Quantifying radiative forcing impacts of a shift to a hydrogen economy using a chemistry-climate model

Paul Griffiths, James Keeble

Nicola Warwick, N. Luke Abraham, Fiona M. O'Connor

Keith Shine, Alex Archibald, John Pyle, Peter Coleman

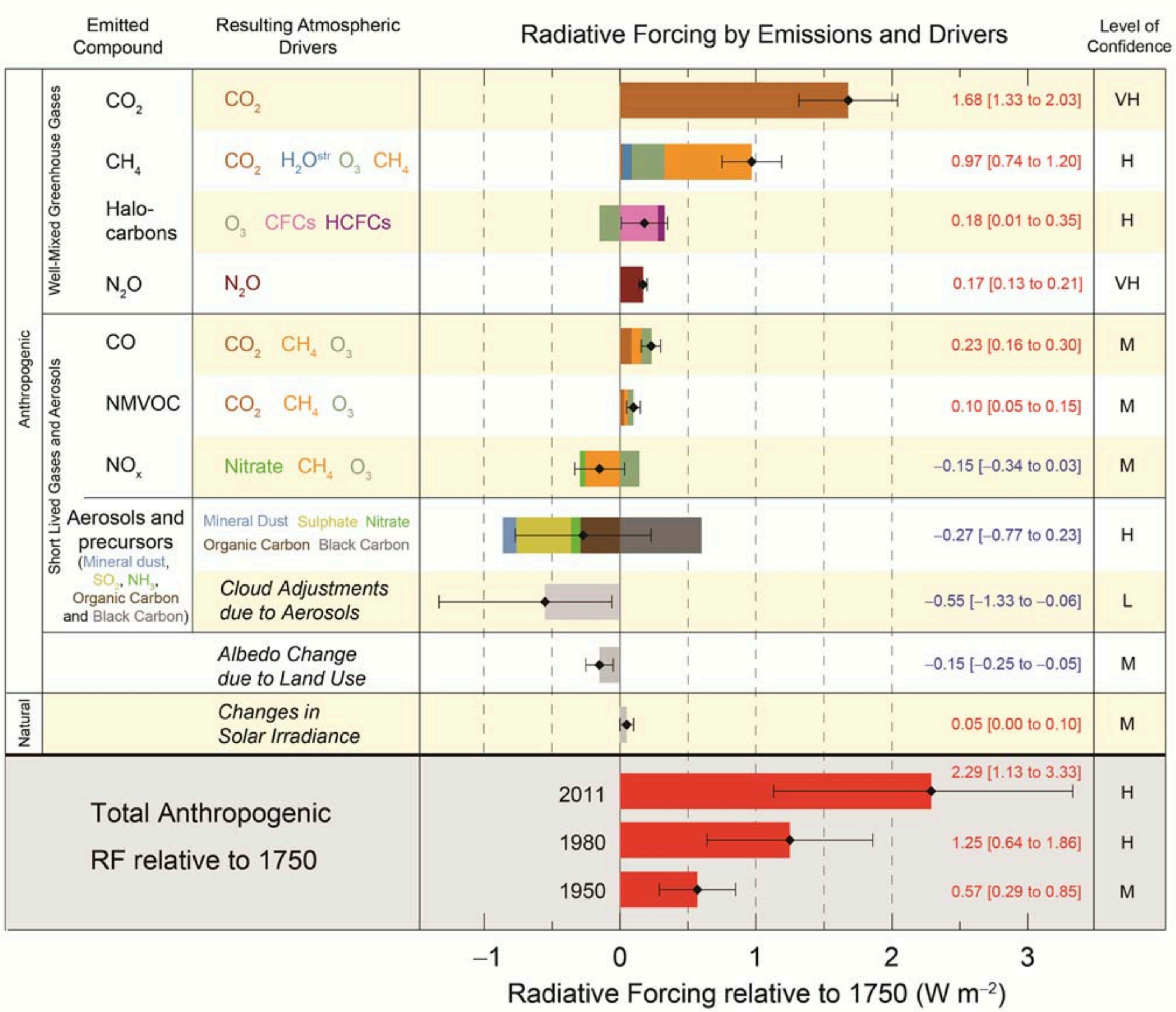
