~~Causal~~ Causal inference for the impacts of policy on air pollution

Congbo Song[1], Bowen Liu[2], Kai Cheng[2], Matthew A. Cole[2], Qili Dai[3], Robert J.R. Elliott[2], Zongbo Shi[1]

[1]School of Geography, Earth and Environmental Science, University of Birmingham, Birmingham, B15 2TT, UK

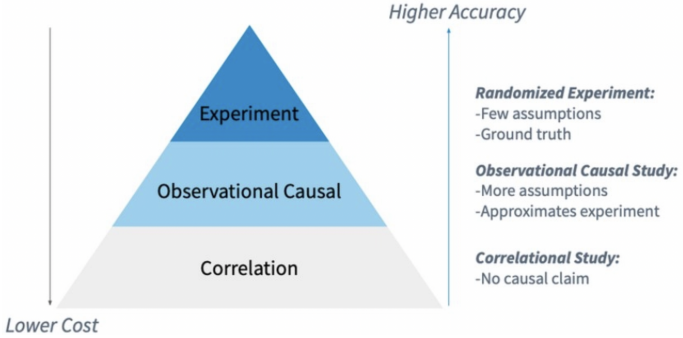
[2]Department of Economics, University of Birmingham, Birmingham B15 2TT, UK

[3]College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China

Winter School 2021 on Data Science for Climate and Air Quality Research
December 15, 2021

Definition of causal inference[1]

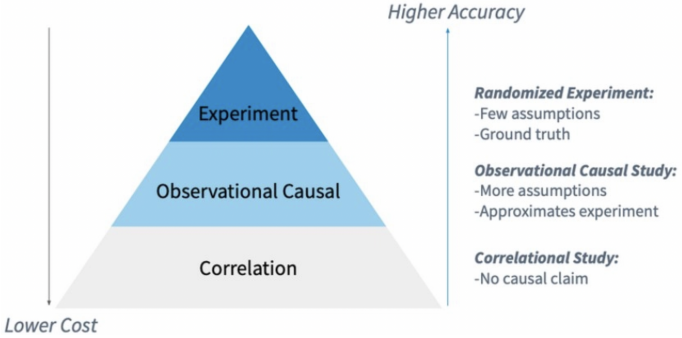
Causal inference is about inferring the cause of something by eliminating plausible alternative causes. Casual inference $\neq$ Inference of association, causal inference analyzes the response of an effect variable when a cause of the effect variable is changed. "Causal inference" is the winner of 2021 Nobel Prize in Economics.



[1] Wikipedia contributors (2021). Causal inference — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Causal_inference&oldid=1050494098. [Online; accessed 11-December-2021].

Definition of causal inference[1]

Causal inference is about inferring the cause of something by eliminating plausible alternative causes. Casual inference $\neq$ Inference of association, causal inference analyzes the response of an effect variable when a cause of the effect variable is changed. "Causal inference" is the winner of 2021 Nobel Prize in Economics.



- Epidemiological studies
- Economics and social science
- Atmospheric Science?

[1] Wikipedia contributors (2021). Causal inference — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Causal_inference&oldid=1050494098. [Online; accessed 11-December-2021].

Empirical analysis from observations[2]

A number of the empirical work in economics about policy questions are based on **observational causal** rather than **randomized experiment**. Inferring causal effect of a policy from observational data is quite challenging.

[2] Susan Athey and Guido W. Imbens (May 2017b). "The State of Applied Econometrics: Causality and Policy Evaluation". In: Journal of Economic Perspectives 31.2, pp. 3–32. DOI: 10.1257/jep.31.2.3.

Empirical analysis from observations[2]

A number of the empirical work in economics about policy questions are based on **observational causal** rather than **randomized experiment**. Inferring causal effect of a policy from observational data is quite challenging.

The widely used approaches include:

- Regression discontinuity (RD) design
- Differences in differences (DID)
- Synthetic control method (SCM)
- ...

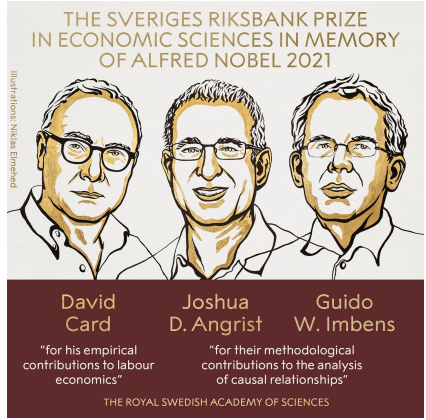
[2] Susan Athey and Guido W. Imbens (May 2017b). "The State of Applied Econometrics: Causality and Policy Evaluation". In: Journal of Economic Perspectives 31.2, pp. 3–32. DOI: 10.1257/jep.31.2.3.

Empirical analysis from observations[2]

A number of the empirical work in economics about policy questions are based on **observational causal** rather than **randomized experiment**. Inferring causal effect of a policy from observational data is quite challenging.

The widely used approaches include:

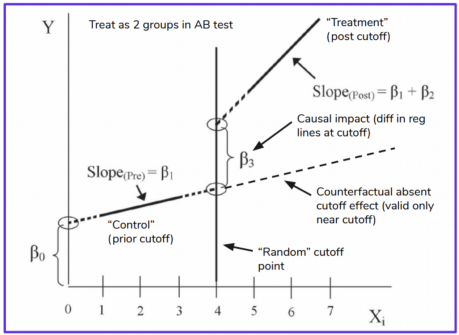
- Regression discontinuity (RD) design
- Differences in differences (DID)
- Synthetic control method (SCM)
- ...



