Global Warming Potential (GWP) Modelling & Climate Impacts of Increased Hydrogen Production and Use

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Hydrogen indirectly impacts Earth’s climate

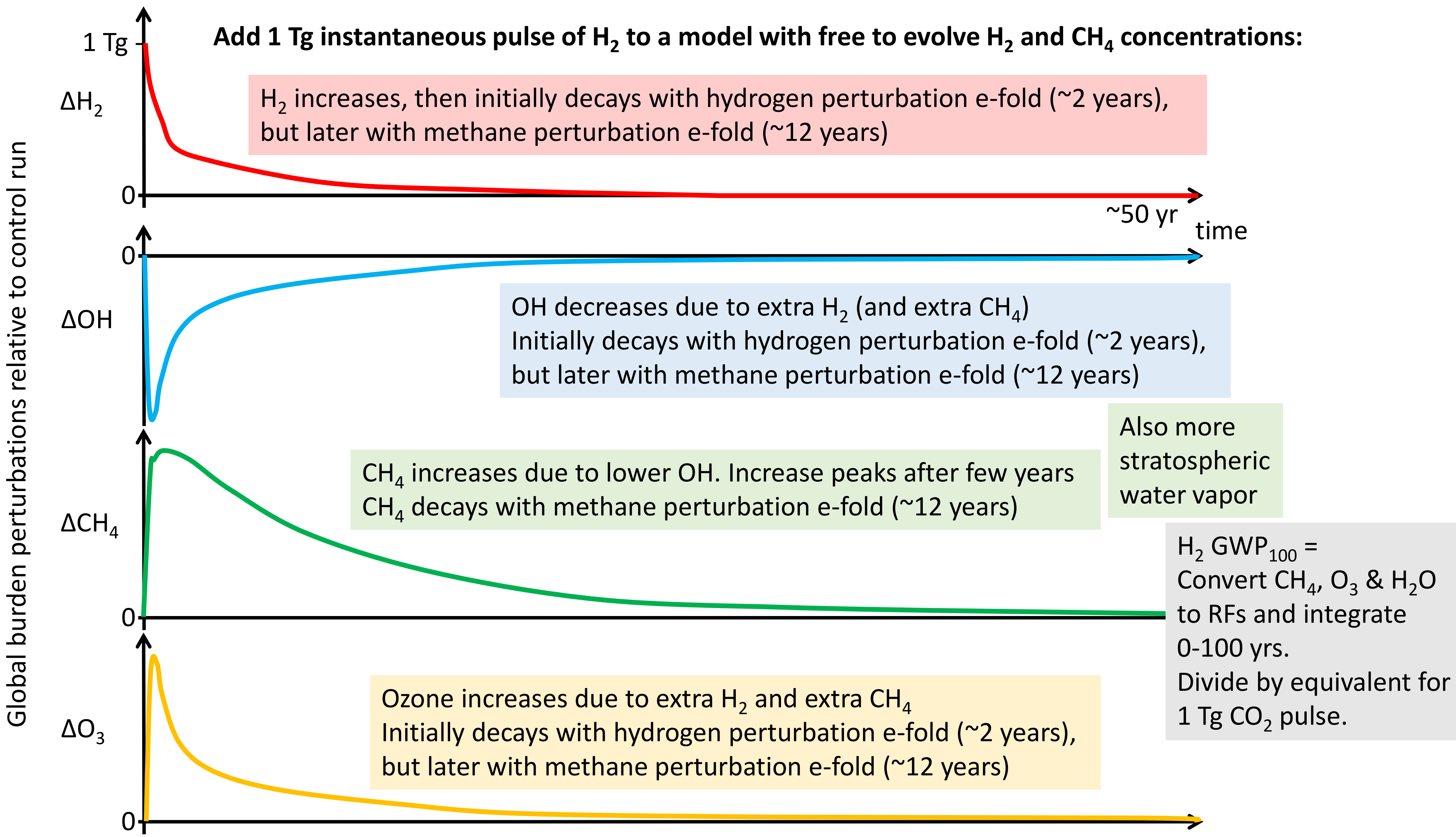
- H_2 is not a direct greenhouse gas
- But it reacts with hydroxyl (OH) to produce ozone
- Reduction of OH lengthens methane’s lifetime
- It increases stratospheric water vapour
- By changing oxidants it affects aerosol formation and clouds
- Need to quantify these impacts
- The GWP climate metric is one way of doing this

Global Warming Potential (GWP)

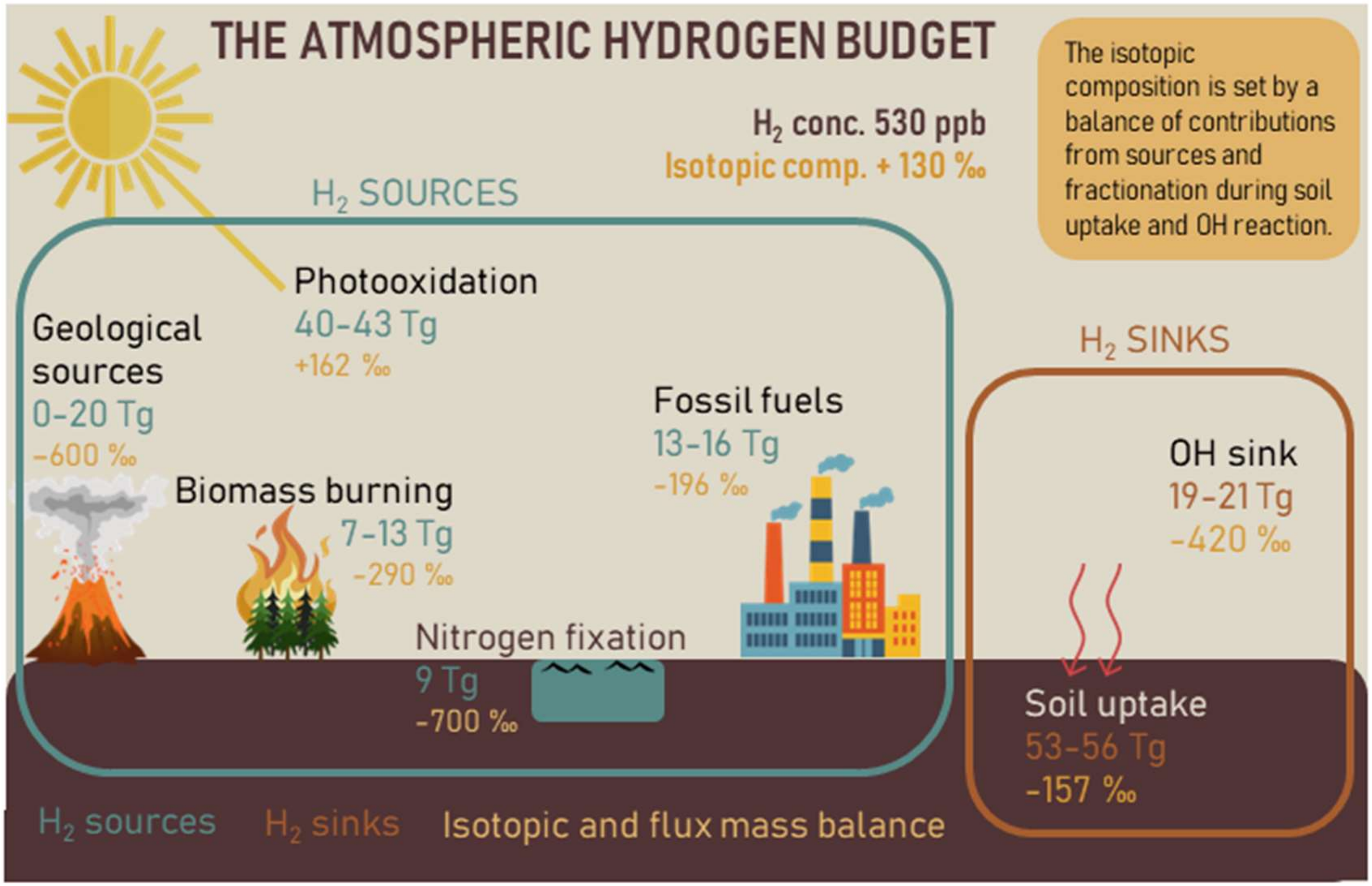
- Integrates the impact of an emission on radiative forcing (RF) over a specified time horizon
- The GWP is normalised to CO_2 – i.e. CO_2 has a GWP=1
- Model emission of a pulse of a unit mass of a gas, compare the time evolution of the resulting RF with that of emission of same mass of CO_2
- Formal definition:

