Inherent Uncertainty Disguises Attribution of Reduced Atmospheric CO$_2$ Growth to Emission Reductions for up to a Decade

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This talk will also be delivered by videoconferencing Friday May 8th 17:45 via zoom. You can find the agenda here and you can sign up here.
The global carbon cycle is sensitive towards climate-driven internal variability, which might obscure the identification of changes in anthropogenic emissions.

- Long-term dominance of the forced signal undisputed
- When are emission reductions detectable in atmospheric CO$_2$ measurements?
  - Policy-relevant when emission reduction efficacy is assessed by global stocktake.
  - COVID19 signal not yet detectable at Mauna Loa
- On which time-scales does internal variability in atmospheric CO$_2$ dominate over changes in the forced signal?
Research questions: Inherent uncertainty in atmospheric CO$_2$ projections and attribution of emission reductions

- On what time-scales are trend reductions in atmospheric CO$_2$ attributable to emission reduction?
  - What is the probability that even if emissions are reduced, the trend in atmospheric CO$_2$ keeps rising even stronger?
  - How many years after reduced emissions can we be certain that these reduced emissions caused a reduction in atm. CO$_2$ trend?
MPI-ESM Grand Ensemble provides a 1% resolution in climate event attribution [Marotzke, 2019].

- Uninitialised ensemble to separate internal variability from forced signal [Maher et al., 2019]:
  - 100 ensemble members from piControl
  - 3 scenarios

- Causal Theory [Hannart et al. 2016]
  - Factual world
  - Counter-factual world
  - Necessary and sufficient causality

- MPI-ESM1.1-LR historical + RCPs
  - Atmosphere & Land: T63 (1.8°)
  - Ocean: GR15 (1.5°)
  - prescribed atmospheric CO$_2$ forcing
Diagnosing global atmospheric CO\textsubscript{2} variations from the prescribed CO\textsubscript{2} signal and the global carbon sinks ensemble mean residuals.

\[
X_{\text{CO}_2, \text{atm}}(t) = \sum_{t' = t_{\text{start}}}^{t} (\text{CO}_2 \text{flux'}(t')) \text{ppm} \frac{2.12 \text{ PgC}}{\text{yr}} + \text{forcing}(t) \]

Assumptions:

- Instantaneous global atmospheric mixing [Ballantyne et al. 2012]
- Internal variability of carbon cycle driven by climate variability
- Disregards short-term influence of atm. CO\textsubscript{2} variability on carbon cycle
Where are we?

Global fossil-fuel emissions (gigatonnes of CO₂)

1.5 °C
Mitigation required to meet Paris goals (SSP1-1.9) [Hausfather and Peters, 2020]

2.5 °C
Modest mitigation (SSP2-4.5)

3 °C
Weak mitigation (SSP4-6.0)

4 °C
Average no policy (SSP3-7.0)

5 °C†
Worst-case no policy (SSP5-8.5)‡

Historical emissions
Pledged policies
Current policies

Highly unlikely
Often wrongly used as ‘business as usual’

Unlikely
Reversal of some current policies

Likely
Given current policies

IEA* projections suggest a more plausible path.
The MPI-ESM Grand Ensemble provides a 2°C Target (RCP2.6) and current pathway (RCP4.5) scenario with diverging CO₂ forcing after 2020.

- Expected climate response to emission cuts: decrease in atm. CO₂ trend
- Uninitialised large ensemble simulations:
  - 100 ensemble members
  - 2 scenarios:
    - RCP2.6: emission reduction to reach Paris goals
    - RCP4.5: current: no emis. reductions before 2040
    - Emission cuts as policy change from RCP4.5 to RCP2.6
- Probabilities of reduction in 5-year trends

\[
P_{RCPx} = \sum_{ens=1}^{100} (trend_{ens}^{2016-2020} > trend_{ens}^{2021-2025}) \%\]

[adopted from Marotzke, 2019]
Atmospheric CO$_2$ 5-year trends might even increase despite of implemented mitigation policy due to internal variability.
Three facets of causation

- **necessary**
  - without switch C₁, bulb E is off. Yet C₁ not always turns on E as C₂ is also required
  - ask retrospectively whether policy change was necessary

- **sufficient**
  - bulb E is lit every time C₁ is turned on. Yet if C₁ is off E might still be lit by C₂
  - ask in advance whether a policy change would be sufficient to cause a trend reduction

- **necessary and sufficient**
  - turning on C₁ always lights E, and E may not be lighted unless C₁ is on.
  - policy change is both necessary and sufficient

\[ P_N = 1 - \frac{P_{RCP4.5}}{P_{RCP2.6}} = 0.31 \]

\[ P_S = \frac{P_{RCP2.6} - P_{RCP4.5}}{1 - P_{RCP4.5}} = 0.42 \]

\[ P_{NS} = P_{RCP2.6} - P_{RCP4.5} = 0.22 \]

Switch C₁ = policy change from RCP4.5 to RCP2.6
Switch C₂ = internal variability (less natural outgassing)
Light bulb E = reduced atm. CO₂ trends

[Pearl 2020, Hannart et al. 2018]
Reduced emissions are certain to cause reduced trends in atmospheric CO₂ in a sufficient causation sense when considering 10-year trends.