The 2021 Nobel Prize in Economics has been awarded to three scholars for their contribution to empirical analysis and methodological contribution to causal inference.

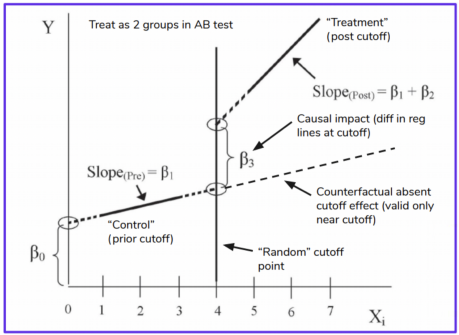
[2] Susan Athey and Guido W. Imbens (May 2017b). "The State of Applied Econometrics: Causality and Policy Evaluation". In: Journal of Economic Perspectives 31.2, pp. 3–32. DOI: 10.1257/jep.31.2.3.

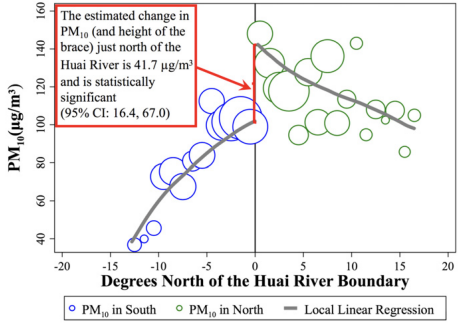
Regression discontinuity (RD) design



[3] Avraham Ebenstein et al. (2017). "New evidence on the impact of sustained exposure to air pollution on life expectancy from Chinas Huai River Policy". In: Proceedings of the National Academy of Sciences 114 (39), pp. 10384–10389. DOI: 10.1073/pnas.1616784114.

Regression discontinuity (RD) design

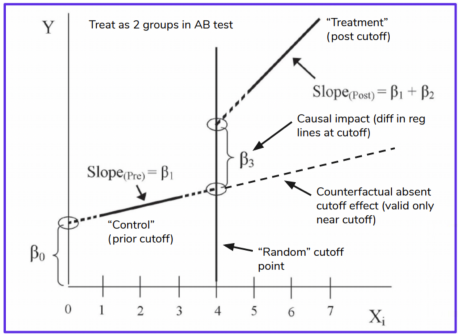


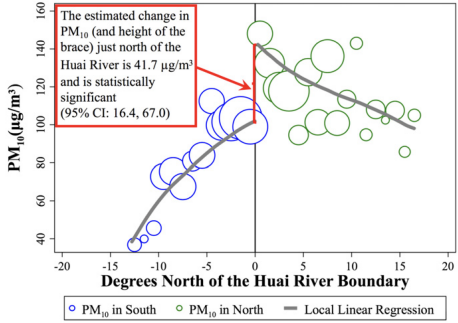


Ebenstein et al. (2017)[3] used RD and found that the estimated change in PM_{10} just north of the Huai River is 41.7 μg m^{-3} and is statistically significant.

[3] Avraham Ebenstein et al. (2017). "New evidence on the impact of sustained exposure to air pollution on life expectancy from Chinas Huai River Policy". In: Proceedings of the National Academy of Sciences 114 (39), pp. 10384–10389. DOI: 10.1073/pnas.1616784114.

Regression discontinuity (RD) design





Ebenstein et al. (2017)[3] used RD and found that the estimated change in PM_{10} just north of the Huai River is 41.7 μg m^{-3} and is statistically significant.

RD needs an obvious cut-off/jump. The estimated effect is the local effect just over the cut-off.

[3] Avraham Ebenstein et al. (2017). "New evidence on the impact of sustained exposure to air pollution on life expectancy from Chinas Huai River Policy". In: Proceedings of the National Academy of Sciences 114 (39), pp. 10384–10389. DOI: 10.1073/pnas.1616784114.

Differences in differences (DID)

- DID studies the differential effect of a treatment on a 'treatment group' versus a 'control group' in a natural experiment.

[4] Guojun He, Yuhang Pan, and Takanao Tanaka (2020). "The short-term impacts of COVID-19 lockdown on urban air pollution in China". In: Nature Sustainability 3 (12), pp. 1005–1011. ISSN: 2398-9629. DOI: 10.1038/s41893-020-0581-y.

Differences in differences (DID)

- DID studies the differential effect of a treatment on a 'treatment group' versus a 'control group' in a natural experiment.
- Causal effects: difference between the average change over time in the outcome variable for the treatment group and that for the control group.

[4] Guojun He, Yuhang Pan, and Takanao Tanaka (2020). "The short-term impacts of COVID-19 lockdown on urban air pollution in China". In: Nature Sustainability 3 (12), pp. 1005–1011. ISSN: 2398-9629. DOI: 10.1038/s41893-020-0581-y.

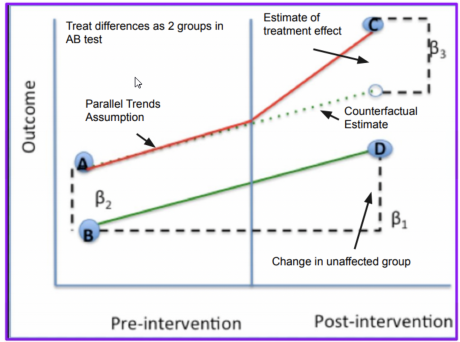
Differences in differences (DID)

- DID studies the differential effect of a treatment on a 'treatment group' versus a 'control group' in a natural experiment.
- Causal effects: difference between the average change over time in the outcome variable for the treatment group and that for the control group.

