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.

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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?
  - COVID19 signal not yet detectable at Mauna Loa [@PFriedling]
  - Policy-relevant when emission reduction efficacy is assessed by global stocktake.
- On which time-scales does internal variability in atmospheric CO$_2$ dominate over changes in the forced signal?

![Graph showing CO$_2$ emissions and variability](Peters et al. 2017 Figs. 1&2)
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 [Pearl 2020, 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 CO₂ forcing

Intro - Methods - Results - Conclusion
Diagnosing global atmospheric CO$_2$ variations from the prescribed CO$_2$ signal and the global carbon sinks ensemble mean residuals.

\[
\text{XCO}_2(t) = \sum_{t'=t_{\text{start}}}^{t} \left( \text{CO}_2\text{flux}'(t') \right) \frac{\text{ppm}}{2.12 \text{ PgC}} + \text{forcing}(t)
\]

- = time mean control
- = member mean

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$_2$ variability on carbon cycle
Where are we?

- **5 °C**
  - Worst-case no policy (SSP5–8.5)
  - [Hausfather and Peters, 2020]

- **4 °C**
  - Average no policy (SSP3–7.0)

- **3 °C**
  - Weak mitigation (SSP4–6.0)

- **2.5 °C**
  - Modest mitigation (SSP2–4.5)

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

**IEA** projections suggest a more plausible path.

**Likely**
- Given current policies

**Unlikely**
- Reversal of some current policies

**Highly unlikely**
- Often wrongly used as ‘business as usual’
The MPI-ESM Grand Ensemble provides a **Paris targets (RCP2.6)** and **current pledges 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

\[ P_{RCPx} = \sum_{ens=1}^{100} \left( \text{trend}_{ens}^{2016-2020} > \text{trend}_{ens}^{2021-2025} \right) \% \]

[adopted from Marotzke, 2019]
Atmospheric CO₂ 5-year trends might even increase despite of implemented emission reductions policy due to internal variability.

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Three facets of causation

Does policy change cause reduced atm. CO$_2$ trends?

- **necessary causation**
  - Without switch C$_1$, bulb E is off. Yet C$_1$ not always turns on E, as C$_2$ is also required
  - ask retrospectively whether policy change was **necessary**

- **sufficient causation**
  - Bulb E is lit every time C$_1$ is turned on. Yet if C$_1$ is off, E might still be lit by C$_2$
  - ask in advance whether a policy change would be **sufficient** to cause a trend reduction

- **necessary and sufficient causation**
  - Turning on C$_1$ always lights E, and E may not be lighted unless C$_1$ is on.
  - policy change is both **necessary and sufficient** $P_{NS} = P_{RCP2.6} - P_{RCP4.5} = 0.22$

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Switch C$_1$ = policy change from RCP4.5 to RCP2.6
Switch C$_2$ = internal variability (no strong natural C outgassing)
Light bulb E = reduced atm. CO$_2$ trends

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

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

\[
P_N = 1 - P_{RCP4.5} = 0.42
\]
Reduced emissions are certain to cause reduced trends in atmospheric CO$_2$ 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:

$$P_N = 1 - \frac{P_{RCP4.5}}{P_{RCP2.6}}$$

Ask retrospectively whether policy change was **necessary**:

$$P_S = \frac{P_{RCP2.6} - P_{RCP4.5}}{1 - P_{RCP4.5}}$$

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**) years.
- Results are based on one model. All models have internal variability.
- Policy-makers should be informed by initialized predictions about near-term internal variability in atmospheric CO$_2$ evolution [Spring and Ilyina, 2020].
- 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

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

- 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”

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Verification: Diagnosing global atmospheric CO\textsubscript{2} variations tracks actual global atm. CO\textsubscript{2} concentrations in emission-driven simulations.

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

- \text{time mean control}
- \text{Historical: CO}_2,\text{atm} \text{ forcing (IAM)}
- \text{member mean}
- \text{esmHistorical: member mean CO}_2,\text{atm}

Verification of detrended diagnostic CO\textsubscript{2, atm} with prognostic from a 9-member CMIP6 esmHistorical MPI-ESM ensemble

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MPIESM Grand Ensemble simulates a realistic range of the atmospheric CO$_2$ annual growth rate.

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

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