$$\boxed{GWP_i \equiv \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_r(t)\,dt}}$$

i = specific gas
r = reference gas (CO_2)
TH = ‘time horizon’
RF = radiative forcing



Add 1 Tg instantaneous pulse of H_2 to a model with free to evolve H_2 and CH_4 concentrations:
Global burden perturbations relative to control run
1 Tg
ΔH_2
0
~50 yr
time
H_2 increases, then initially decays with hydrogen perturbation e-fold (~2 years), but later with methane perturbation e-fold (~12 years)
0
ΔOH
OH decreases due to extra H_2 (and extra CH_4)
Initially decays with hydrogen perturbation e-fold (~2 years), but later with methane perturbation e-fold (~12 years)
ΔCH_4
0
CH_4 increases due to lower OH. Increase peaks after few years
CH_4 decays with methane perturbation e-fold (~12 years)
Also more stratospheric water vapor
H_2 GWP_{100} = Convert CH_4, O_3 & H_2O to RFs and integrate 0-100 yrs. Divide by equivalent for 1 Tg CO_2 pulse.
ΔO_3
0
Ozone increases due to extra H_2 and extra CH_4
Initially decays with hydrogen perturbation e-fold (~2 years), but later with methane perturbation e-fold (~12 years)



Burden: 136-157 Tg
Lifetime: 1.4-2.1 yr

Uncertainty in soil sink leads to uncertainty in lifetime (and GWP)

Ratio of soil sink : OH sink controls the total lifetime.

Only H_2 oxidised by OH affects climate.

Paulot et al (2021) https://doi.org/10.1016/j.ijhydene.2021.01.088
Price et al. (2007) https://doi.org/10.1029/2006JD008152

Add H_2 pulse to model: CH_4 increases

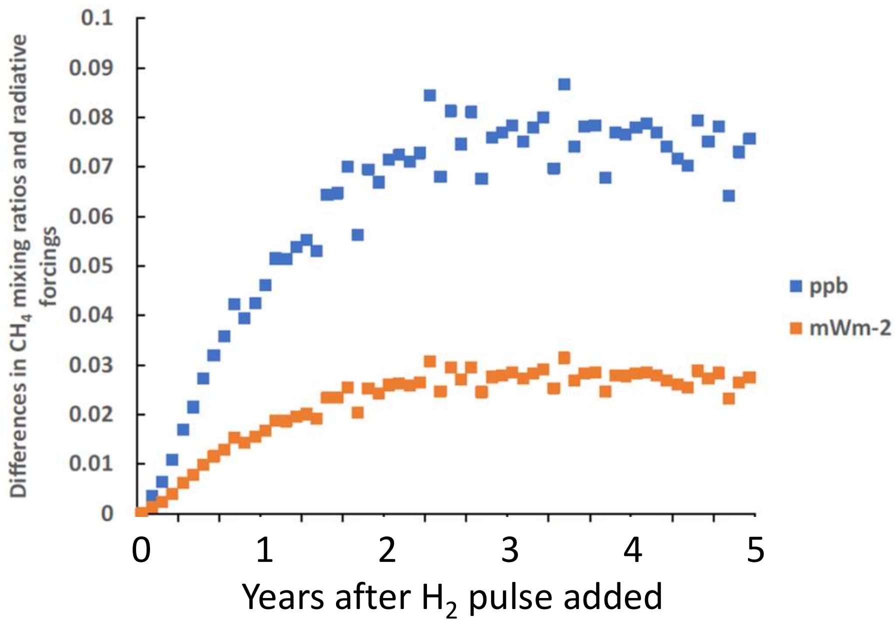


Fig. 1 — Differences in global mean CH_4 mixing ratios and radiative forcing between the base case and perturbed scenario model runs.

Derwent et al. (2020) https://doi.org/10.1016/j.ijhydene.2020.01.125

H_2 depletes OH:

$$H_2 + OH \rightarrow H + H_2O$$

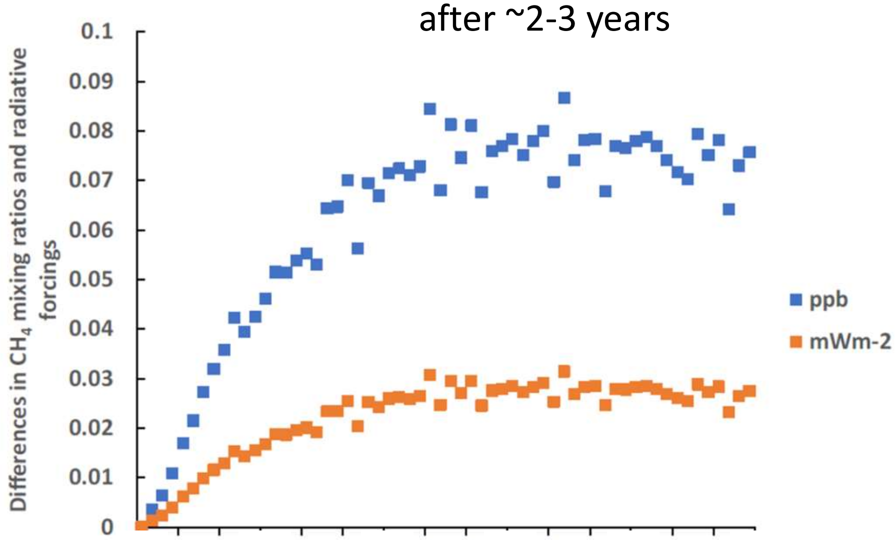
Less OH leads to a longer CH_4 lifetime; CH_4 increases over ~3 years.

Extra CH_4 then decays with CH_4 perturbation lifetime (~12 yrs) – extrapolate to 100 years

Convert ppb to radiative forcing.