[4] Guojun He, Yuhang Pan, and Takanao Tanaka (2020). "The short-term impacts of COVID-19 lockdown on urban air pollution in China". In: Nature Sustainability 3 (12), pp. 1005–1011. ISSN: 2398-9629. DOI: 10.1038/s41893-020-0581-y.

Differences in differences (DID)

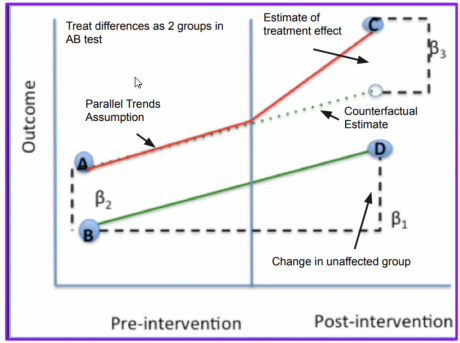
- DID studies the differential effect of a treatment on a 'treatment group' versus a 'control group' in a natural experiment.
- Causal effects: difference between the average change over time in the outcome variable for the treatment group and that for the control group.



[4] Guojun He, Yuhang Pan, and Takanao Tanaka (2020). "The short-term impacts of COVID-19 lockdown on urban air pollution in China". In: Nature Sustainability 3 (12), pp. 1005–1011. ISSN: 2398-9629. DOI: 10.1038/s41893-020-0581-y.

Differences in differences (DID)

- DID studies the differential effect of a treatment on a 'treatment group' versus a 'control group' in a natural experiment.
- Causal effects: difference between the average change over time in the outcome variable for the treatment group and that for the control group.

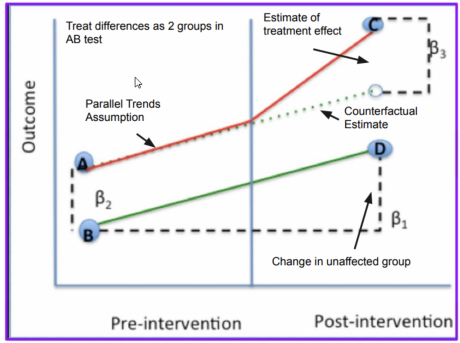


He et al. (2020)[4] used DID to compare air quality in Chinese cities with and without COVID-19 lockdown policies.

[4] Guojun He, Yuhang Pan, and Takanao Tanaka (2020). "The short-term impacts of COVID-19 lockdown on urban air pollution in China". In: Nature Sustainability 3 (12), pp. 1005–1011. ISSN: 2398-9629. DOI: 10.1038/s41893-020-0581-y.

Differences in differences (DID)

- DID studies the differential effect of a treatment on a 'treatment group' versus a 'control group' in a natural experiment.
- Causal effects: difference between the average change over time in the outcome variable for the treatment group and that for the control group.



He et al. (2020)[4] used DID to compare air quality in Chinese cities with and without COVID-19 lockdown policies.

DID requires a parallel trend assumption!

[4] Guojun He, Yuhang Pan, and Takanao Tanaka (2020). "The short-term impacts of COVID-19 lockdown on urban air pollution in China". In: Nature Sustainability 3 (12), pp. 1005–1011. ISSN: 2398-9629. DOI: 10.1038/s41893-020-0581-y.

Synthetic control method (SCM)

The synthetic control method involves the construction of a **weighted combination** of groups used as controls, to which the treatment group is compared. Unlike DID, this method can account for the effects of confounders changing over time, by weighting the control group to better match the treatment group before the intervention.

[5] Susan Athey and Guido W Imbens (May 2017a). "The State of Applied Econometrics: Causality and Policy Evaluation". In: Journal of Economic Perspectives 31 (2), pp. 3–32. DOI: 10.1257/jep.31.2.3.

Synthetic control method (SCM)

The synthetic control method involves the construction of a **weighted combination** of groups used as controls, to which the treatment group is compared. Unlike DID, this method can account for the effects of confounders changing over time, by weighting the control group to better match the treatment group before the intervention.

Susan Athey and Guido W. Imbens (Nobel Prize winner in 2021): The synthetic control approach is arguably the most important innovation in the policy evaluation literature in the last 15 years[5].

[5] Susan Athey and Guido W Imbens (May 2017a). "The State of Applied Econometrics: Causality and Policy Evaluation". In: Journal of Economic Perspectives 31 (2), pp. 3–32. DOI: 10.1257/jep.31.2.3.

Synthetic control method (SCM)

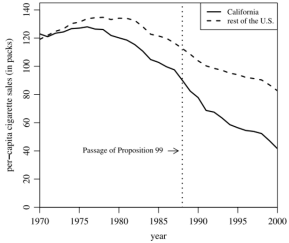


Figure 1. Trends in per-capita cigarette sales: California vs. the rest of the United States.

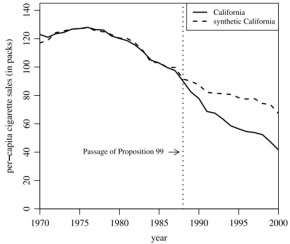


Figure 2. Trends in per-capita cigarette sales: California vs. synthetic California.

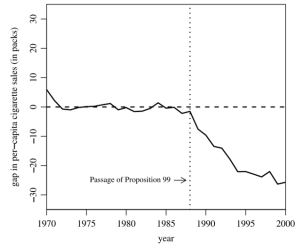


Figure 3. Per-capita cigarette sales gap between California and synthetic California.

Estimating the Effect of California's Tobacco Control Program in 1988 by Abadie et al. (2010)[6].