paul.griffiths@atm.ch.cam.ac.uk

Slides available at

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

paultgriffiths

Effective radiative forcing - CMIP5 picture

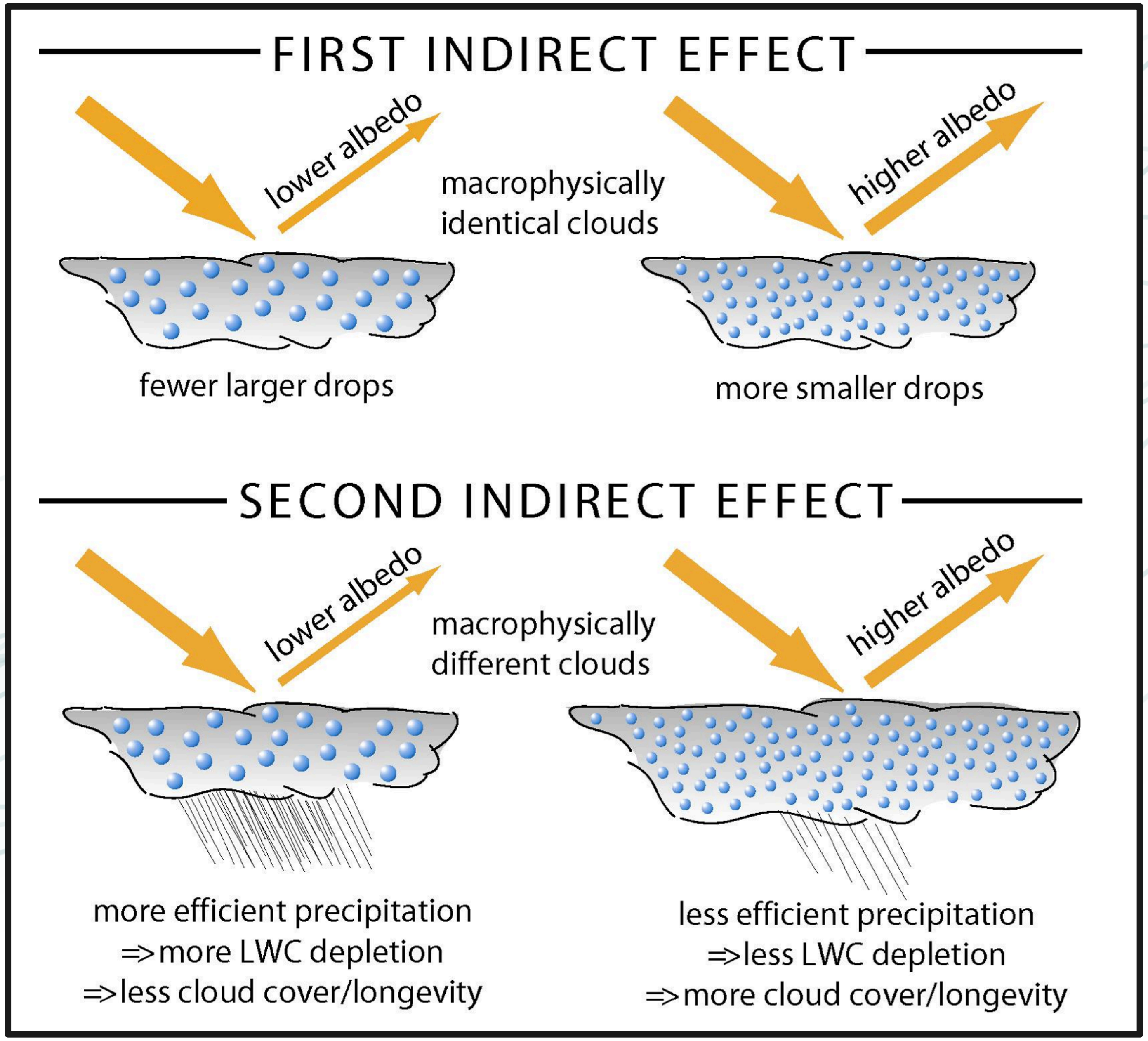


- The radiative forcing can be used to estimate the resulting global temperature change via