Add H_2 pulse to model: CH_4 increases

Peak CH_4 response
after ~2-3 years



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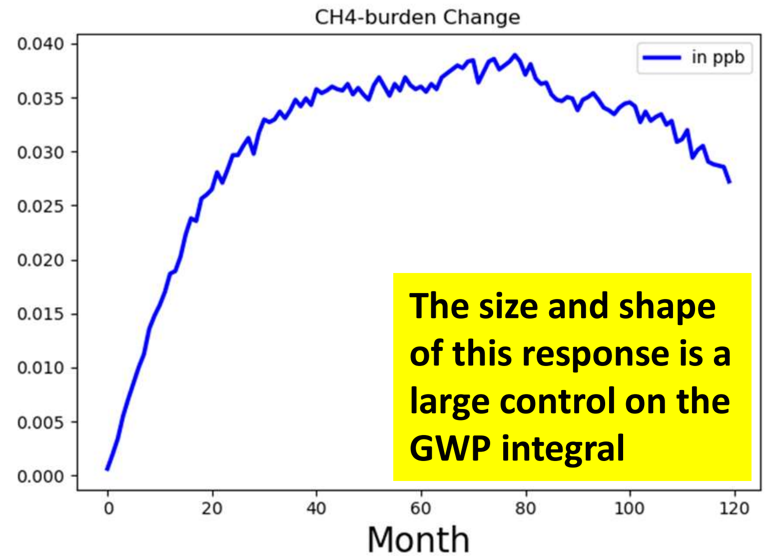


New results using UKESM with interactive CH_4

(Bill Collins & Tanu Chakraborty, using model developed by Hannah Bryant & Megan Brown)

Add H_2 pulse to model: O_3 increases

O_3 responds faster
~6 months

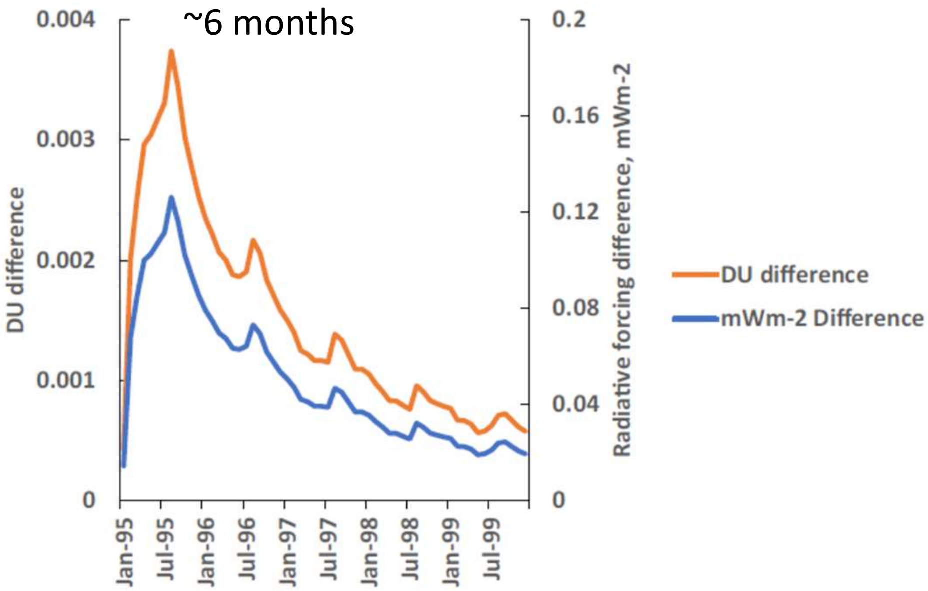


Fig. 2 — Differences in tropospheric ozone amounts in Dobson Units and radiative forcing between the base case and perturbed scenario model runs.

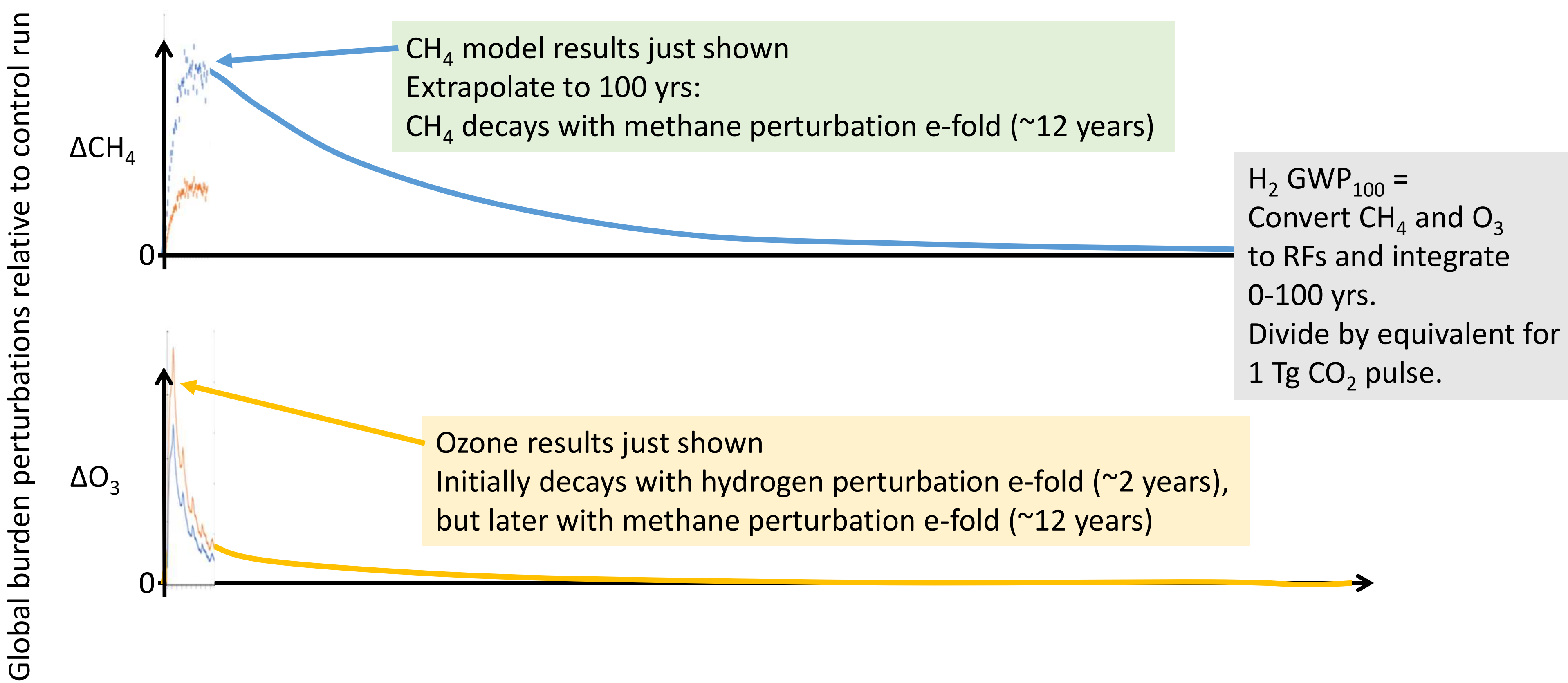
H_2 increases HO_2, NO_2 and O_3:

$$H_2 + OH \rightarrow H + H_2O$$
$$H + O_2 \rightarrow HO_2$$
$$HO_2 + NO \rightarrow NO_2 + OH$$
$$NO_2 + h\nu \rightarrow NO + O$$
$$O + O_2 + M \rightarrow O_3 + M$$

O_3 increases over first year, then decays with H_2 perturbation lifetime (~2 years).

The extra CH_4 will also produce O_3.
Convert DU to radiative forcing.