- Ask in advance whether a policy change would be **sufficient** to cause a trend reduction:
  
  \[ P_S = \frac{P_{RCP2.6} - P_{RCP4.5}}{1 - P_{RCP4.5}} \]

- Ask retrospectively whether policy change was **necessary**:
  
  \[ P_N = 1 - \frac{P_{RCP4.5}}{P_{RCP2.6}} \]

- Policy change from RCP4.5 to RCP2.6 is both **necessary and sufficient**:
  
  \[ P_{NS} = P_{RCP2.6} - P_{RCP4.5} \]
Take home messages: Inherent uncertainty in atmospheric CO$_2$ projections might disguise emission reduction effects up to a decade.

- Policy change from RCP4.5 to RCP2.6 is **sufficient** to cause 5-year CO$_2$ trend reduction with P=42% and **necessary** with P=31% and **necessary and sufficient** with P=22%.

- These probabilities, when covering the time-scales of the global stocktake, are **far from certain**.

- Certainty is reached after 10 (**sufficient** causation) and 15 (**necessary** c.) years.

- Results are based on one model. All models have internal variability.

- This influence of internal variability in atm. CO$_2$ on sub-decadal time-scales in emission reduction attribution is challenging to communicate to the public.
References

Assumptions about diagnosed atmospheric CO2

\[ X_{CO2,atm}(t) = \sum_{t'=t_{start}}^{t} (CO2_{flux}'(t')) \frac{ppm}{2.12 \text{PgC}} + \text{forcing}(t) \]

- = time mean control
- = member mean

Assumptions:

- Instantaneous global atmospheric mixing: conversion factor 2.12 PgC to 1 ppm [Ballantyne et al. 2012]
- Internal variability driven by climate-induced variability (temperature effect on biogeochemistry, circulation changes, …)
- Ignores short-term terrestrial CO2 fertilisation effect and oceanic sensitivity to variability in CO2 (as all concentration-driven experiments)
- Same approach as diagnosing compatible emissions from concentration-driven simulations [Jones, 2013] but “backwards”
Verification: Diagnosing global atmospheric CO$_2$ variations tracks actual global atm. CO$_2$ concentrations in emission-driven simulations.

$$X_{CO_2, atm}(t) = \sum_{t' = t_{start}}^{t} \left( CO_2_{flux}'(t') \right) \frac{ppm}{2.12 \text{ PgC}} + \text{forcing}(t)$$

- $t_{start}$ = time mean control
- $t$ = Historical: CO$_2$,atm forcing (IAM)
- $t'$ = member mean
- $t'$ = esmHistorical: member mean CO$_2$,atm

Verification of detrended diagnostic CO$_2$,atm with prognostic from a 9-member CMIP6 esmHistorical MPI-ESM ensemble
MPI-ESM Grand Ensemble simulates a realistic range of the atmospheric CO$_2$ annual growth rate.

**Growth Rate of atmospheric CO$_2$ 1958-2018**

- **MPI-ESM GE modelled global diagnostic CO$_2$ Growth Rate**
- **NOAA ESRL Mauna Loa Annual CO$_2$ Growth Rate**

**Modelled vs Observed CO$_2$ Growth Rate**

- **modelled**
  - count: 6000.00
  - mean: 1.54
  - std: 0.85
  - min: -1.34
  - 25%: 0.95
  - 50%: 1.54
  - 75%: 2.12
  - max: 4.50

- **observed**
  - count: 60.00
  - mean: 1.58
  - std: 0.87
  - min: 0.28
  - 25%: 1.04
  - 50%: 1.52
  - 75%: 2.04
  - max: 3.01

**Graphs**

- **Histogram** showing the growth rate distribution with modelled and observed data.
- **Time series** plot showing the annual growth rate from 2004 to 2014 with NOAA observations.
Differences in prescribed forcing

Intro - Methods - Results - Conclusion
emissions over time in RCP scenarios