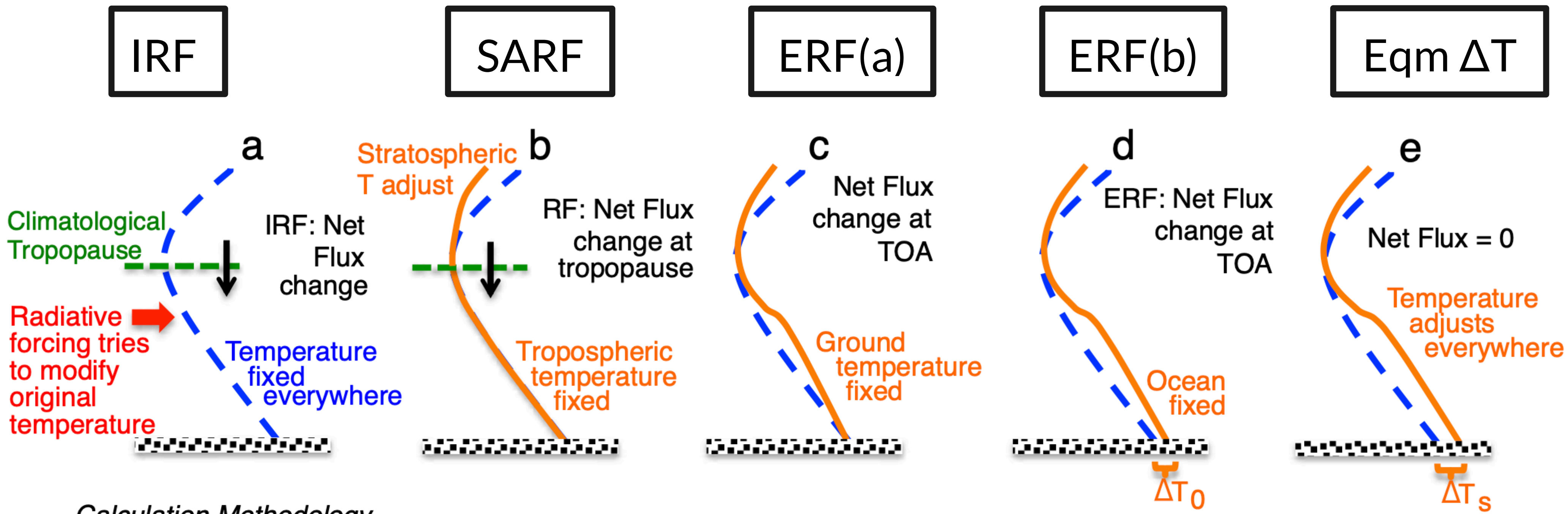
$$\Delta F = \lambda \Delta T$$

Cloud radiative properties respond to aerosol changes

- Aerosol (CCN) controlled by atmospheric oxidation of gases like SO2, biogenic emissions, NOx.
- Clouds form on the aerosol (CCN) present in the atmosphere
- The cloud properties are sensitive to the number of aerosols
  - more aerosol → more cloud droplets
- More droplets means
  - a brighter cloud
  - a longer cloud lifetime
- Leading to negative forcing (increased energy at the top of the atmosphere) and less energy reaching the surface