[6] Alberto Abadie, Alexis Diamond, and Jens Hainmueller (June 2010). "Synthetic Control Methods for Comparative Case Studies: Estimating the Effect of California's Tobacco Control Program". In: Journal of the American Statistical Association 105 (490), pp. 493–505. ISSN: 0162-1459. DOI: 10.1198/jasa.2009.ap08746.

Synthetic control method (SCM)

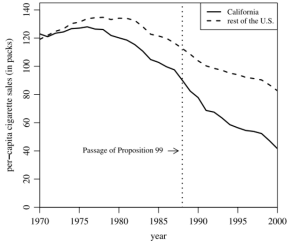


Figure 1. Trends in per-capita cigarette sales: California vs. the rest of the United States.

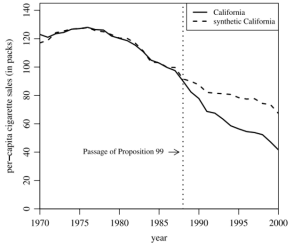


Figure 2. Trends in per-capita cigarette sales: California vs. synthetic California.

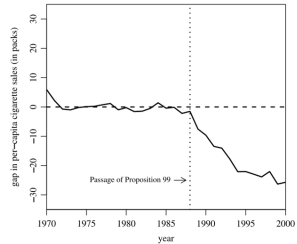


Figure 3. Per-capita cigarette sales gap between California and synthetic California.

Estimating the Effect of California's Tobacco Control Program in 1988 by Abadie et al. (2010)[6].

SCM doesn't require a parallel trend assumption (required by DID), doesn't require a sudden change over the cut-off (required by RD), it has more broad application scenarios.

[6] Alberto Abadie, Alexis Diamond, and Jens Hainmueller (June 2010). "Synthetic Control Methods for Comparative Case Studies: Estimating the Effect of California's Tobacco Control Program". In: Journal of the American Statistical Association 105 (490), pp. 493–505. ISSN: 0162-1459. DOI: 10.1198/jasa.2009.ap08746.

Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns[7]

Zongbo Shi[1], Congbo Song[1], Bowen Liu[2], Gongda Lu[1], Jingsha Xu[1], Tuan Van Vu[3], Robert J.R. Elliott[2], Weijun Li[4], William J. Bloss[1], Roy M. Harrison[1]

[1]School of Geography, Earth and Environmental Science, University of Birmingham, Birmingham, B15 2TT, UK

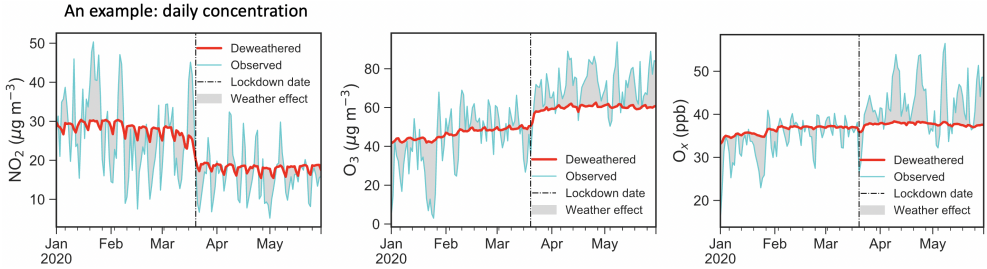
[2]Department of Economics, University of Birmingham, Birmingham B15 2TT, UK

[3]School of Public Health, Imperial College London, London W2 1PG, UK

[4]Department of Atmospheric Sciences, School of Earth Sciences, Zhejiang University, Hangzhou 310027, China

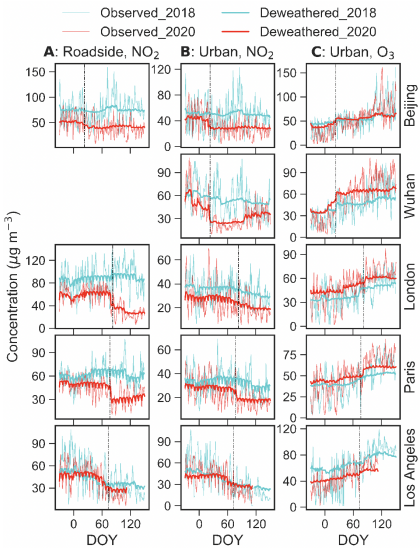
[7]Zongbo Shi et al. (2021). "Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns". In: Science advances 7.3, eabd6696.

Deweathered changes



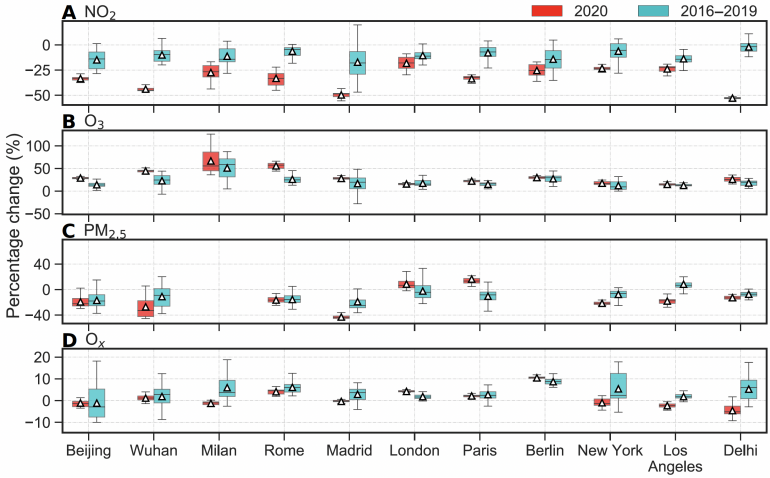
- Observed daily concentrations were largely affected by meteorological fluctuations.
- Decoupling the effect of emission changes from meteorology is crucial for quantifying true air quality changes attributable to the lockdown-associated emission changes.

