*10^8$ mol/yr (essentially as HNO)

List of metabolisms

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Acetotrophy: $CH_3COOH \rightarrow CO_2 + CH_4$	-55.0	16.2
NO_3 Methanotrophy: $0.25 \cdot CH_4 + NO_3^- \rightarrow 0.25 \cdot CO_2 + NO_2^- + 0.5 \cdot H_2O$	-125.5	-120
NO_2 Methanotrophy: $0.375 \cdot CH_4 + NO_2^- + H^+ \rightarrow 0.375 \cdot CO_2 + 0.5 \cdot N_2 + 1.25 \cdot H_2O$	-393.14	-372.24
Acetogenic fermentors: $CH_{1.8}O_{0.5}N_{0.2} + 5/6H_2O + 0.2 \cdot H^+ \rightarrow 1/3CH_3COOH + 1/3CO_2 + 2.3/3H_2 + 0.2 \cdot NH_4^+$	-12.71	10.066
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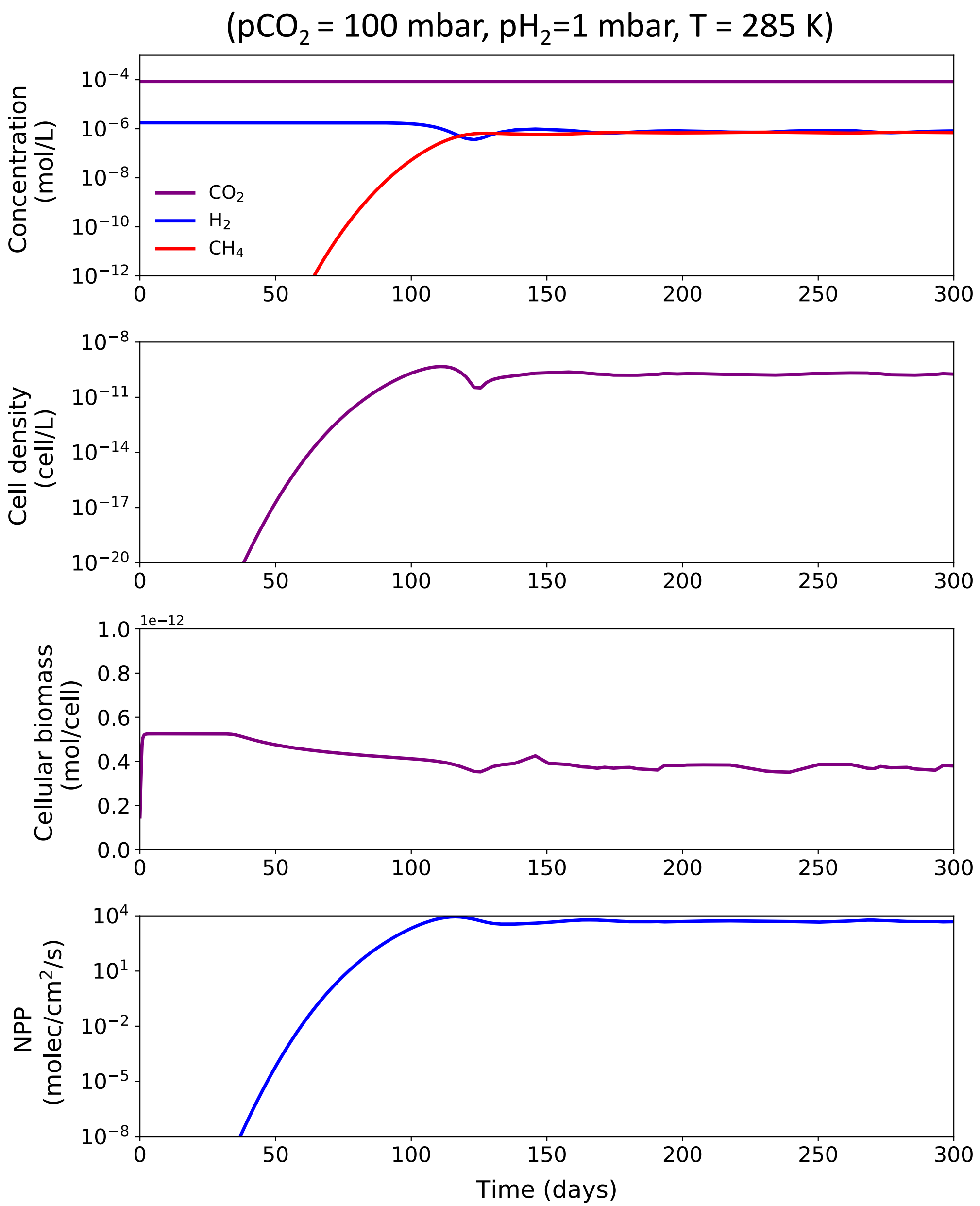
low flux of NOx (NO3 and NO2 Methanotrophy)

Dynamics of methanogens



Present day Earth under a 20% weaker Sun