Effective radiative forcing - definitions



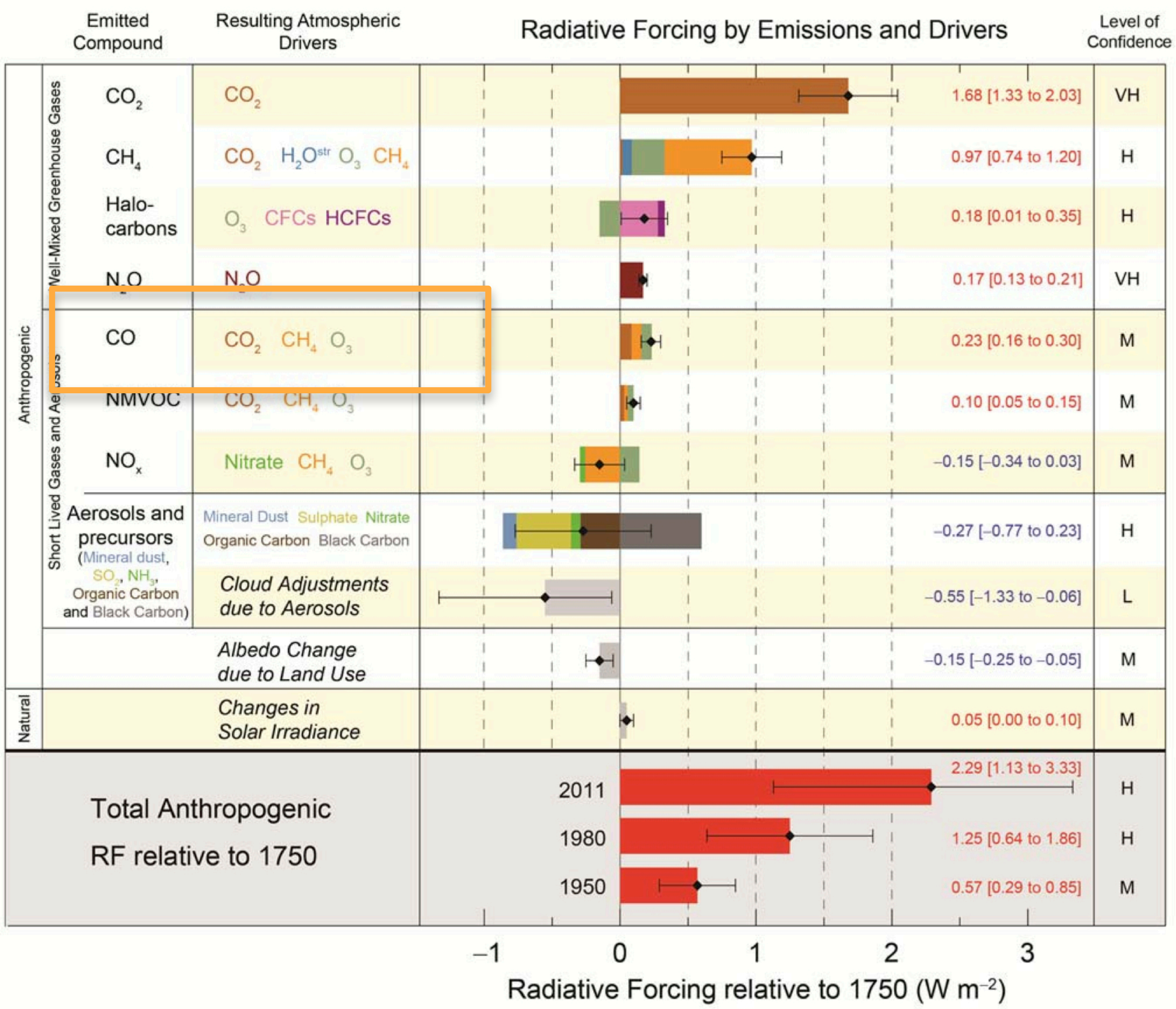
Calculation Methodology

IRF	SARF	ERF(a)	ERF(b)	Eqm ΔT
Online or offline pair of radiative transfer calculations within one simulation	Difference between two offline radiative transfer calculations with prescribed surface and tropospheric conditions allowing stratospheric temperature to adjust	Difference between two full atmospheric model simulations with prescribed surface conditions everywhere or estimate based on regression of response in full coupled atmosphere-ocean simulation	Difference between two full atmospheric model simulations with prescribed ocean conditions (SSTs and sea ice)	Difference between two full coupled atmosphere-ocean model simulations

$$\Delta F = \lambda \Delta T$$

- Calculation of ERF (Wm^{-2}) as the change in energy flux at the top of the atmosphere following a perturbation (natural or anthropogenic).
- ERF includes all the tropospheric and land-surface adjustments - all the responses on a short timescale that occur as a result of the forcing agent, distinct from the slow feedbacks that arise due to temperature perturbations.

Effective radiative forcing - anthropogenic emissions



- Anthropogenic emissions affect the concentration of radiatively important gases such as CH4, O3
- Oxidants such as O3 also affect aerosol formation which can also perturb cloud properties
- ERF = ΔCS + ΔCRE - clear-sky (GG-dominated in the long wave) + Cloud Radiative Effects

Atmospheric chemistry of H_2

- H_2 emissions occur at the surface from a variety of sources
- The lifetime of H_2 is controlled by physical deposition at the surface (H_2 is removed predominantly by soil uptake) but atmospheric chemistry plays a role
- Present-day sources

Sources	Fossil fuel	Biomass burning	N_2 fixation	Photochemical production	Total
Strength / Tg per yr	17 ± 4	15 ± 6	9 ± 3	36 ± 7	76 ± 10

- Present day sinks

Sinks	Photochemical removal	Uptake by soil	Total
Strength / Tg per yr	23 ± 8	50 +30 / -20	70 ± 30

- Low temperature combustion in the atmosphere (without the 'squeaky pop')
- Giving an atmospheric burden of 155 Tg H_2, a mean mixing ratio of 550 ppb and a lifetime of 2.5 years