Deweathered changes



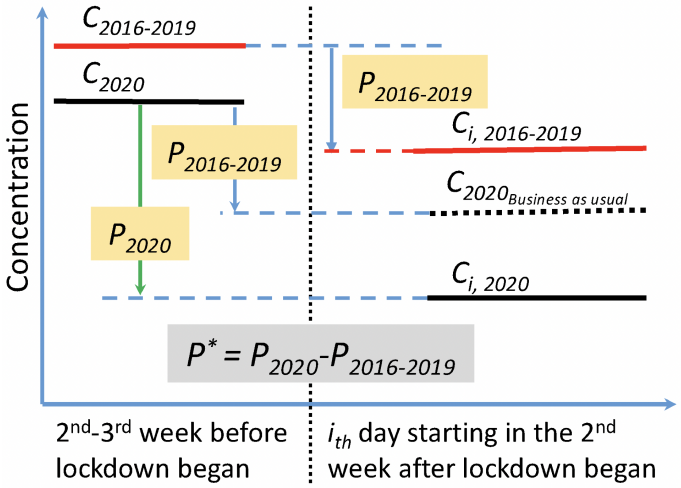
- NO_2 dropped abruptly.
- Sudden increase in O_3 around lockdown date: $NO + O_3 \rightarrow NO_2$.
- More gradual changes in NO_2 and O_3 in London and Los Angeles.
- Same increasing trend from winter to summer for O_3 in previous years.

Deweathered percentage changes



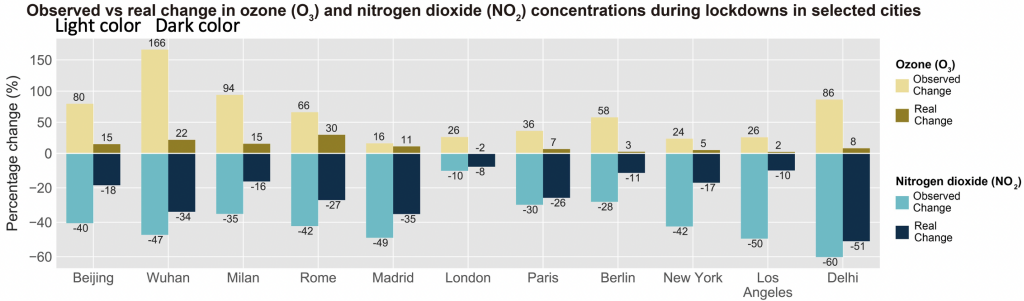
Causal effects $\neq$ Deweathered changes. Counterfactual deweathered changes?

Detrended percentage changes



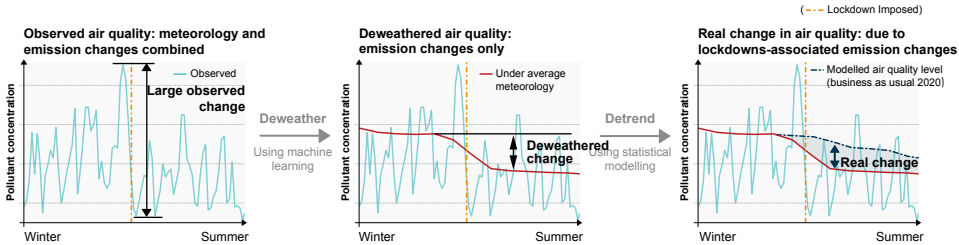
- Deweathered changes: P_{2020}
- "Counterfactual" deweathered changes: $P_{2016-2019}$
- "Causal" effects: P_{2020} - $P_{2016-2019}$

Observed versus real changes



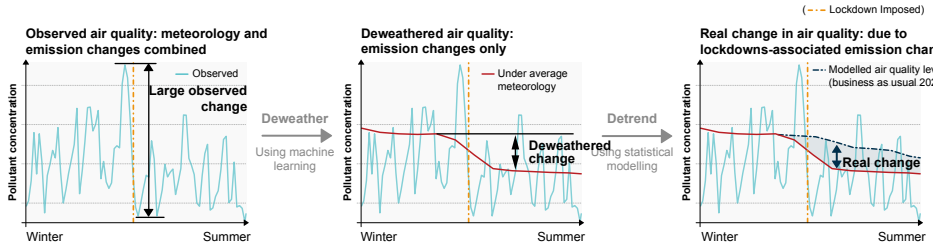
Observed changes are generally larger than detrended changes due to improved meteorological condition from winter to summer

Implication for cause inference in air quality studies



[8] Zongbo Shi et al. (2021). "Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns". In: Science advances 7.3, eabd6696.

Implication for cause inference in air quality studies

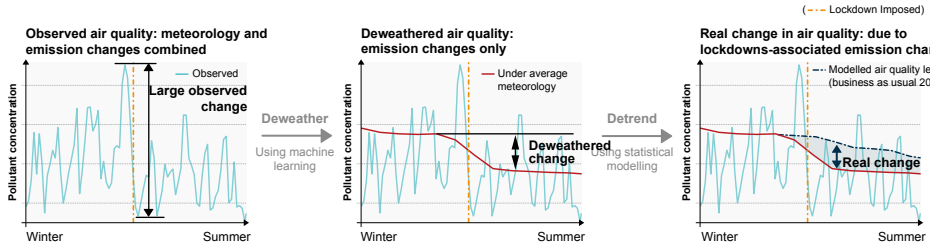


Two key message from Shi, et al. (2020)[8]:

1. The effects of intervention on air quality are often masked by meteorology changes.–Pointing towards **"deweathering"**.