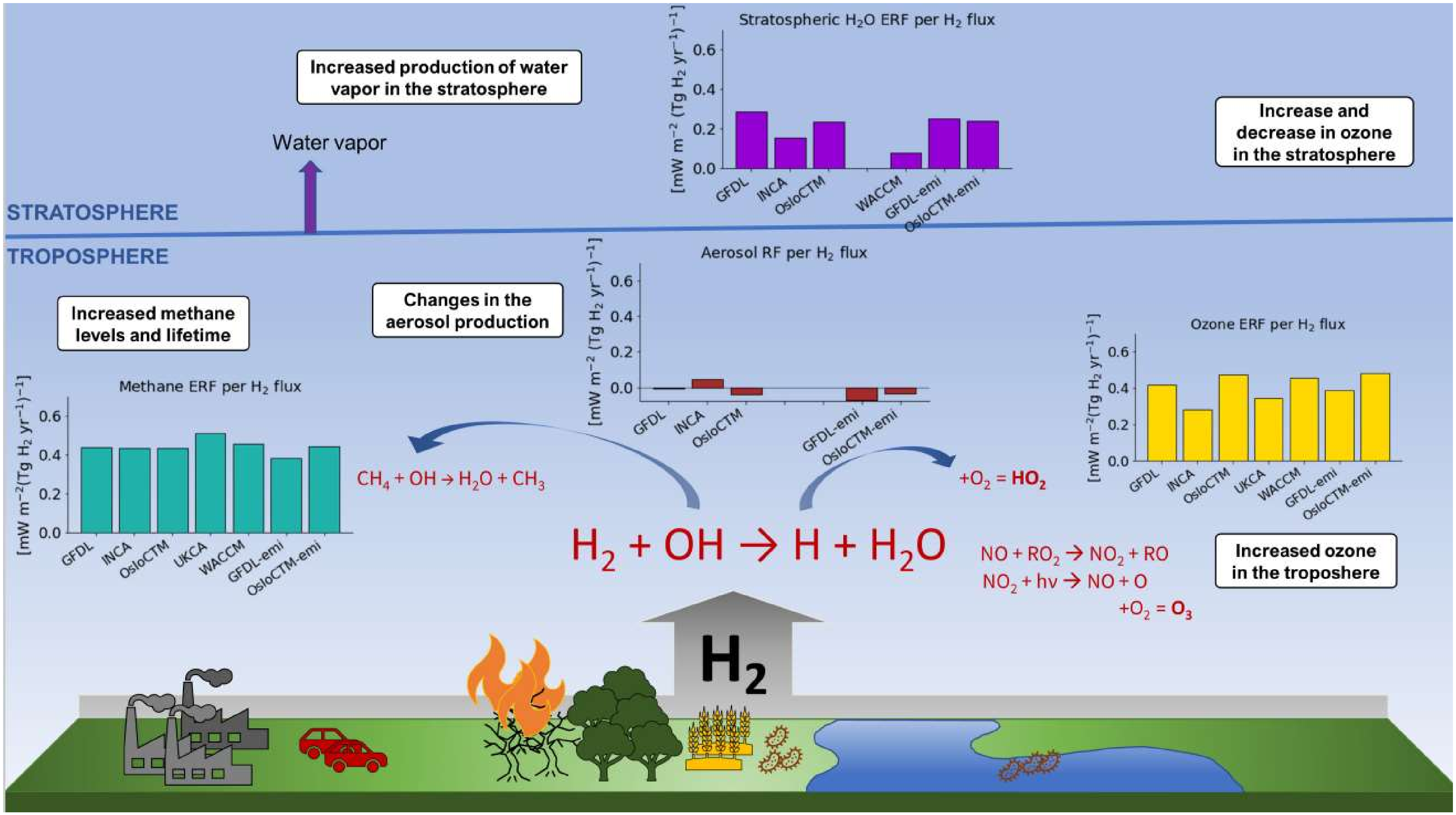
Derwent et al. (2020) https://doi.org/10.1016/j.ijhydene.2020.01.125



Global burden perturbations relative to control run
ΔCH_4
0
CH_4 model results just shown
Extrapolate to 100 yrs:
CH_4 decays with methane perturbation e-fold (~12 years)
H_2 GWP_{100} =
Convert CH_4 and O_3
to RFs and integrate
0-100 yrs.
Divide by equivalent for
1 Tg CO_2 pulse.
ΔO_3
0
Ozone results just shown
Initially decays with hydrogen perturbation e-fold (~2 years),
but later with methane perturbation e-fold (~12 years)

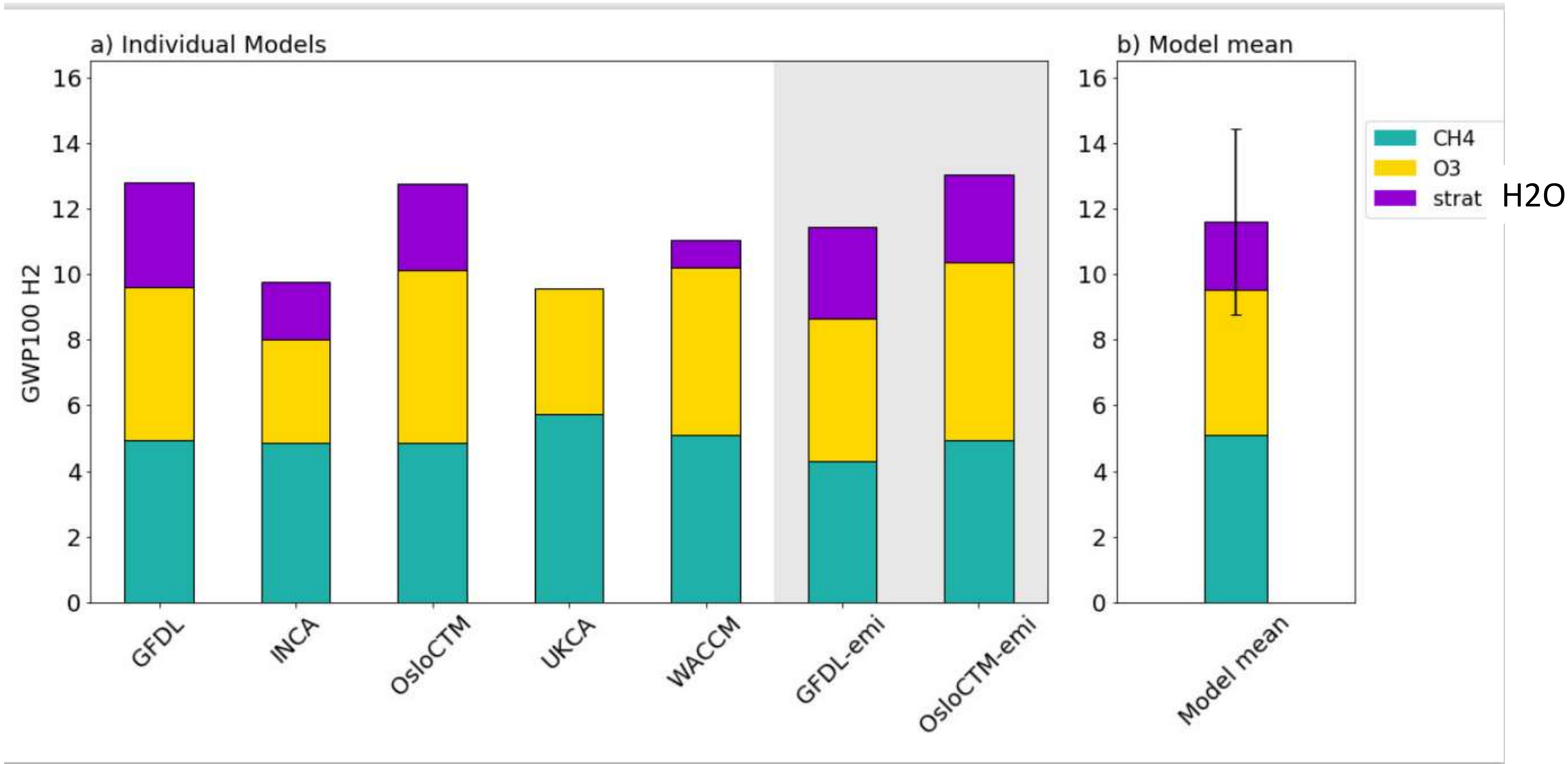
Step change experiments vs pulses

- Several studies use step changes in emissions rather than pulses to evaluate GWP.
  - Sand et al. (2023) and Warwick et al. (2023) use step-changes
  - Derwent et al. (2001, 2020) use pulses
- Both are examples of using idealised model experiments that can be scaled to real-world situations
- It is generally accepted that these methodologies are equivalent, although the analysis of the initial transient responses is more obviously seen in pulse experiments
- Need to check for differences in GWPs between methodologies
- Now possible with free-running CH_4 flux models