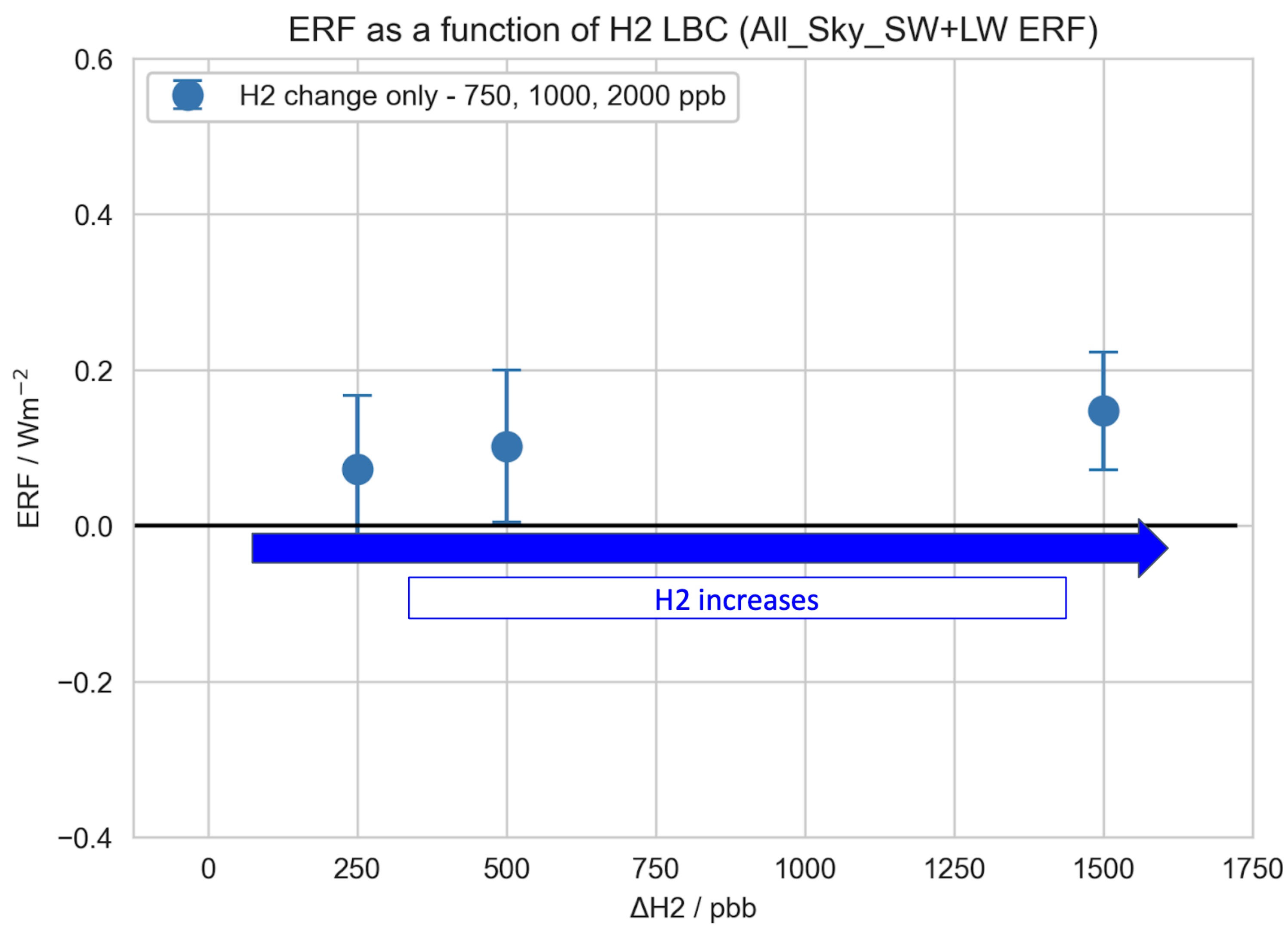
Scenarios studied

1. H_2 leakage emissions increase as a result of a move to H_2 as a fuel source.
    - 750 ppb, 1000 ppb and 2000 ppb (approx increase from 76 Tg to >200 Tg H_2 emissions)
2. Adoption of H_2 as a fuel source means that there is a co-benefit of reduction in other anthropogenic emissions such as CO, NOx, NMVOCs.
    - Consider this under low-H_2 and high-H_2 leakage scenarios
3. Adoption of H_2 as a fuel source means there are CH_4 emissions decreases and other other anthropogenic emissions such as CO, NOx, NMVOCs
    - Consider this under low-H_2 and high-H_2 leakage scenarios

- Using the UKCA chemistry-climate atmospheric model (a component of the UK's CMIP6 Earth System Model)
    - Numerical experiments with different levels of H_2 to capture different leakage scenarios.
    - Atmospheric conditions representative of year 2014 - uses standard forcings.
    - Hold sea-surface temperatures constant to focus the radiative response onto the ERF, method (c). Gives us numbers comparable to IPCC assessments.