[8] Zongbo Shi et al. (2021). "Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns". In: Science advances 7.3, eabd6696.

Implication for cause inference in air quality studies



Two key message from Shi, et al. (2020)[8]:

1. The effects of intervention on air quality are often masked by meteorology changes.–Pointing towards **"deweathering"**.
2. Air quality changes before and after the intervention date under business-as-usual scenario should be subtracted.–Pointing towards **"detrending"**.

[8] Zongbo Shi et al. (2021). "Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns". In: Science advances 7.3, eabd6696.

Implication for cause inference in air quality studies

- The **"deweathering"** is to remove major **confounding effects** from meteorology.

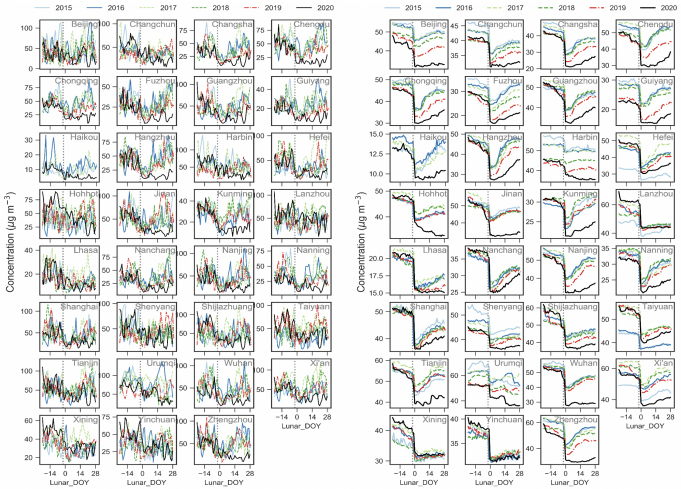
Implication for cause inference in air quality studies

- The **"deweathering"** is to remove major **confounding effects** from meteorology.
- The **"detrending"** is to subtract **counterfactual** deweathered concentrations from factual deweathered concentrations.

Implication for cause inference in air quality studies

- The **"deweathering"** is to remove major **confounding effects** from meteorology.
- The **"detrending"** is to subtract **counterfactual** deweathered concentrations from factual deweathered concentrations.
- Air quality changes after both deweathering and detrending can then be **attributed** to COVID-19 lockdowns.

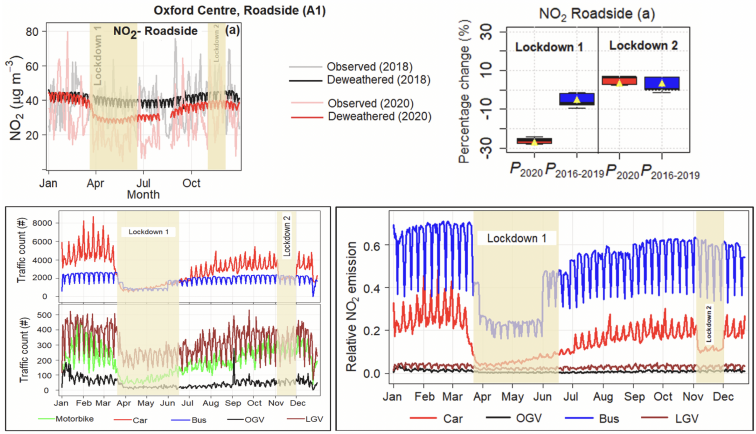
Applications - holiday effects[9]



NO_2-Spring festival

[9] Qili Dai et al. (2021). "Spring Festival and COVID-19 lockdown: disentangling PM sources in major Chinese cities". In: Geophysical research letters, e2021GL093403.

Applications - double lockdowns[10]



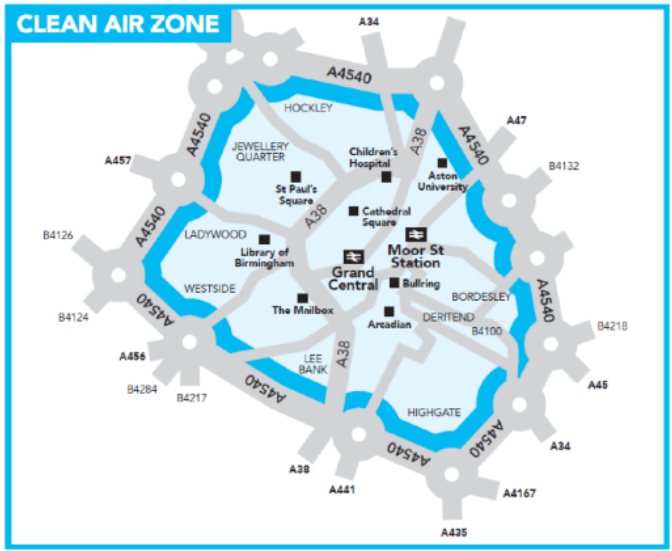
Small changes in air pollutant concentrations during the second lockdown in Oxford were due to little changes in traffic emissions.

[10] Ajit Singh et al. (2022). "Impacts of emergency health protection measures upon air quality, traffic and public health: evidence from Oxford, UK". In: Environmental Pollution 293, p. 118584. ISSN: 0269-7491. DOI: 10.1016/j.envpol.2021.118584.

Birmingham Clean Air Zone

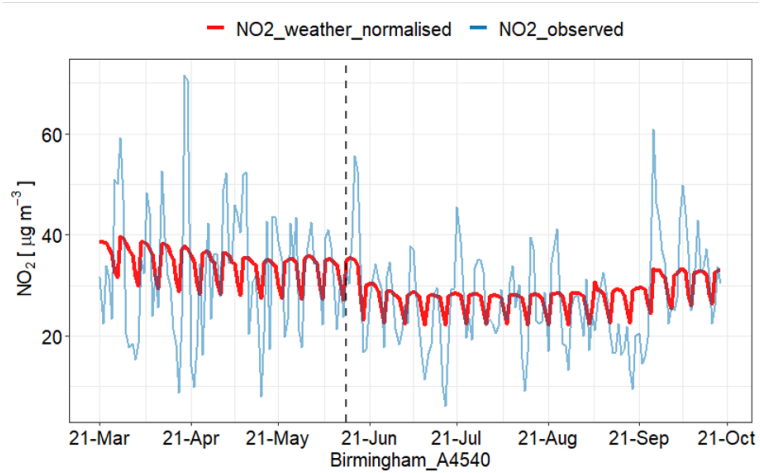
Liu et al. –In preparation

Background



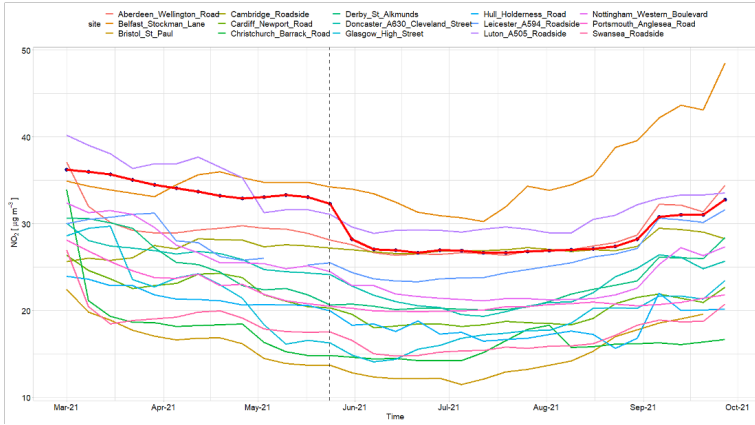
- Starting 1 June 2021
- Charge for polluting vehicles
- No charge for compliance vehicles

Deweathering (Ring-Road)



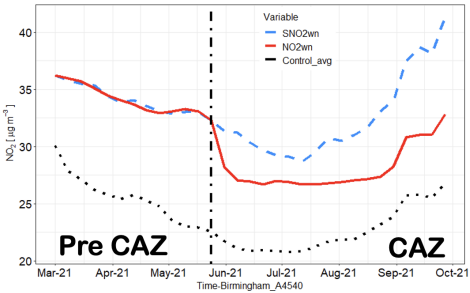
Sudden drop in deweathered NO_2 at a roadside station.

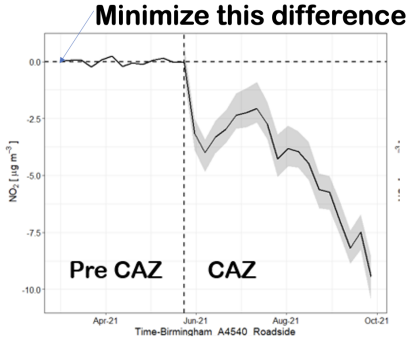
Treatment versus Control



Sudden drop in NO_2 was detected for the treatment group but not for the control groups.

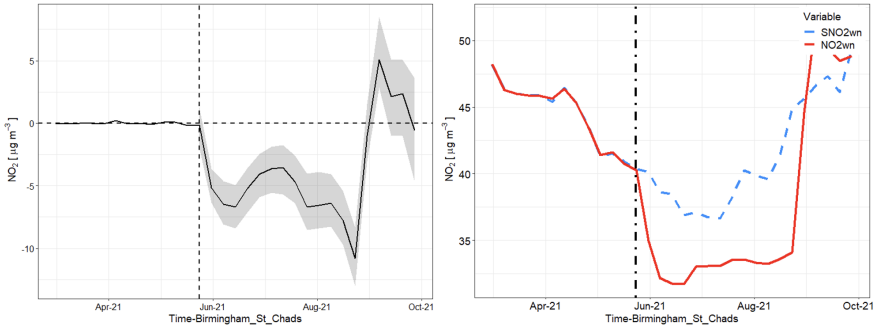
Causal effects on Ring-road NO_2





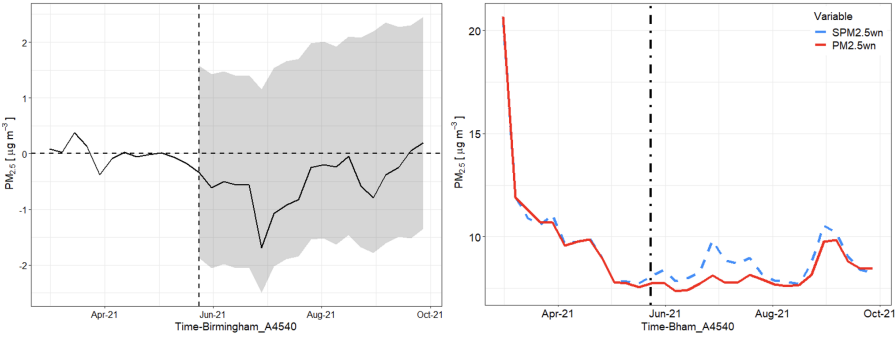
Weather-normalised NO_2: NO2wn
Synthetic (weather normalised) NO_2 : sNO2wn

Causal effects on Roadside NO_2



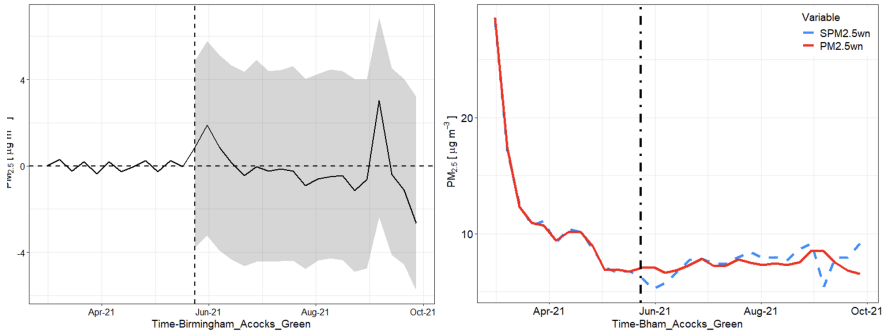
Weather-normalised NO_2: NO2wn
Synthetic (weather normalised) NO_2 : sNO2wn

Causal effects on Ring-road $PM_{2.5}$



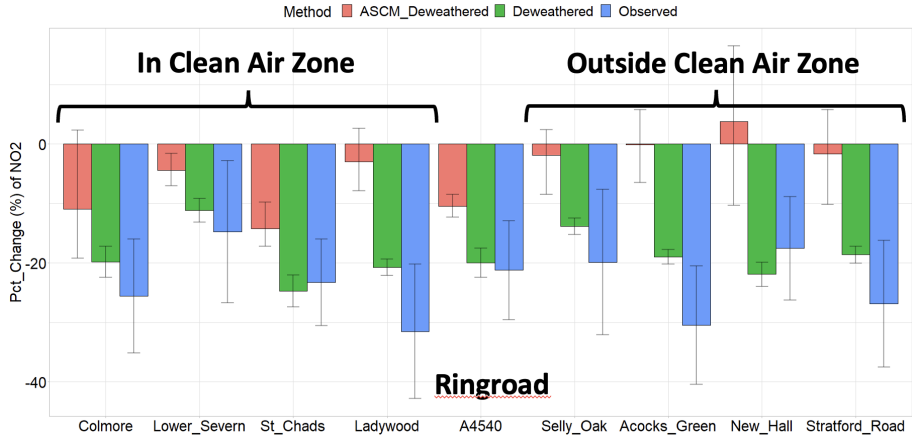
Weather-normalised $PM_{2.5}$: $PM_{2.5}$wn
Synthetic (weather normalised) NO_2 : s$PM_{2.5}$ wn

Causal effects on non-CAZ urban background $PM_{2.5}$



Weather-normalised $PM_{2.5}$: $PM_{2.5}$wn
Synthetic (weather normalised) NO_2 : s$PM_{2.5}$ wn

CAZ versus Non-CAZ



NO_2 at CAZ show larger drops than those at non-CAZ, this causal effects can only be detected by the SCM.

Summary

1. "Deweathering" plus "Detrending" provides an effective measure to evaluate the response of air quality to short-term emission intervention.

Summary

1. "Deweathering" plus "Detrending" provides an effective measure to evaluate the response of air quality to short-term emission intervention.
2. Large potential to extend the casual inference tools developed in the Economics to Atmospheric science.

References I

Abadie, Alberto, Alexis Diamond, and Jens Hainmueller (June 2010). "Synthetic Control Methods for Comparative Case Studies: Estimating the Effect of California's Tobacco Control Program". In: Journal of the American Statistical Association 105 (490), pp. 493–505. ISSN: 0162-1459. DOI: 10.1198/jasa.2009.ap08746.

Athey, Susan and Guido W Imbens (May 2017a). "The State of Applied Econometrics: Causality and Policy Evaluation". In: Journal of Economic Perspectives 31 (2), pp. 3–32. DOI: 10.1257/jep.31.2.3.

— (May 2017b). "The State of Applied Econometrics: Causality and Policy Evaluation". In: Journal of Economic Perspectives 31.2, pp. 3–32. DOI: 10.1257/jep.31.2.3.

Dai, Qili et al. (2021). "Spring Festival and COVID-19 lockdown: disentangling PM sources in major Chinese cities". In: Geophysical research letters, e2021GL093403.

Ebenstein, Avraham et al. (2017). "New evidence on the impact of sustained exposure to air pollution on life expectancy from Chinas Huai River Policy". In: Proceedings of the National Academy of Sciences 114 (39), pp. 10384–10389. DOI: 10.1073/pnas.1616784114.

He, Guojun, Yuhang Pan, and Takanao Tanaka (2020). "The short-term impacts of COVID-19 lockdown on urban air pollution in China". In: Nature Sustainability 3 (12), pp. 1005–1011. ISSN: 2398-9629. DOI: 10.1038/s41893-020-0581-y.

References II


Shi, Zongbo et al. (2021). "Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns". In: Science advances 7.3, eabd6696.


Singh, Ajit et al. (2022). "Impacts of emergency health protection measures upon air quality, traffic and public health: evidence from Oxford, UK". In: Environmental Pollution 293, p. 118584. ISSN: 0269-7491. DOI: 10.1016/j.envpol.2021.118584.


Wikipedia contributors (2021). Causal inference — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Causal_inference&oldid=1050494098. [Online; accessed 11-December-2021].

Questions?