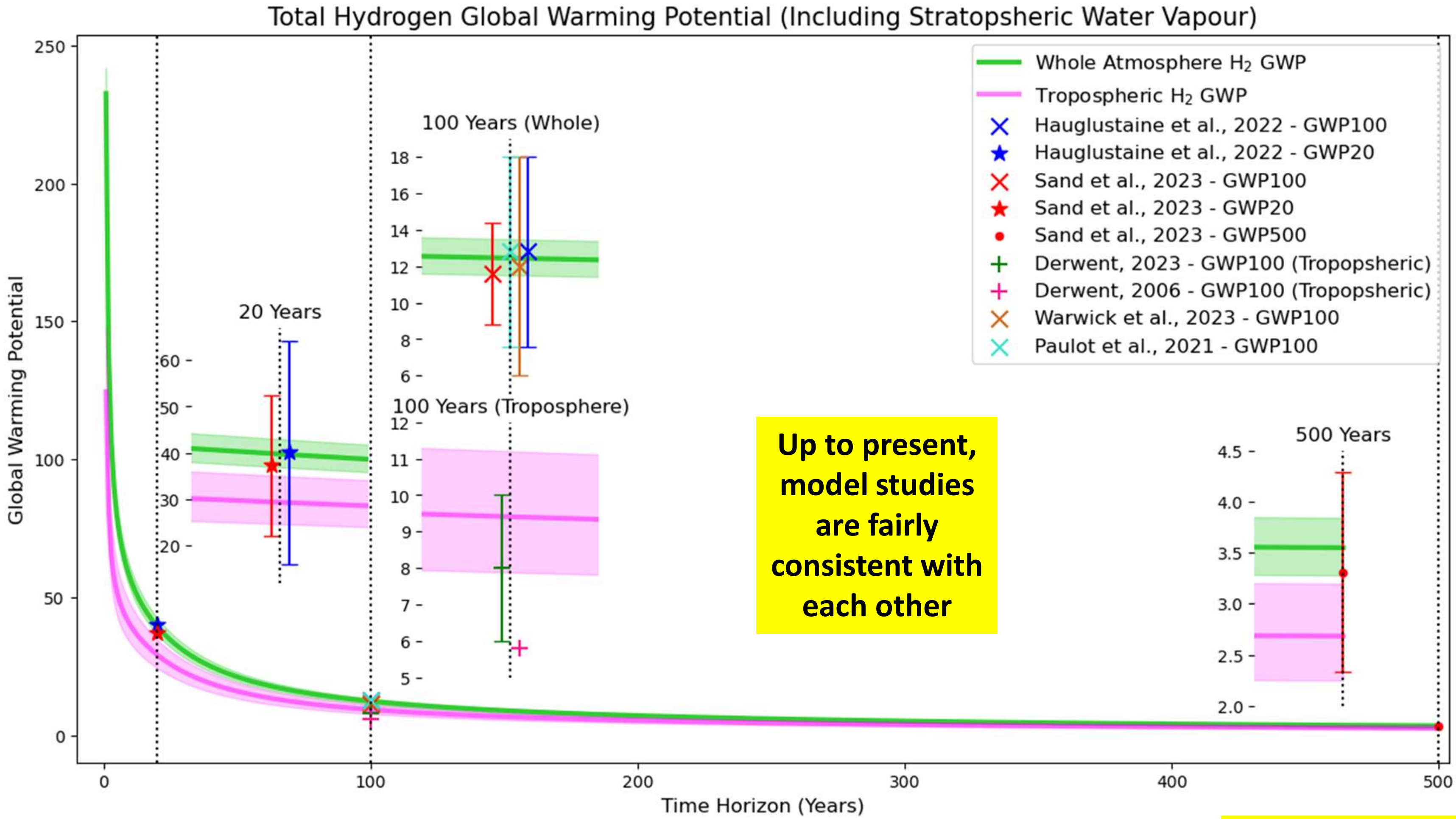
Sand et al., 2023

GWP$_{100}$ of H_2



Sand et al., 2023

All literature estimates compared (Hauglustaine et al., 2022, Warwick et al., 2023, Sand et al., 2023 and Derwent, 2023) fit within the deposition range, except Derwent et al., 2006.



**Uncertainty is based on the range of deposition fluxes in Sand et al., 2023*

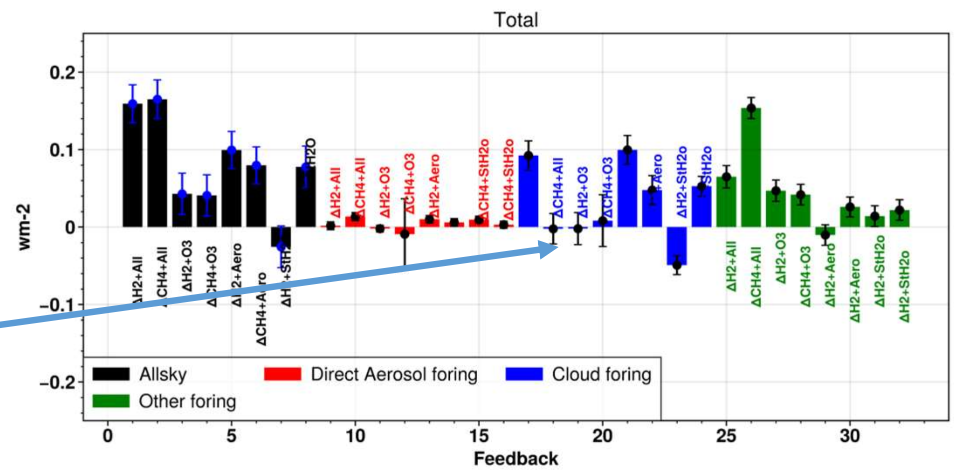
Hannah Bryant, PhD work

Sources of uncertainty in H_2 GWP_{100}

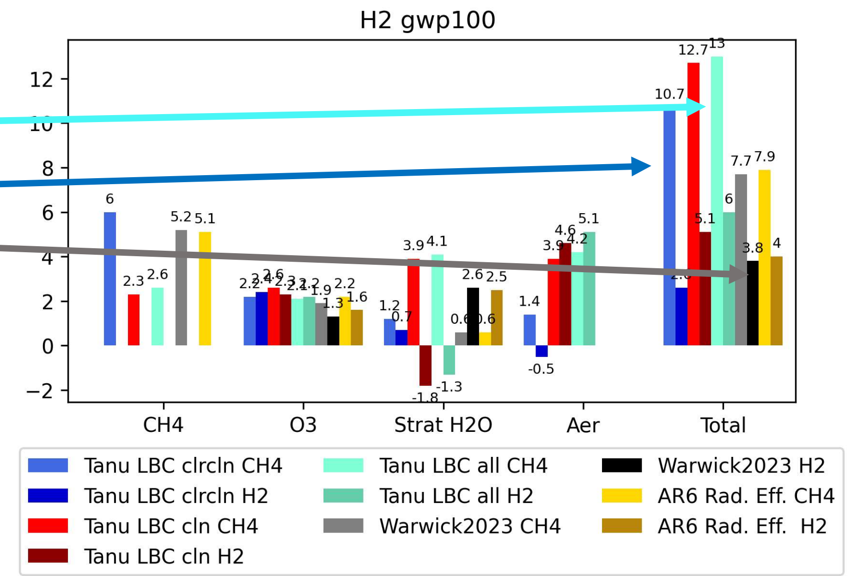
- Model range (various studies) ~12 $\pm$ 6
- Methodology (pulse v step change; transient shapes) – ongoing
- ERFs (including cloud adjustments) – UKESM model suggests large effect
- Soil sink – H_2 lifetime
- Background composition (different NOx levels; small effects in UKESM)
- Emission location (land v sea; SH v NH)
- Chemistry (e.g. HCHO chemistry)
- Aerosol effects

Climate metrics (ERFs)

- Effective radiative forcing (ERF) calculations from UKESM1 model
  - Large contribution from changes in clouds



- Can put these into the FaIR model to calculate climate implications
  - Integrated forcing over 100 years = GWP100
  - Overall results: GWP100 = 19
  - Without clouds: GWP100 = 13.3
  - Use Warwick et al. parameters: GWP100 = 11.5

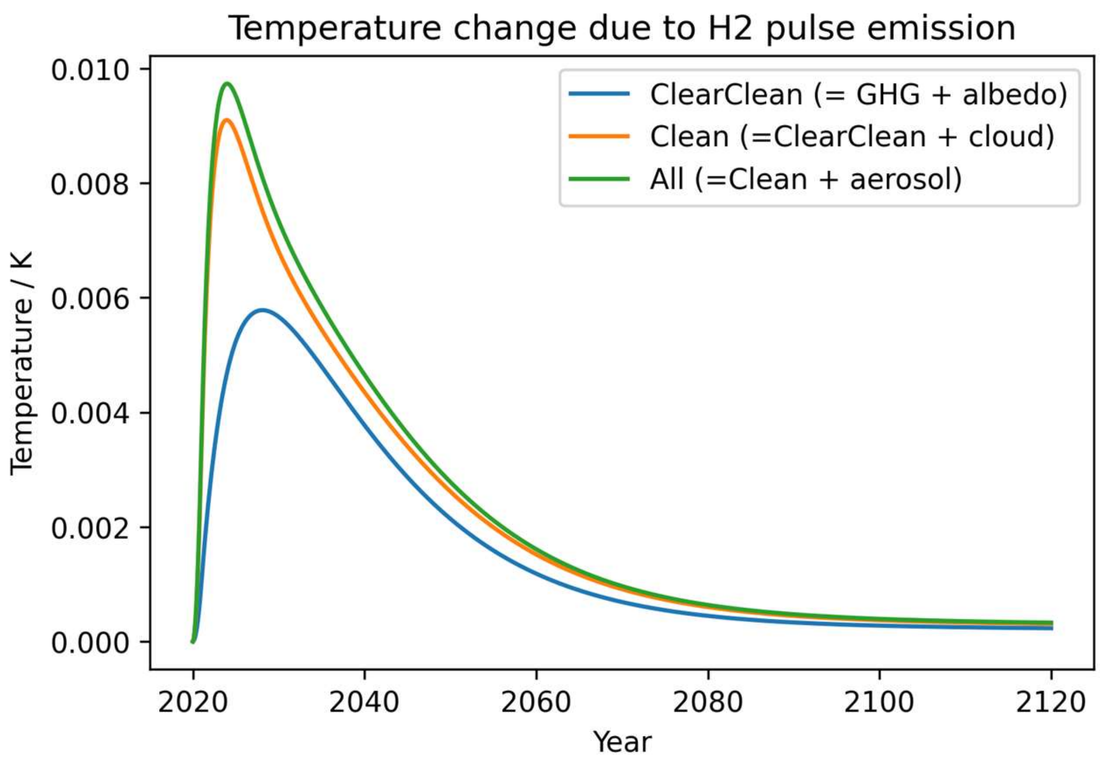


- Clouds seem to make a very large contribution, but may be specific to the UKESM1 model

(Bill Collins, Tanu Chakraborty)

Climate effects

- Temperature evolution following hydrogen emission can't be characterised by a single number such as GWP100
- FaIR tuned to full climate model can generate climate change on any timescale



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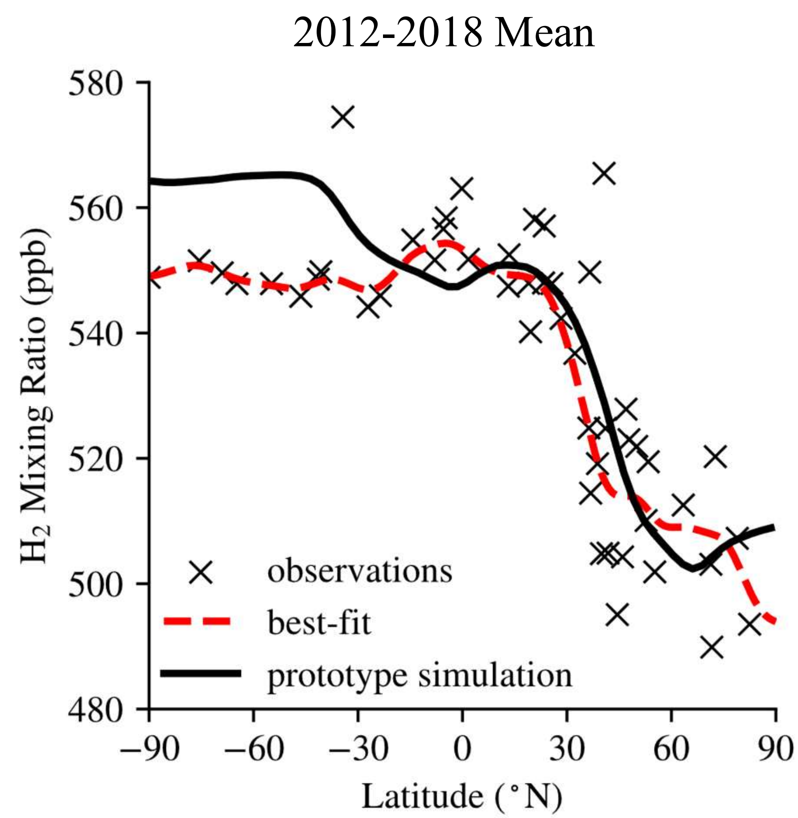
Constraining H_2 soil deposition with planetary scale observations

Observations: NOAA GML surface H_2 measurements since c.2010 (Petron et al. 2023).

Prototype simulation: 2D latitude height model with Sand et al. (2023)/UKCA chemistry fluxes and biophysics based deposition scheme (Ehhalt and Rohrer, 2011 and Bertagni et al., 2021):

$$W_{\text{deposition}} \sim f(\text{soil moisture}) \cdot h(\text{soil temperature})$$

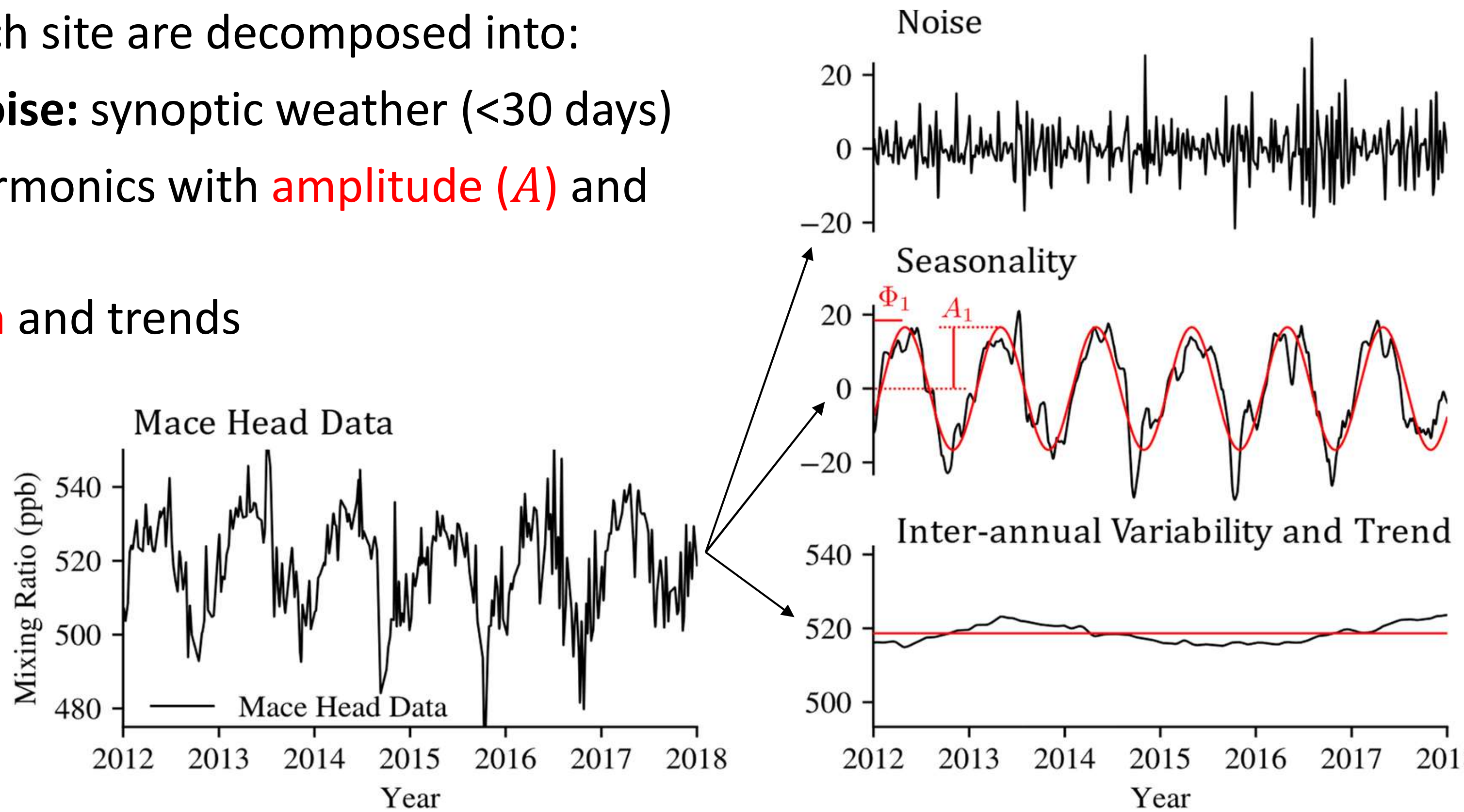


Alex Tardito Chaudhri, David Stevenson, HECTER, Edinburgh

Decomposing the signal at each site

Observations for each site are decomposed into:

- **High-frequency noise:** synoptic weather (<30 days)
- **Seasonality:** fit harmonics with amplitude (A) and phase (Φ)
- **Inter-annual** mean and trends



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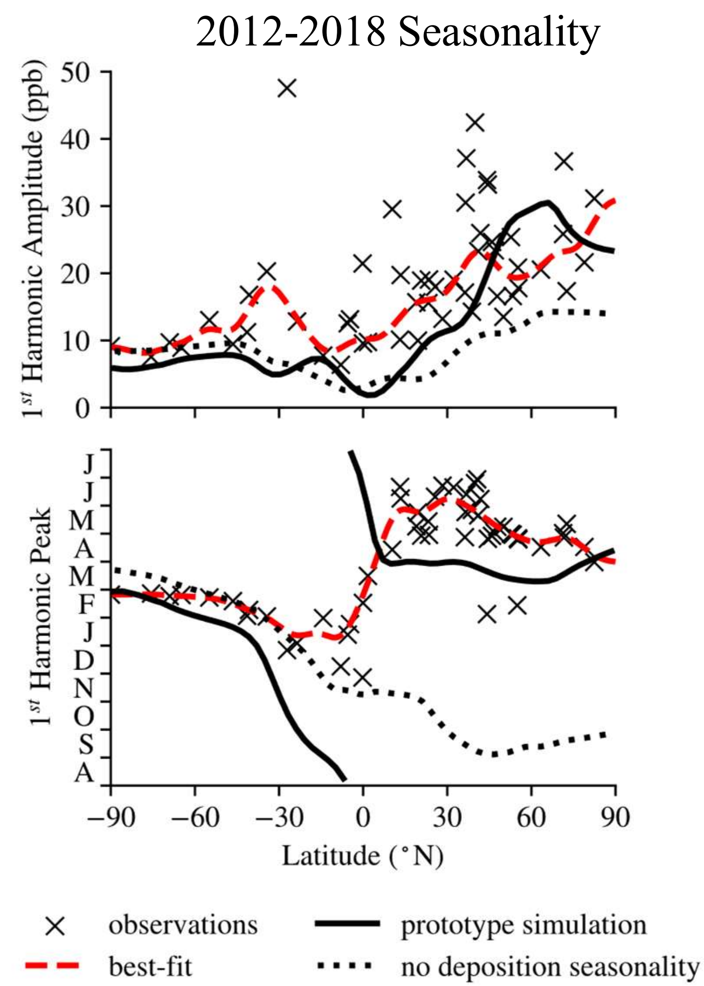
Constraining H_2 deposition

- **The prototype scheme** performs relatively well but results in too high SH mixing ratios, does not capture SH subtropics seasonality, and H_2 peaks too early in the subtropics.
- **Invert 2D model** to identify a deposition scheme that achieves the best-fit H_2 signal as a perturbation to the prototype deposition scheme.
- **Key difference**: $\sim$ 3 month later peak deposition in the sub-tropics and tropics.



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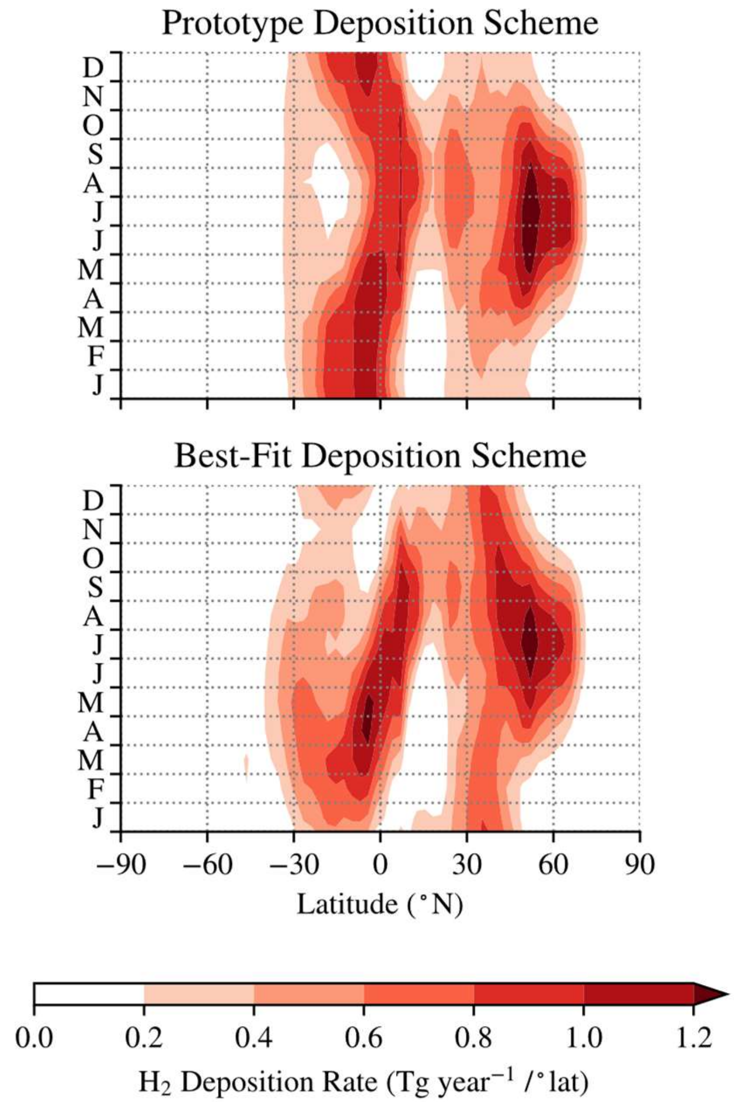

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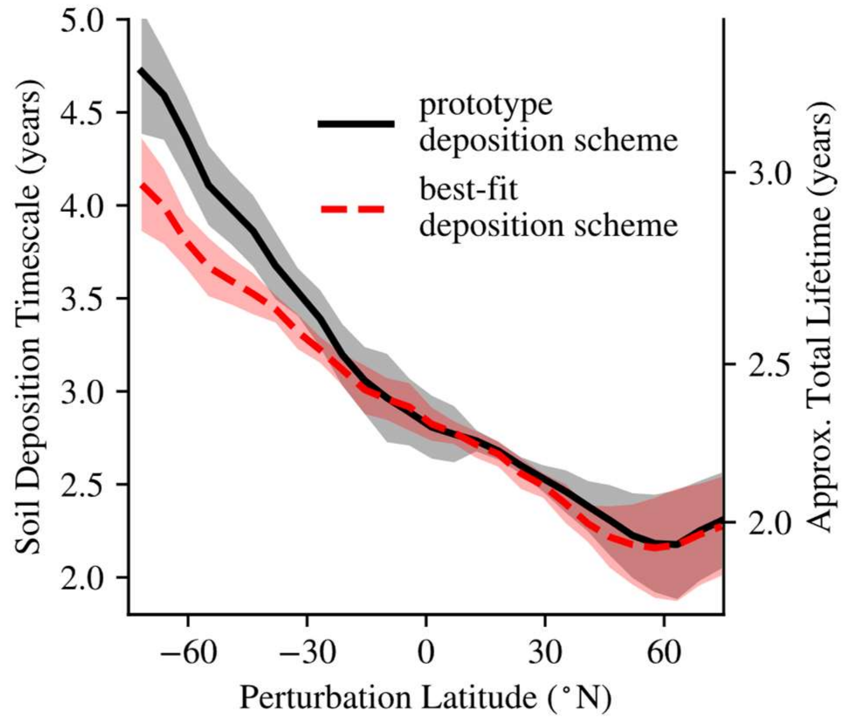
Constrained scheme lowers soil deposition timescales in the Southern Hemisphere

- **Soil deposition timescales** are compared for a series of small H_2 perturbations at different latitudes and different times of year (shading for 1σ).
- **Constrained best-fit scheme has shorter soil deposition timescales for perturbations in the SH** → implies smaller GWP for these emissions compared with prototype scheme (SH emission GWPs are higher than NH, Derwent (2023)).



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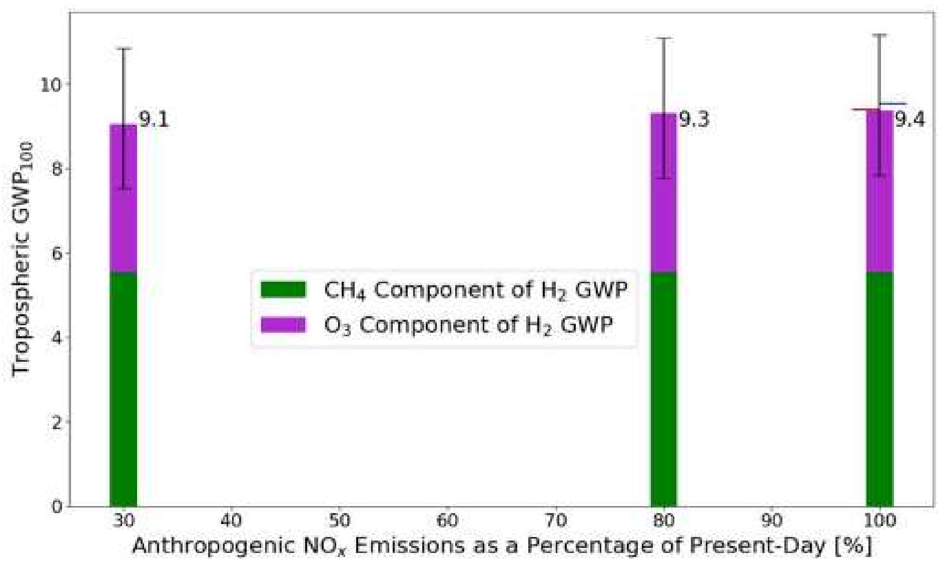
Impacts of hydrogen on tropospheric ozone and methane and their modulation by atmospheric NOx

Hannah N. Bryant[1]*, David S. Stevenson[1], Mathew R. Heal[2] and Nathan Luke Abraham[3,4]

Published last week



We find that the tropospheric GWP_{100} Changes very little for large differences in background NOx.

Suggests changes in background composition will have little effect on the GWP_{100} value for H2.

Summary

H_2 climate impact depends on:

- Production method (Grey, Blue, Green, …CO_2 and CH_4 emissions)
- Leakage rate of H_2 (and CH_4 for non-Green H_2)
- Distribution methods (conversion to NH_3?)
- Climate effect of leaked H_2 is partly encapsulated by the GWP for H_2
  - Large uncertainty soil sink – constrain using global models/measurements
  - Large effect from clouds/aerosols, when we use ERFs
  - Checking GWP methodology and several other factors
- End usage (fuel cell vs combustion – NO_x)

…also impacts on air quality and stratospheric ozone

Much to check to ensure H_2 really is a "clean" fuel…

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HYway

CLIMATE IMPACTS OF A HYDROGEN ECONOMY:
The pathway to knowledge

hywayhorizon.eu

Hydrogen Environmental Impacts Programme
a UKRI/NERC & DESNZ programme

h2envimpacts.org.uk

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