Scenarios studied - what is the effect of H2 fugitive emissions?

- Experiments with varying H2 concentration in the atmosphere.
- The radiative forcing increases with increasing H2 concentration, and is positive = a warming. Maybe a plateau?
- For the highest leak rates (an effective tripling of the global atmospheric H2 source) ERF = 0.15 ± 0.08 Wm^{-2} which is approx 5% of the warming effect of CO2
- Increasing H2 levels see increases in methane lifetime and in ozone burden - can expect positive GG forcing.
- Increasing H2 levels leads to decreased OH
- Potential impacts on stratospheric ozone.
- How to attribute the RF increase?



Experiment	H2 LBC	OH	TAU CH4	O3 Burden
	ppb	$10^6 cm^{-3}$	Years	Tg
Base	500	1.22	8.48	348.6
TS2014_750H2	750	1.20	8.67	347.3
TS2014_1000H2	1000	1.18	8.83	349.7
TS2014_2000H2	2000	1.11	9.46	353.5

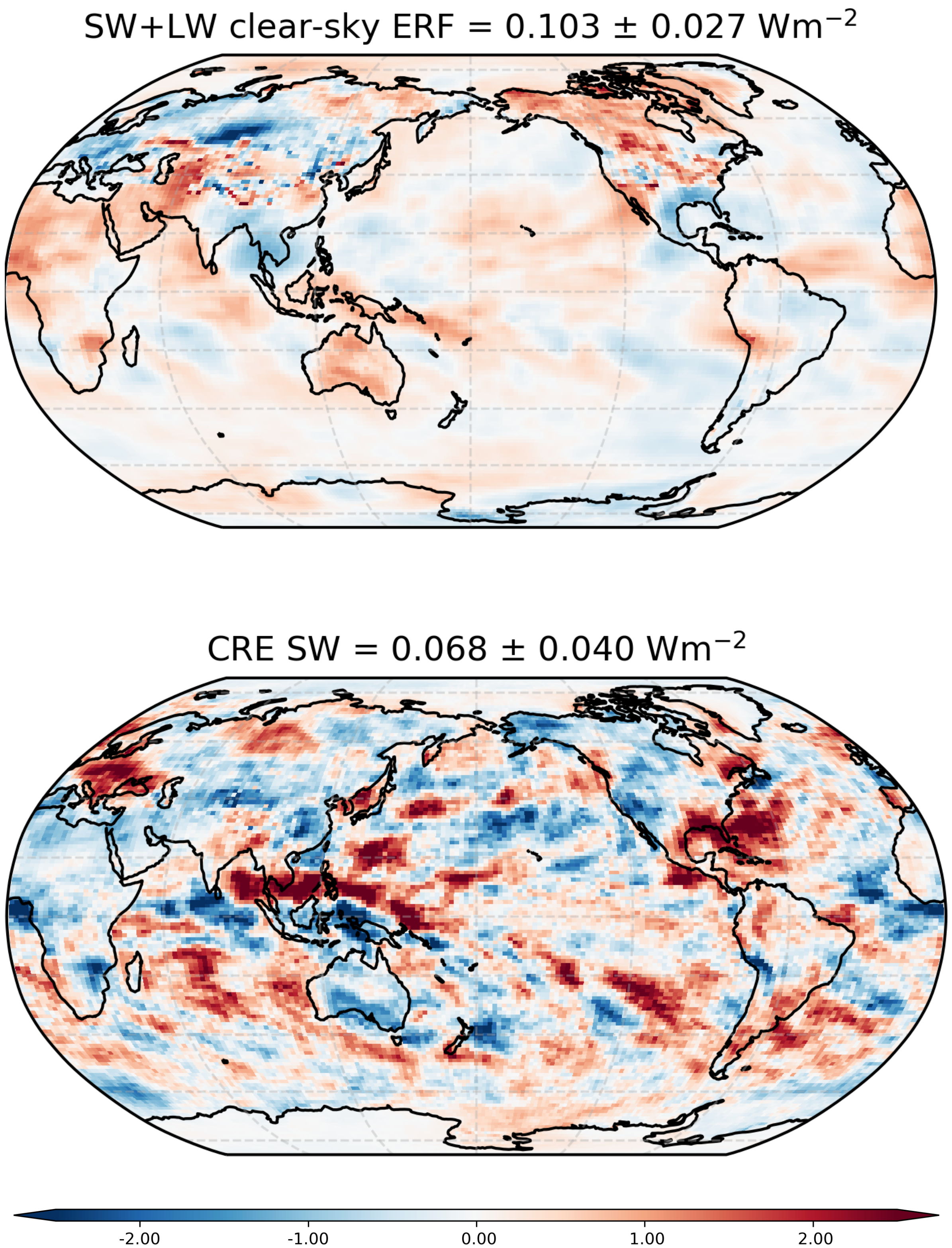
Breaking ERF down into clear-sky and cloud effects

- Can break the change in radiative flux at the top of the atmosphere down further

- The change in the greenhouse gas forcing, a.k.a. the Clear Sky (cloud-free) forcing
  - ERF = 0.103 Wm^{-2}
  - Presumably from the small increase in tropospheric ozone (a greenhouse gas)

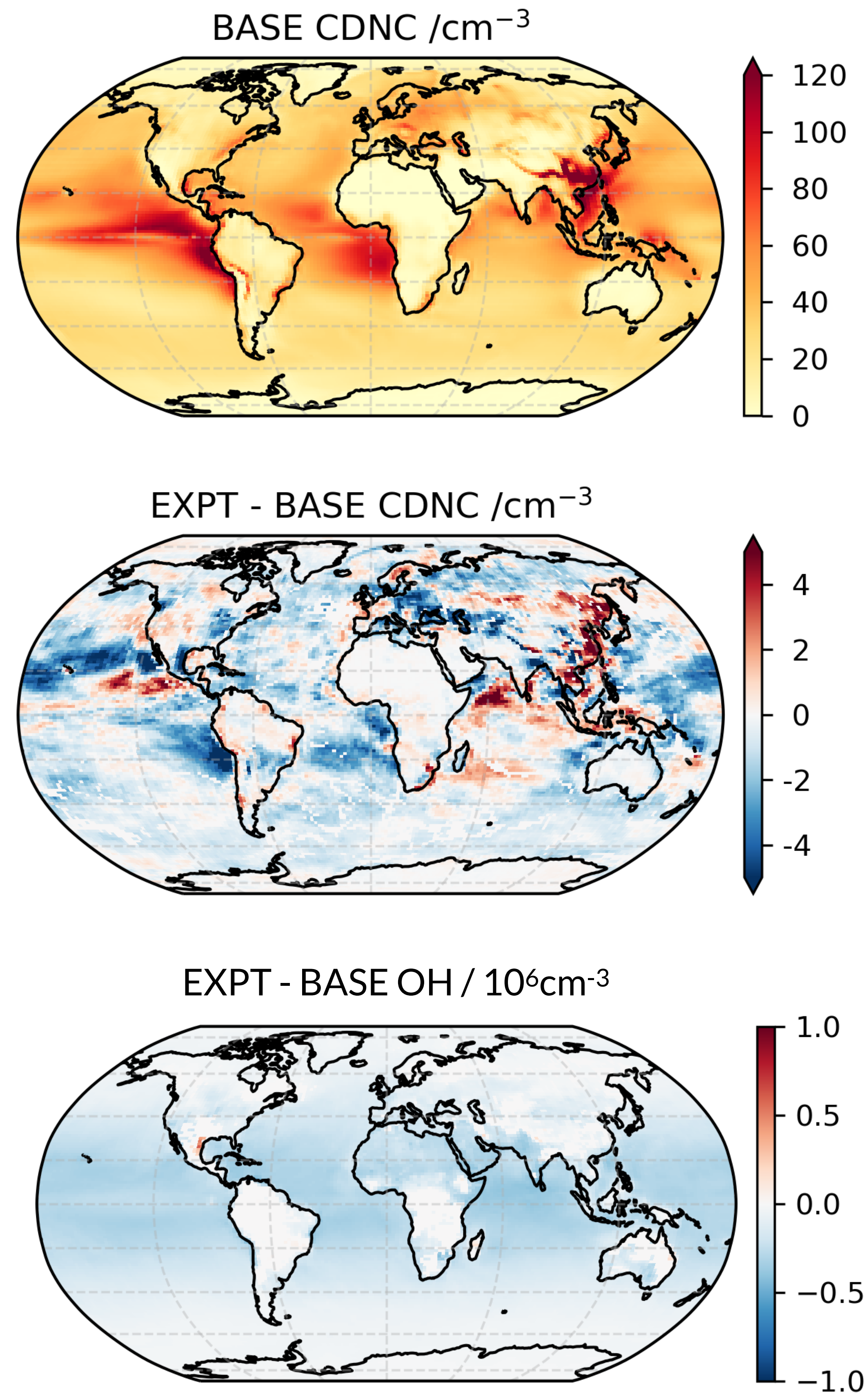
- The change in the radiative properties of the clouds (global averaged effects)
  - ΔCRE = 0.036 Wm^{-2}
- Which can be broken down further
  - Shortwave ΔCRE = 0.068 Wm^{-2}
  - Longwave ΔCRE = -0.032 Wm^{-2}

- i.e. the clear sky forcing is of the same order as the cloud radiative effect



Breaking ERF down into clear-sky and cloud effects

- The additional H2 has caused a decrease in cloud droplet number concentration (CDNC).
- Fewer droplets mean that each has a larger amount of water per droplet, these larger droplets are less reflective and the planetary albedo has slightly decreased.
- We can associate this decrease with lower levels of the OH free radical oxidant in the region where aerosol is formed. There are fewer aerosol particles as a result.
- The effect of elevated H2 is to suppress OH, and this is having knock-on effects on aerosol and on other components (e.g. CH4 and O3).



Conclusions

- H2 couples into the radiative budget of the Earth via its effect on atmospheric oxidants
  - Overall, H2 functions as a source of ozone which is a greenhouse gas
  - H2 is also a sink for OH, which is an important atmospheric oxidant
  - This affects
    - CH4 - increased H2 leads to less OH and a reduced sink for CH4 - CH4 levels would be expected to increase with a positive forcing
    - Aerosol formation process - increased H2 leads to less OH and so less efficient formation of CCN. This has an impact on cloud properties.

- From our studies of other scenarios, we conclude
  - Controlling H2 fugitive emissions is important
  - The effect of H2 on CH4 can be strong - for 2000 ppbv H2, the H2 is affecting CH4 lifetime and increasing CH4 levels significantly.
  - H2 use with strongly controlled leaks can lead to significant benefits, due to reduce co-emissions of CO, NOx and NMVOCs.

Thank you for your attention

Thank you

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Table 1. Major global tropospheric sources and sinks of H_2 (Tg H_2 yr^{-1}) from various authors

	Novelli et al. (1999)	Hauglustaine and Ehhalt (2002)	Sanderson et al. (2003)	Rhee et al. (2006a)	Price et al. (2007)	Xiao et al. (2007)	This work
Fossil fuel	15 ± 10	16	20.0	15 ± 6	18.3	15 ± 10	11 ± 4
Biomass burning	16 ± 5	13	20.0	16 ± 3	10.1	13 ± 3	15 ± 6
Biofuel					4.4		
N_2 fixation, ocean	3 ± 2	5	4.0	6 ± 5	6.0		6 ± 3
N_2 fixation, land	3 ± 1	5	4.0	6 ± 5	0		3 ± 2
Photochemical production							
from methane	26 ± 9		15.2		24.5		23 ± 8
from VOC	14 ± 7		15.0		9.8		18 ± 7
total	40	31	30.2	64 ± 12	34.3	77 ± 10	41 ± 11
Sources total	77 ± 16	70	78.2	107 ± 15	73	105 ± 10	76 ± 14
Oxidation by OH	19 ± 5	15	17.1	19 ± 3	18	18 ± 3	19 ± 5
Soil uptake	56 ± 41	55	58.3	88 ± 11	55 ± 8.3	85 ± 5	60^{+30}_{-20}
Sinks total	75 ± 41	70	75.4	107 ± 11	73	105[a]	79^{+30}_{-20}
Tropospheric Burden, Tg H_2	155 ± 10	136	172[b]	150[c]	141	149 ± 23	155[d] $\pm$ 10
Tropospheric Lifetime, yr	2.1	1.9	2.2[b]	1.4	1.9	1.4	2.0

[a]Includes export to stratosphere of 1.9 Tg H_2 yr^{-1}.

[b]Model domain reached 100 hPa; thus the burden includes about 1/2 of the stratosphere. Reduced to a troposphere holding 0.82 of the total air mass the burden would be 157 Tg H_2 and the tropospheric lifetime 2.0 yr.

[c]Calculated from sources and lifetime.

[d]From Novelli et al. (1999).

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL