An Econometrician's Take on the CO_2-Climate Debate

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NYU-Stern 10th Annual Volatility Conference

April 27, 2018

Thanks to Robert Kaufmann (BU) and Felix Prentis (Oxford/U. Victoria)

Climate science: the political landscape

EPA Administrator Scott Pruitt, CNBC, March 9, 2017

"I think that measuring with precision human activity on the climate is something very challenging to do and there's tremendous disagreement about the degree of impact, so no, I would not agree that it's a primary contributor to the global warming that we see… But we don't know that yet. We need to continue the debate and continue the review and the analysis."

Climate science & climate change skepticism

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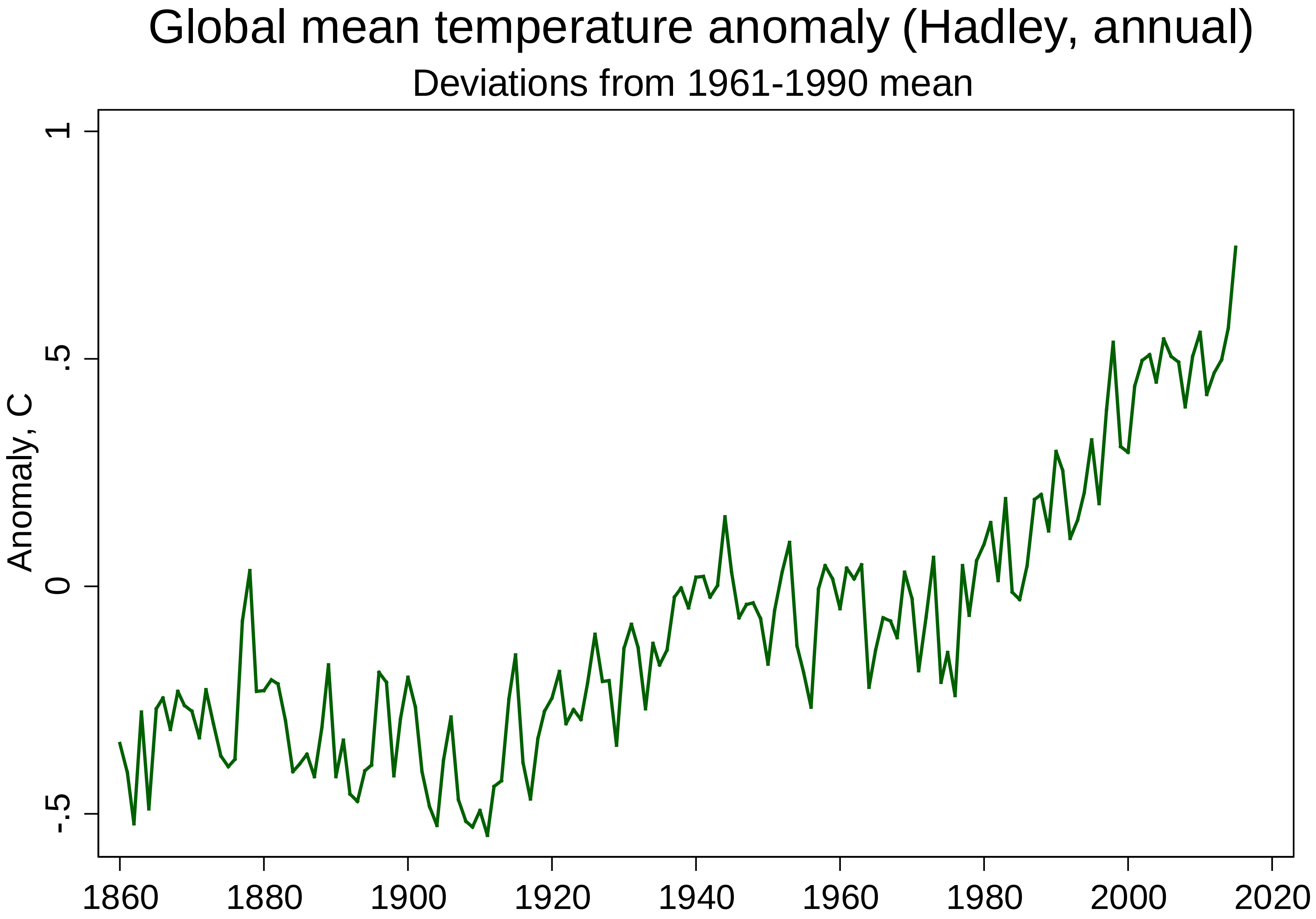
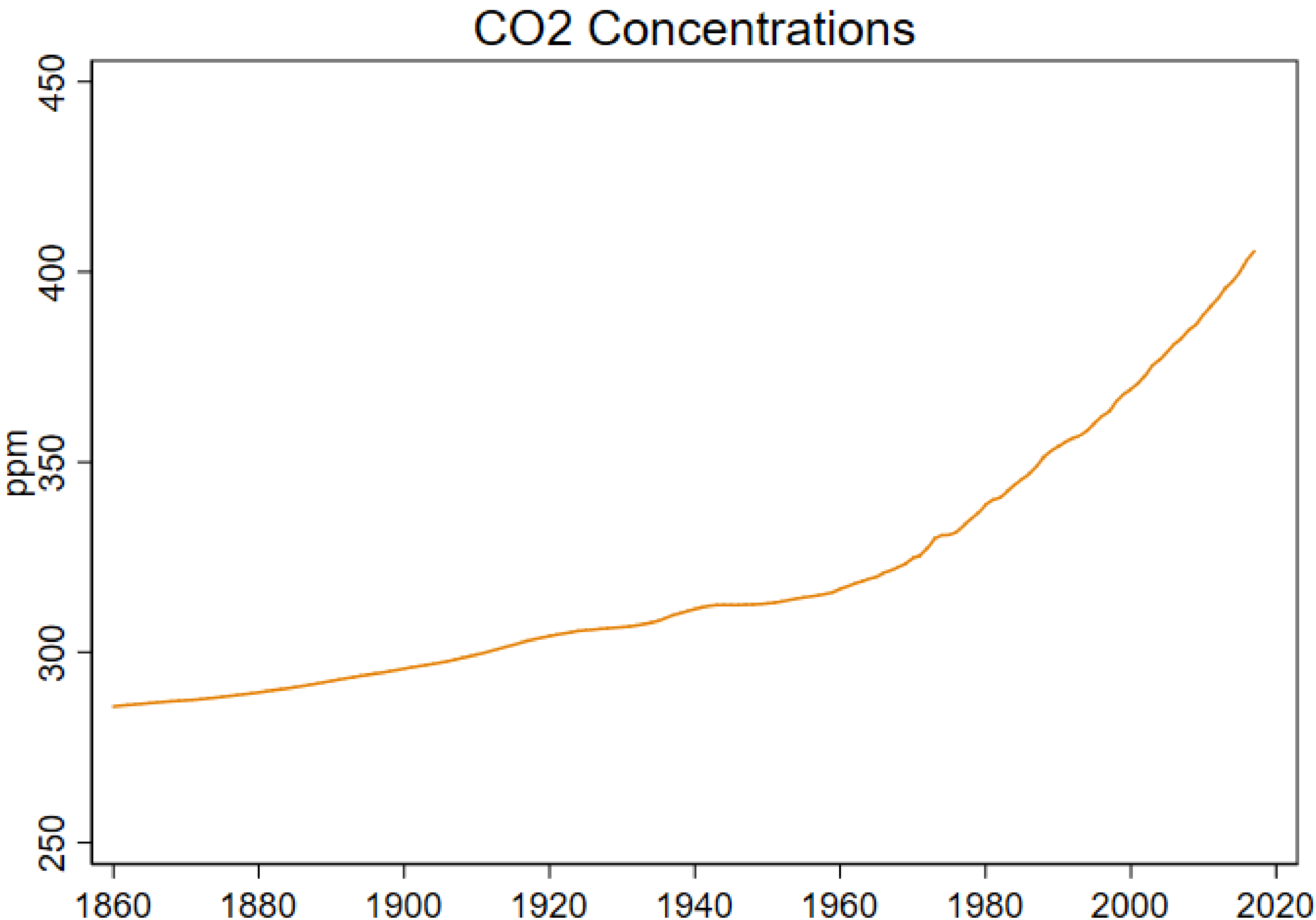
This talk

- What can simple data analysis say about causality, magnitudes, and climate science?
- Use atmospheric physical chemistry but not global circulation models

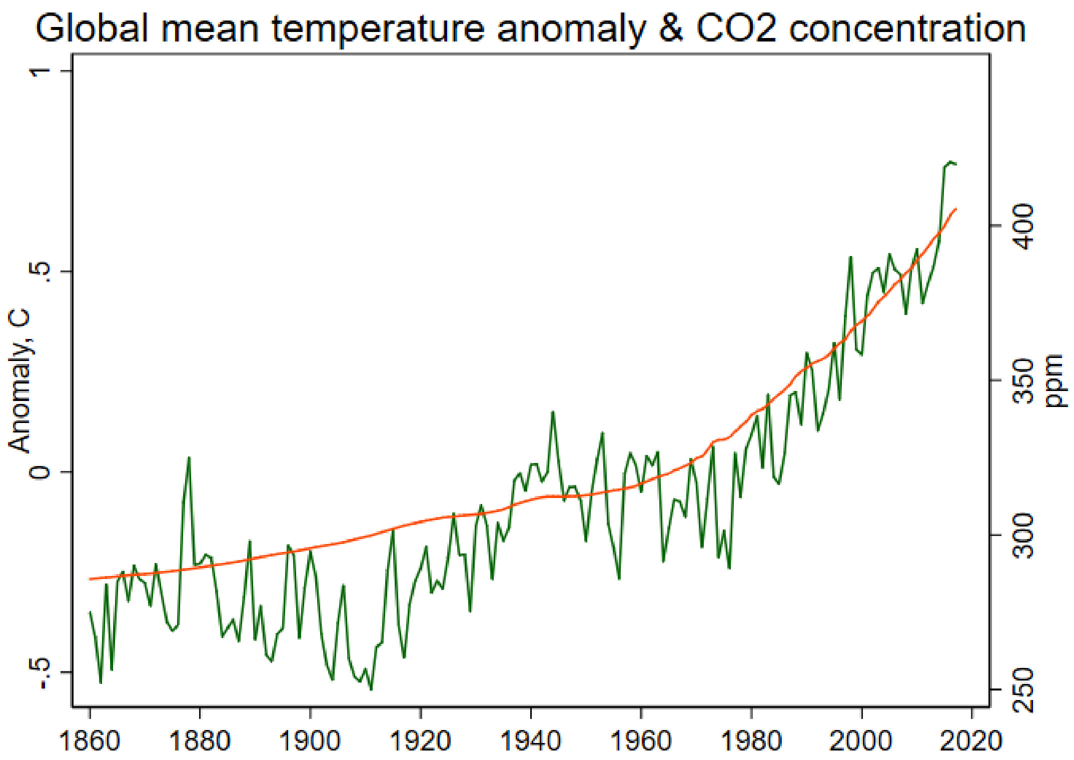
Global data


Global mean temperature anomaly (Hadley, annual)
Deviations from 1961-1990 mean
Anomaly, C
1
.5
0
-.5
1860
1880
1900
1920
1940
1960
1980
2000
2020

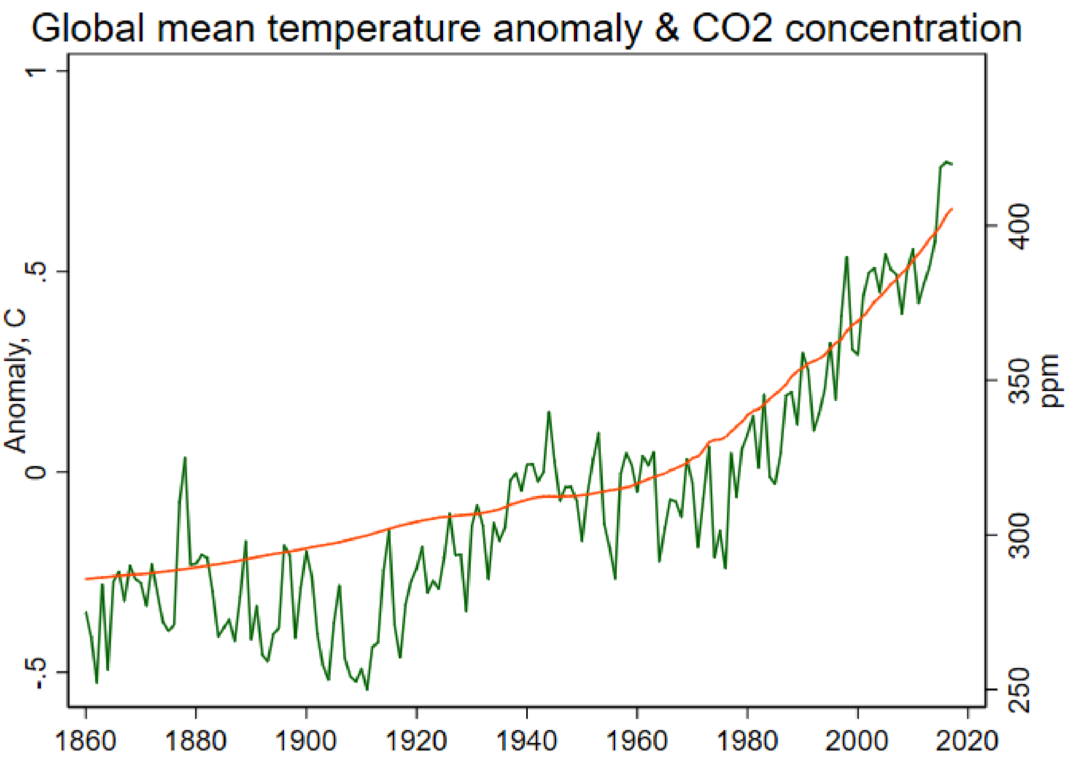
Global data


CO2 Concentrations
ppm
250
300
350
400
450
1860
1880
1900
1920
1940
1960
1980
2000
2020

It seems obvious



It seems obvious, but…



1. **There are other sources of warming & cooling, some natural**
   - Solar
   - Other GHG (CH4, N20, CFCs,…)

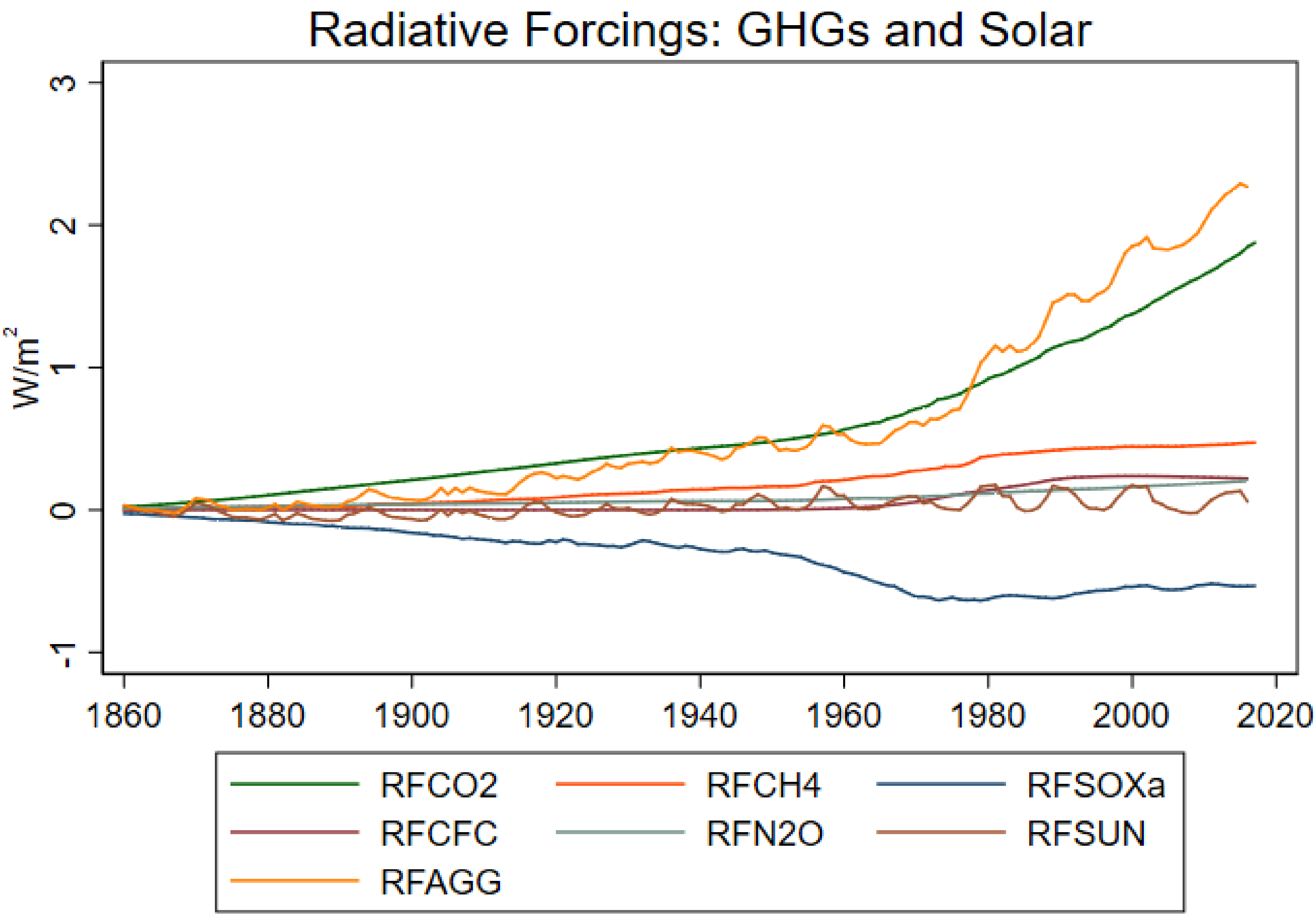
2. **The endogeneity problem**
   - Earth system feedbacks determine some of radiative forcing (e.g. CO2 uptake)

3. **The spurious regression problem**
   - You can generate high correlations in persistent time series, with no true relationship

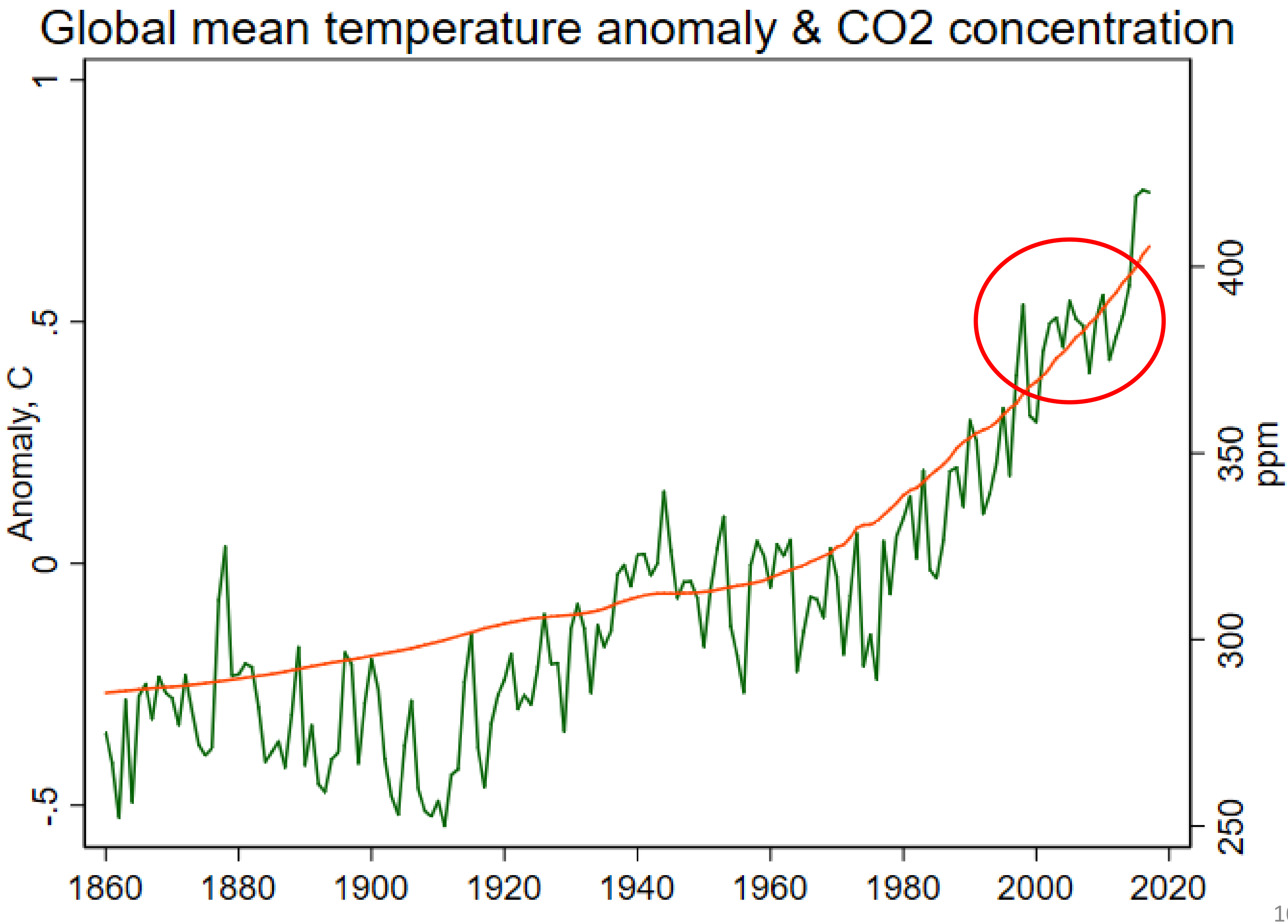
Outline

1. Introduction and some data
    1. Motivation
    2. Radiative forcing
2. Causality 1: Accounting for the 1998-2013 warming hiatus
    1. The hiatus debate
    2. Two simple models
    3. Out of sample conditional predictions
    4. Decomposition
    5. Extensions
3. Causality 2: from anthropogenic emissions to temperatures
4. Transient climate response, equilibrium climate sensitivity, and the Social Cost of Carbon
5. Related work (brief overview)

Radiative Forcing



The 1998-2013 warming hiatus



The hiatus: Multiple explanations

Anthropogenic sulfur

Kaufmann, Kauppi, Mann, Stock (2011)

Declining solar irradiance

Tollefson (2013), Trenberth (2015), Kaufmann et. al. (2011)

Volcanic aerosols

Andersson et. al. (2016)

Gregory et. al. (2016)

Temperature mismeasurement

Karl et. al. (2015)

Fyfe et. al. (2016)

Hausfather et. al. (2017)

Ocean heat uptake (internal variability)

Meehl et al. (2011)

Kosaka and Xie (2013)

Liu, Xie, and Lu (2016)

Not easily explained/poses problems for models

Curry (2014)

The hiatus: two simple models

Can simple models that condition on RF "predict" the hiatus?

- Estimate simple models through 1998, make conditional projections ("dynamic simulations")
- This addresses the spurious regression concern but not necessarily the endogeneity concern

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1. Error-correction model, homogeneous response to RF (Kaufmann, Kauppi, Stock 2006)

$$T_t = \theta_0 + \theta_1 RF_t^{Agg} + u_t$$

$$\Delta T_t = \lambda(T_{t-1} - \theta_1 RF_{t-1}^{Agg}) + \alpha_1 \Delta T_{t-1} + \alpha_2 \Delta RF_t^{Agg} + \varepsilon_t$$

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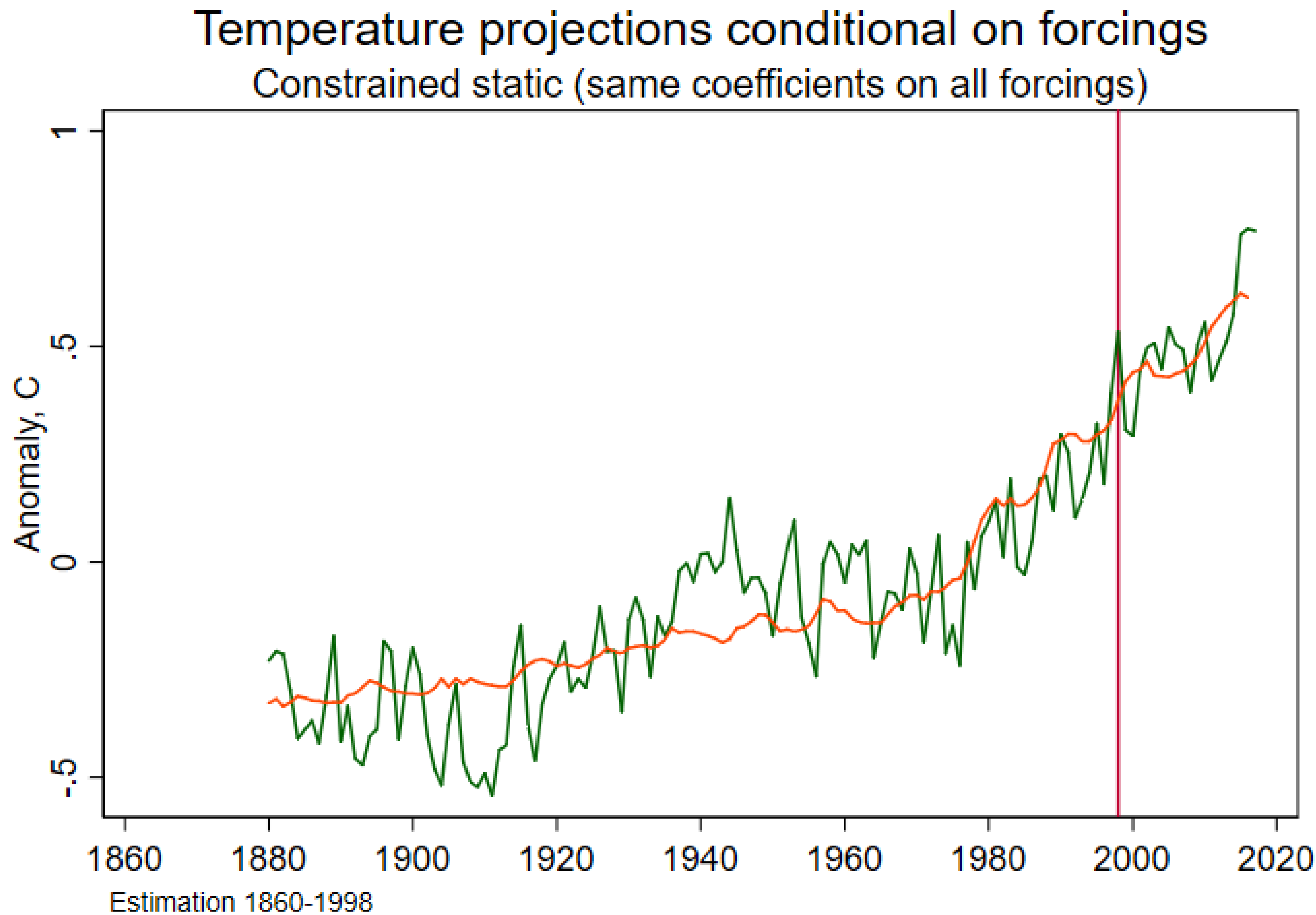
2. Error-correction model, different static response to RF-gas and RF-sun

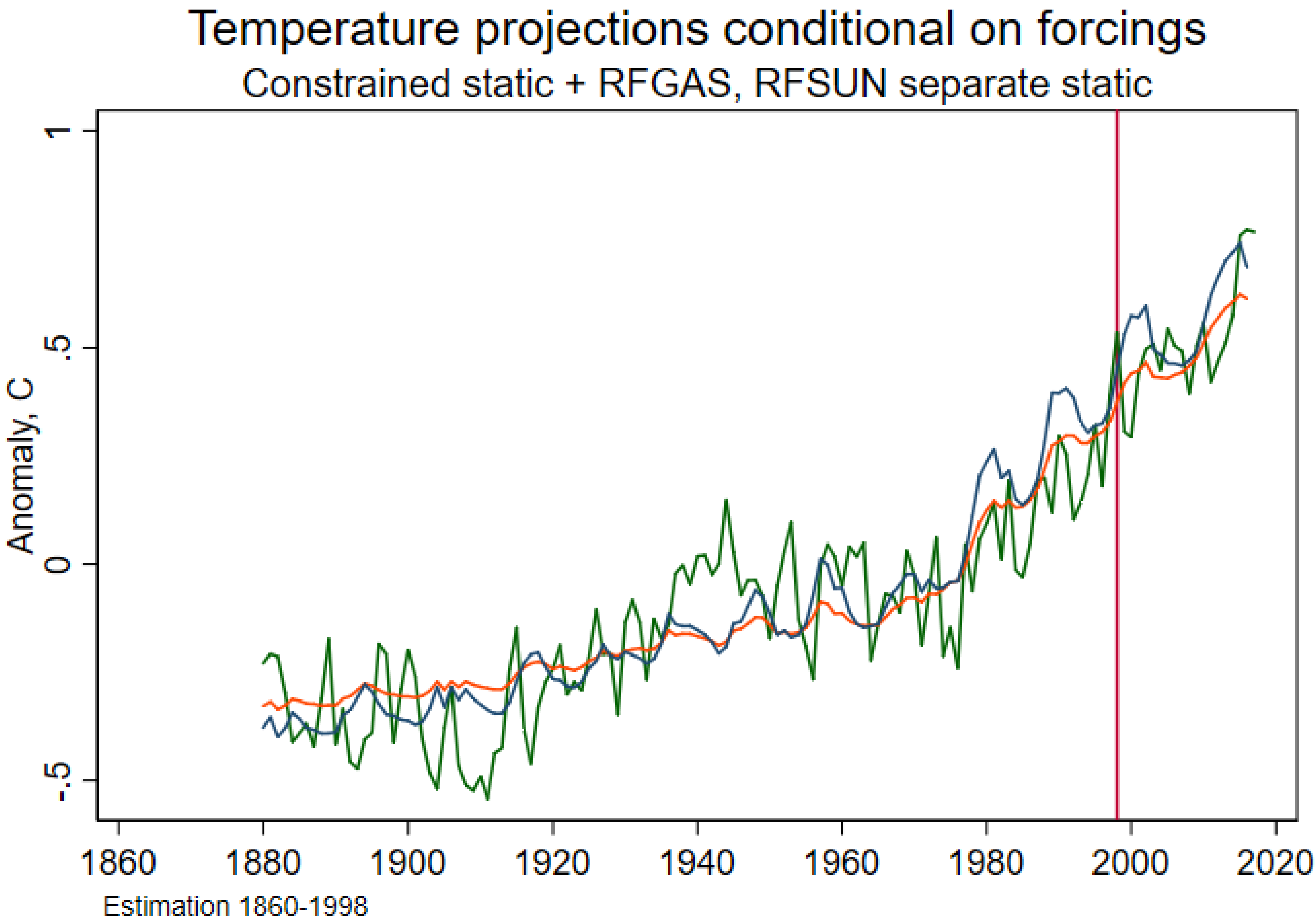
$$T_t = \theta_0 + \theta_1 RF_t^{Gas} + \theta_2 RF_t^{Sun} + u_t$$

$$\Delta T_t = \lambda(T_{t-1} - \theta_1 RF_{t-1}^{Gas} + \theta_2 RF_{t-1}^{Sun}) + \alpha_1 \Delta T_{t-1} + \alpha_2 \Delta RF_t^{Gas} + \alpha_3 \Delta RF_t^{Sun} + \varepsilon_t$$

Hiatus: Simple model 1



Hiatus: Simple models 1 & 2

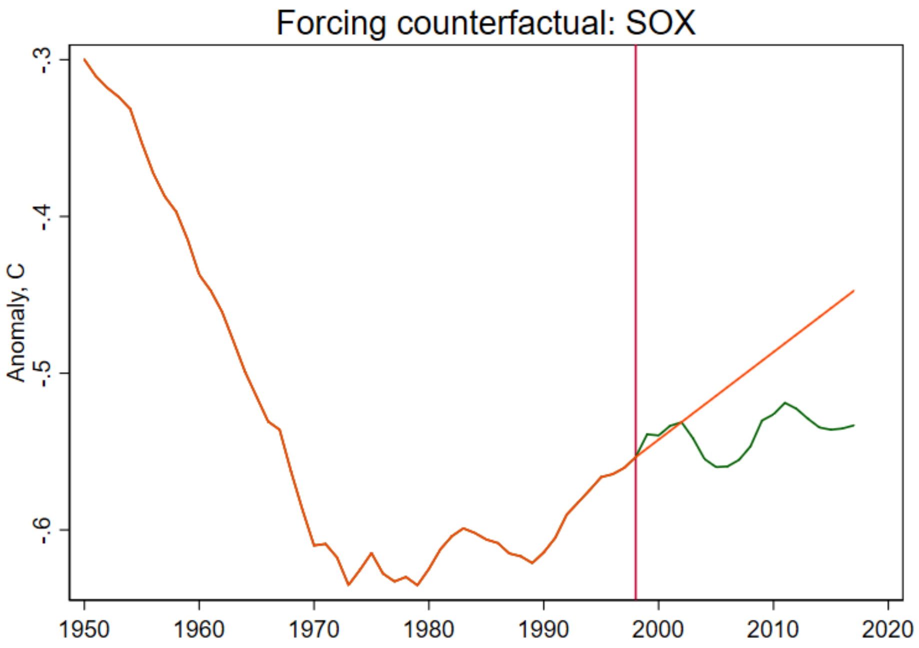


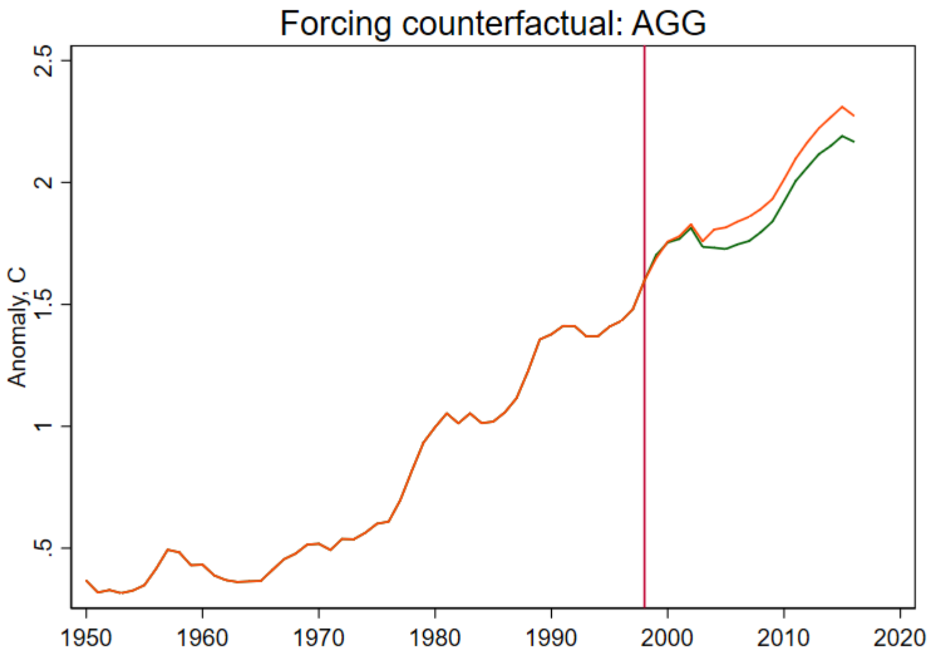
Hiatus: Counterfactual and decomposition

These models admit a linear decomposition of "reasons" for the hiatus.

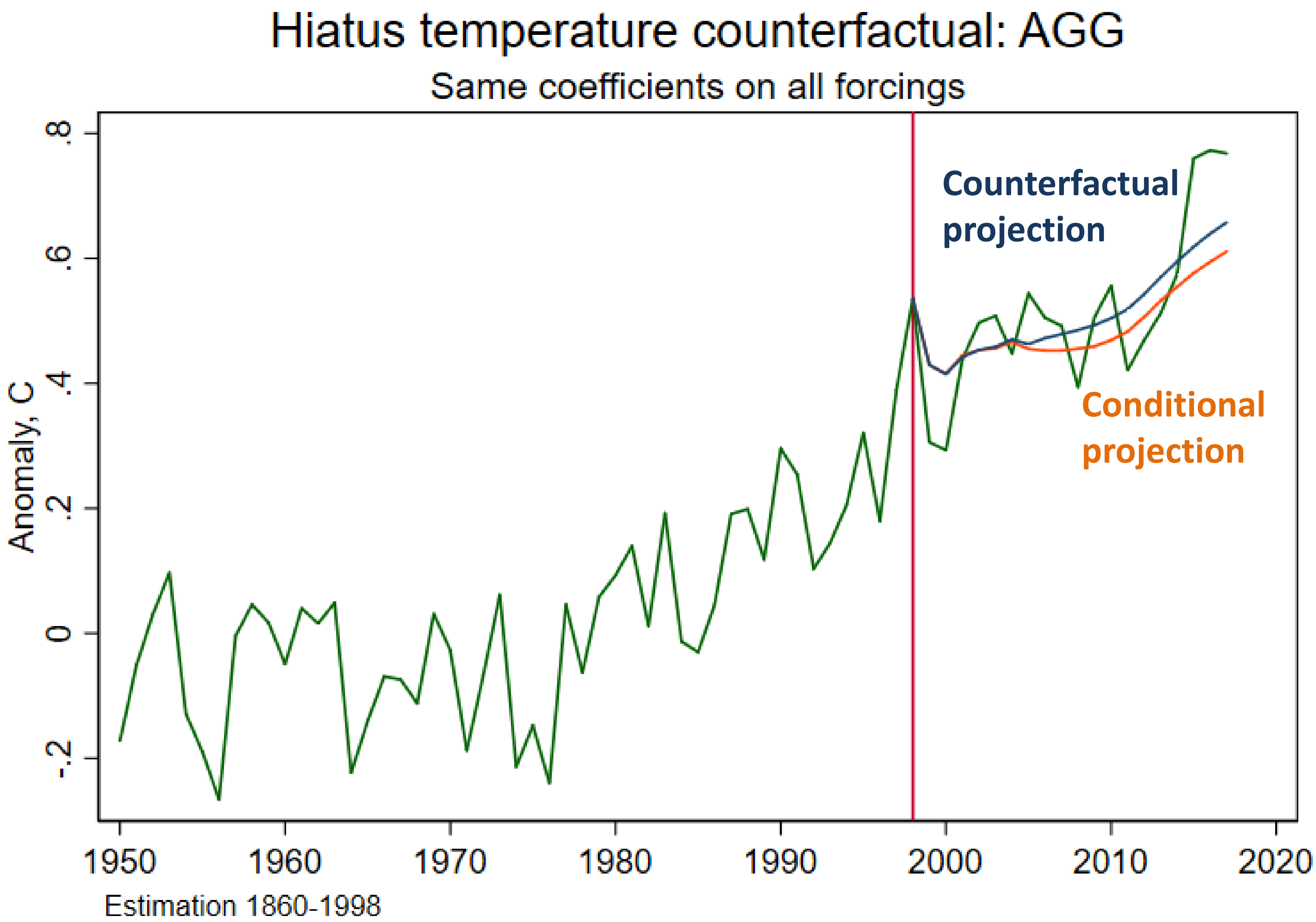
The decomposition requires a counterfactual. Here we consider "BAU":

- All gas radiative forcings grow over 1999-2015 at their rate over the previous 10 years (1989-1998)
- Solar RF mean over the 2004-2015 equals its mean over the 1984-2003 cycles





Hiatus: actual, conditional & counterfactual projection



Hiatus decomposition

	Model 1
Total gap	-0.020
Explained components	
CO_2	0.008
SOX	-0.008
CFC	-0.009
N_2O	0.001
CH_4	-0.004
Subtotal, Gases	**-0.012**
SUN	-0.005
Total explained	**-0.018**
Unexplained	**0.003**

Different counterfactuals give different decompositions.

- Estrada et al (2014), Estrada and Perron (2016) give more weight to CFC reductions.

Hiatus: extensions

Two of many…

Kaufmann, Kaupi, Stock (2006, 2011)

- Endogenize (model) CO_2, CH_4 net emissions sensitivity to temperature changes
- Volcanic sulfates as instrumental variables
- Estimate a small positive feedback

Bruns, Csereklyei, Stern (2017)

- Include endogenous ocean heat uptake (RFAGG exogenous)
- 3-variable error correction model that incorporates ocean heat uptake
- Ocean dynamics
- Lower TCR estimates because of ocean damping (adjustment lags)

Causality 2: from anthropogenic emissions to temperatures

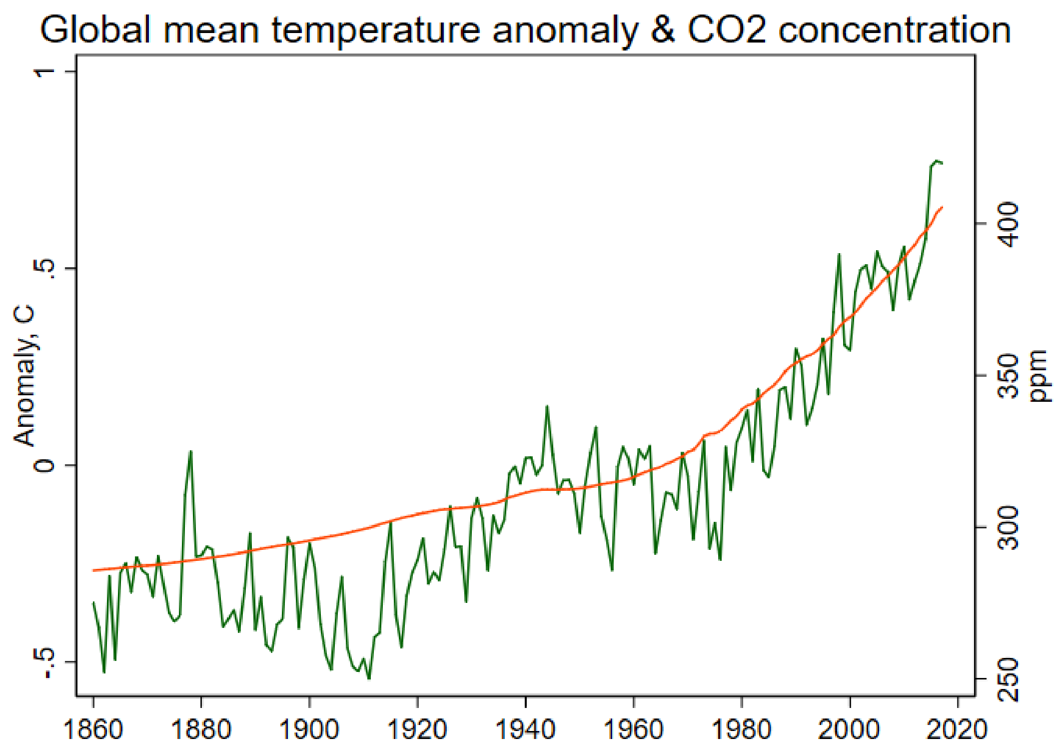
Objects of interest

Equilibrium climate sensitivity (ECS):

- Equilibrium (long-run) temperature response to CO2 doubling.
- IPCC AR5 likely range 1.5-4.5 °C

Transient climate response (TCR):

- Temperature response to CO2 doubling at 1% annual rate over those 70 years.
- IPCC AR5 likely range 1-2.5 °C



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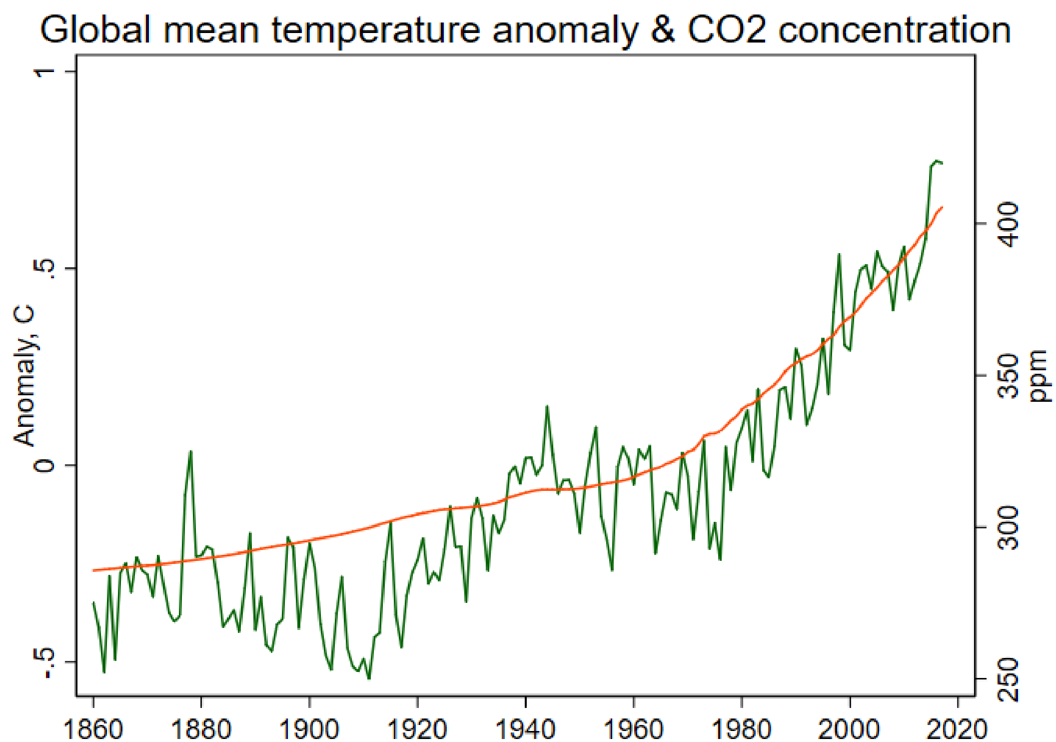

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- Time horizon unclear
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- Inference requires additional modeling (cointegration?)

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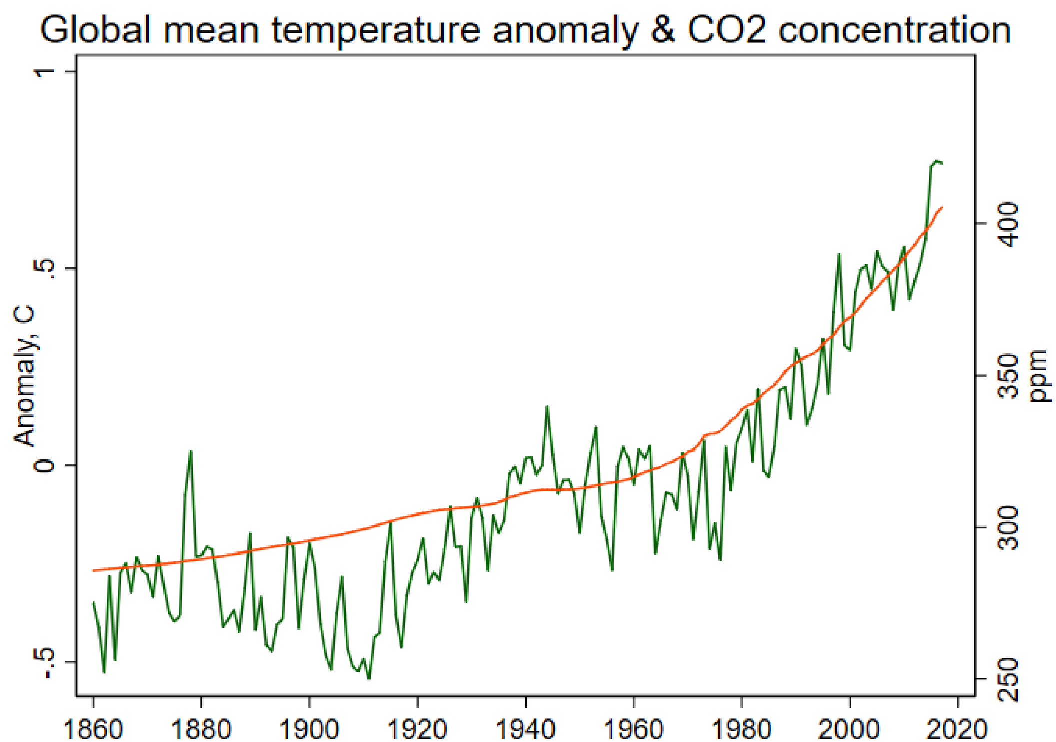

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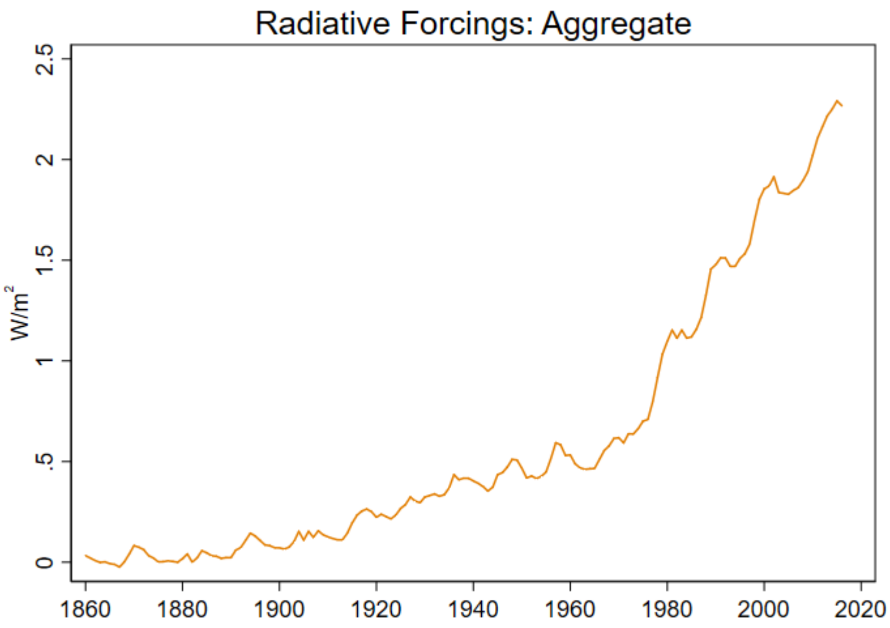
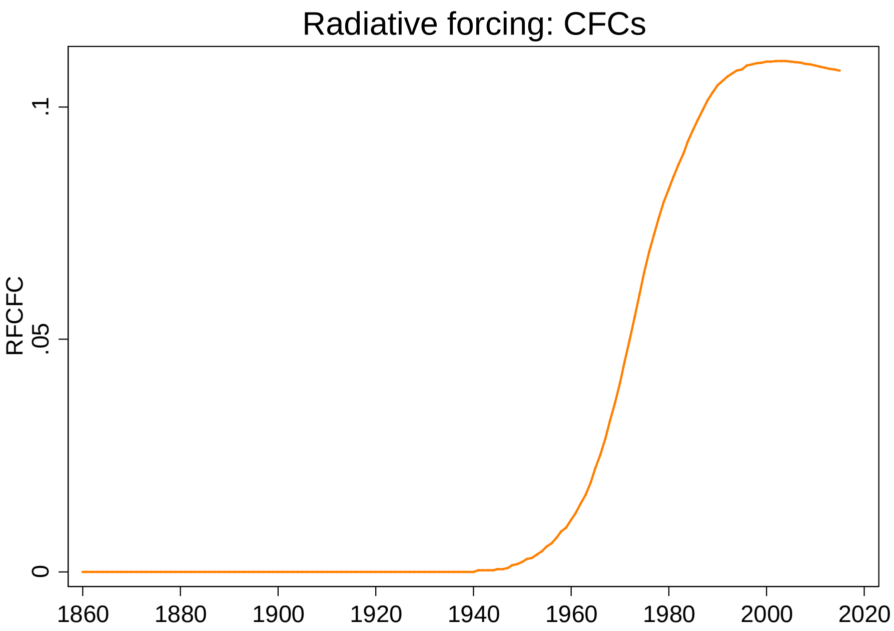
Goal: Causal inference with minimal assumptions
- No GCMs
- No persistent time series
- Credible identification
- Use instrumental record only (1959-)

Causality 2: from anthropogenic emissions to temperatures





One "experiment": Invention and withdrawal of CFS

- CFCs introduced 1930s for refrigeration – use took off after WWII
- Withdrawn under Montreal Protocl

Other "experiments":

- Solar cycles
- Invention of automobile -> CO2 emissions from automobiles
- Perhaps, all anthropogenic CO2 emissions

- *Technical note*: restrict to era of instrumental CO2 measurement (1959-)

IV estimation – methods

$$\Delta_h Temp_t = \beta_0 + \beta_1 \Delta_h RF_t^{Agg} + u_t^h$$

1. Instrument exogeneity: $Eu_t^h z_t = 0$

   u_t includes lag effects
   Instrument (e.g. Δ_h*RFSOLAR*) is serially correlated
   => exogeneity condition violated
   => **use innovation of original instrument as z_t**
   This is basically LP-IV, see Stock & Watson, *EJ* (2018)

2. Instruments are potentially weak

   => **Both strong-IV and Anderson-Rubin confidence intervals**

2. Potential serial correlation in $u_t^h z_t$ process

   => **HAR intervals** (here, use QS kernel with fixed-*b* critical values)
   Lazarus, Lewis, Stock (2017); Lazarus, Lewis, Stock, Watson (2018)

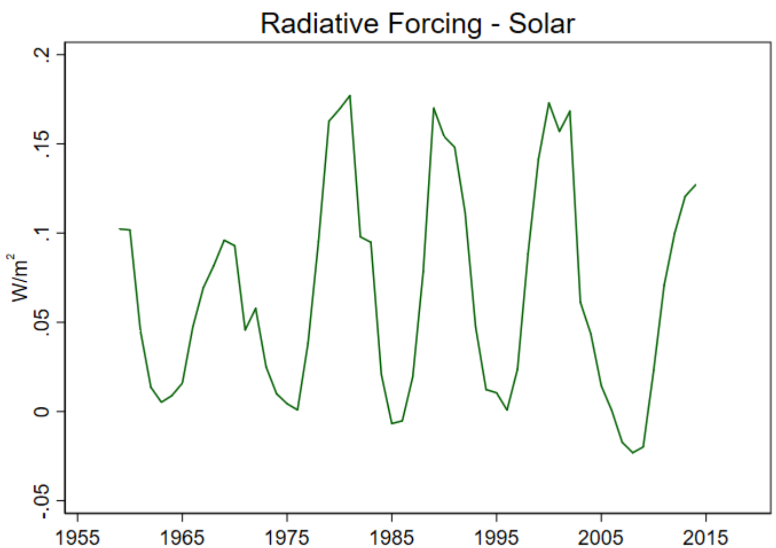
IV estimation – Instruments

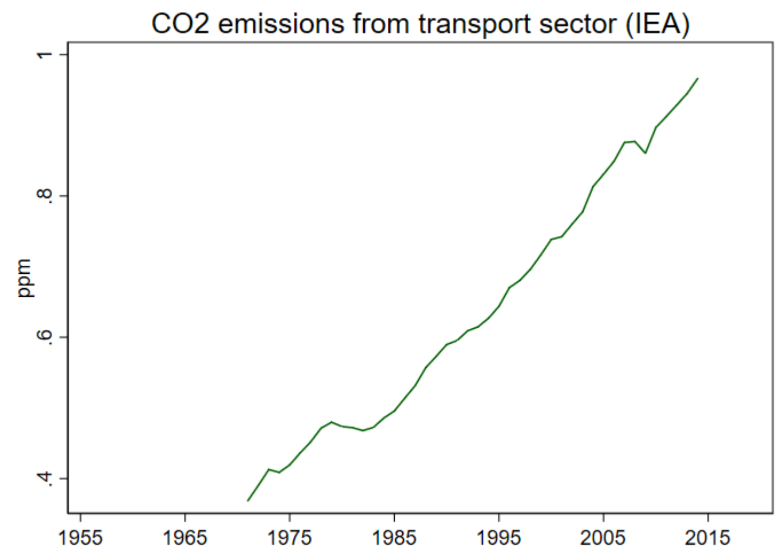
Instrument Group A

1. Radiative forcing – solar
2. Contribution to CO2 RF from CO2 emitted from surface transport
    - IEA, augmented with vehicle production

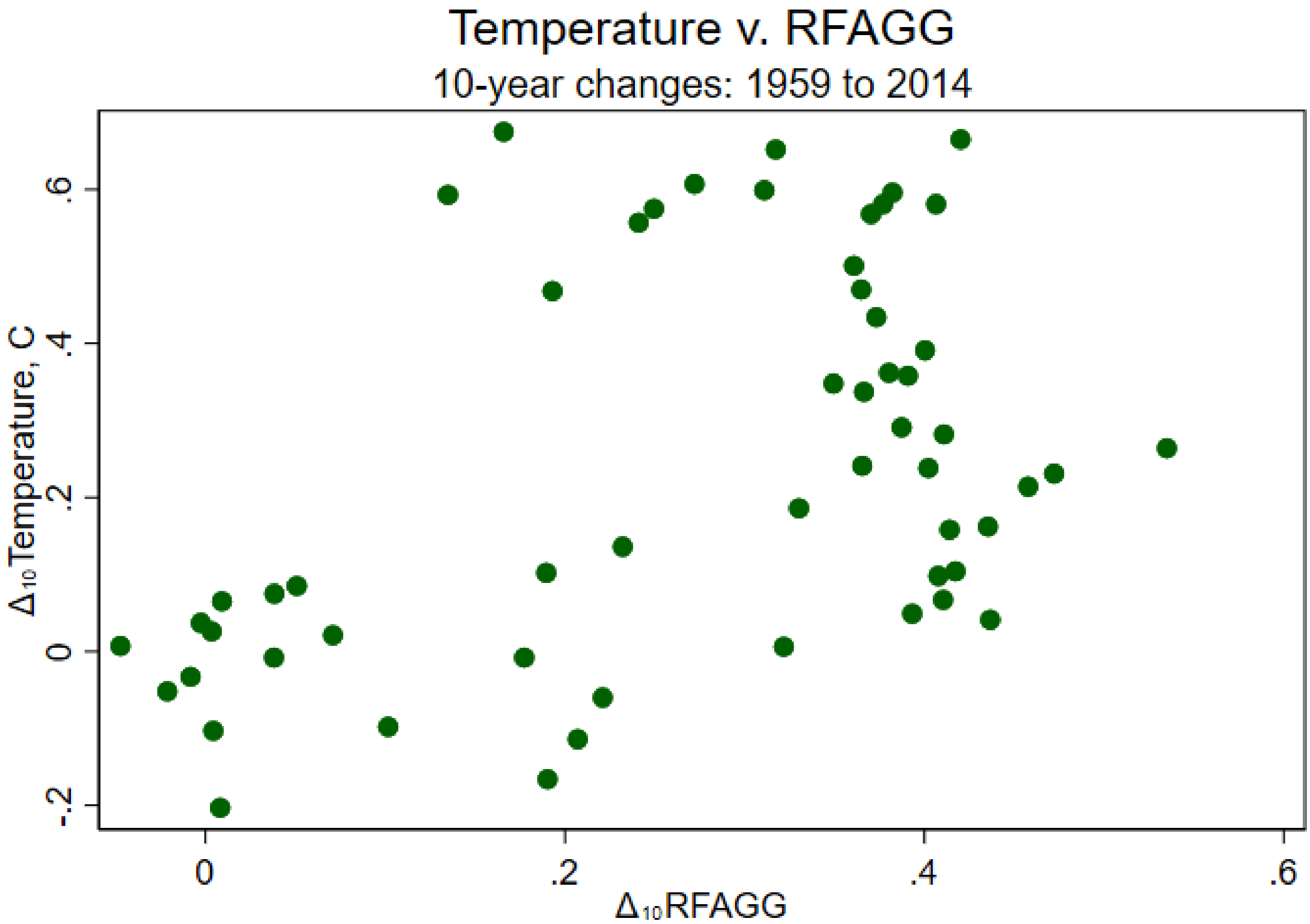
Instrument Group B

3. Contribution to CO2 RF from all anthropogenic
    - IEA, Boden et al (2011)
4. RF from tropospheric SOX
    - University of Melbourne

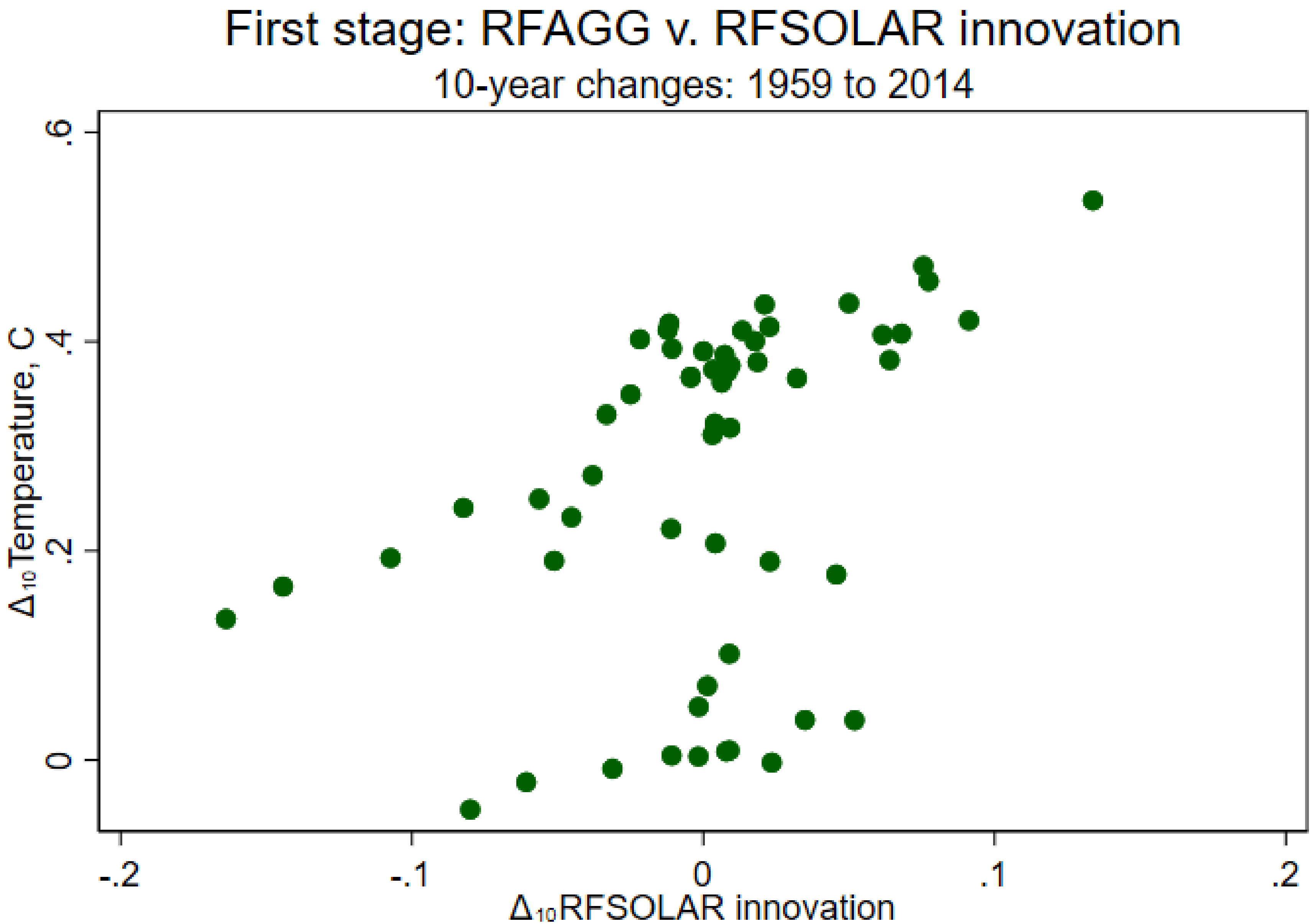




Temperature and Aggregate RF: 10-year changes



First stage scatterplots, 10-year diffs



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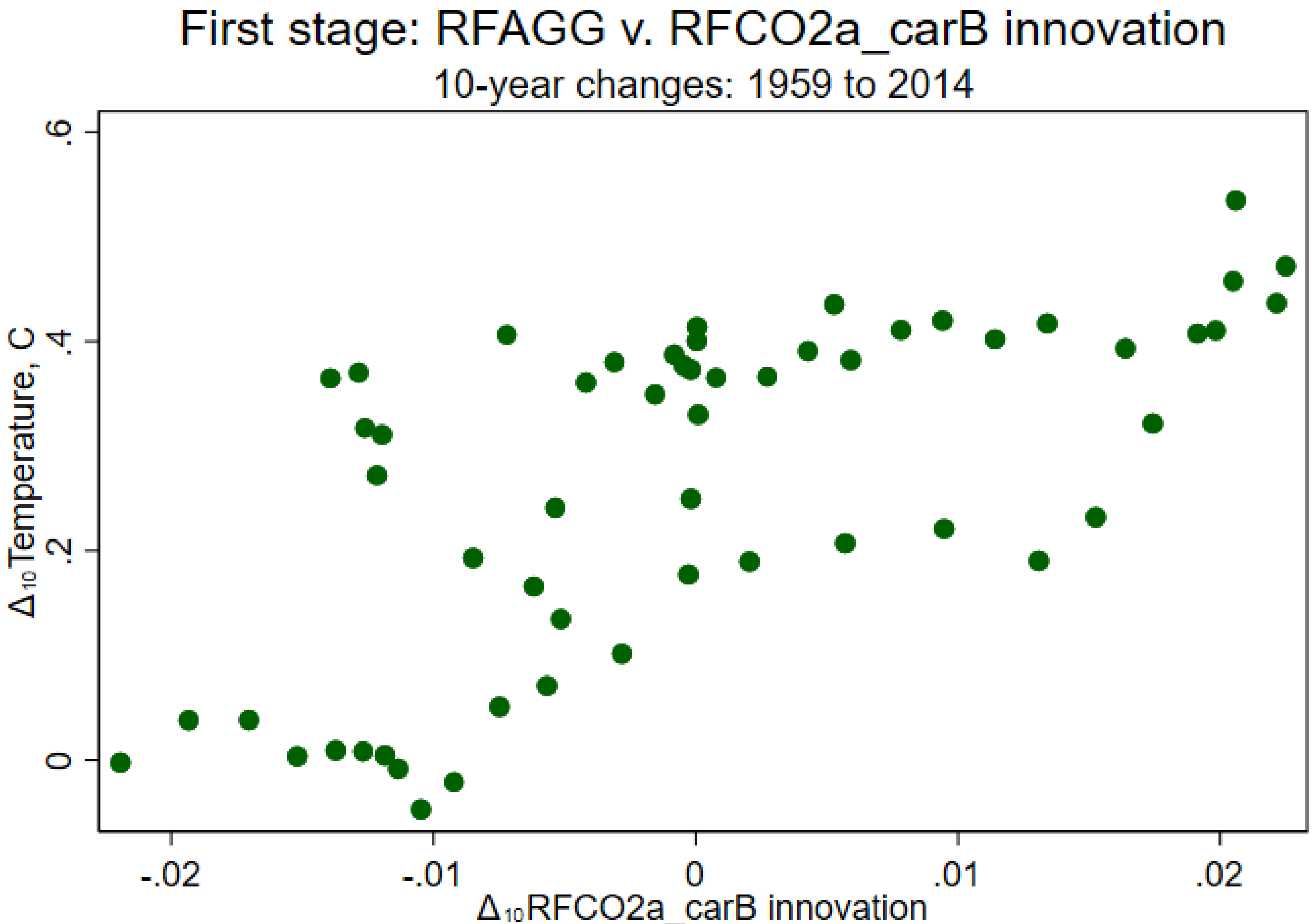
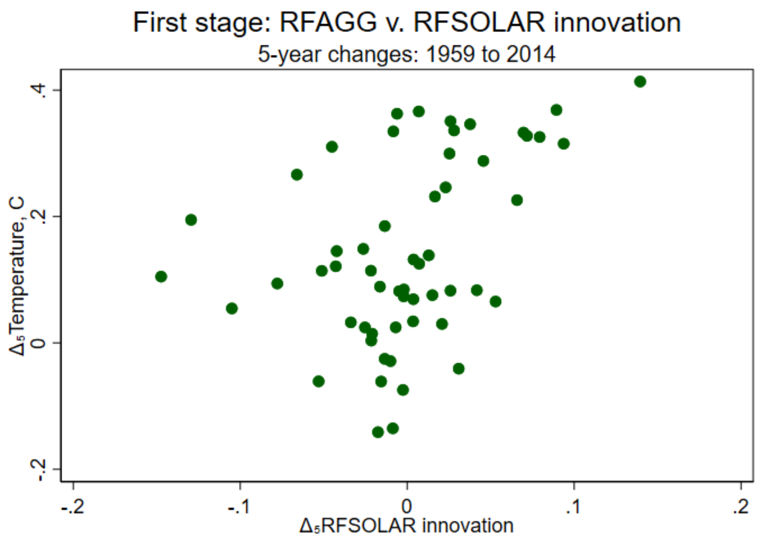
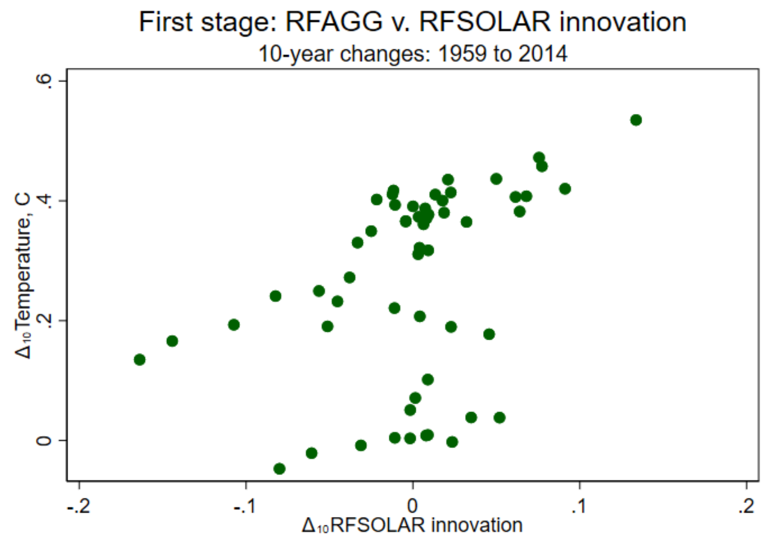
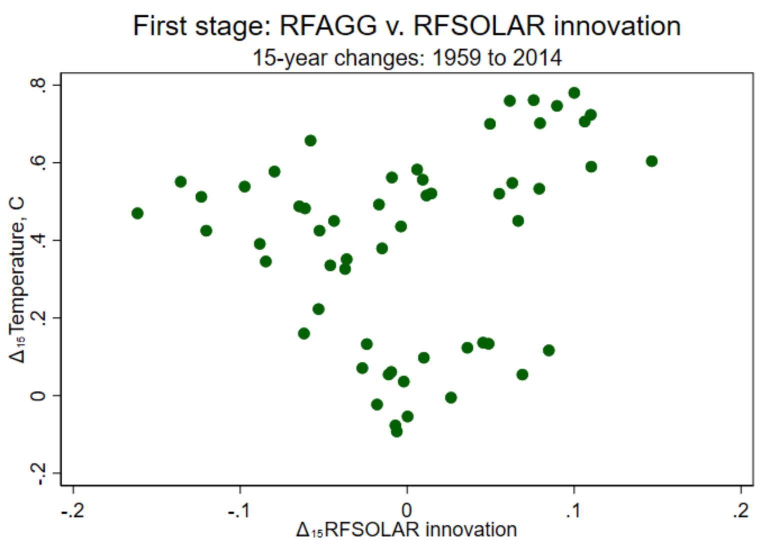
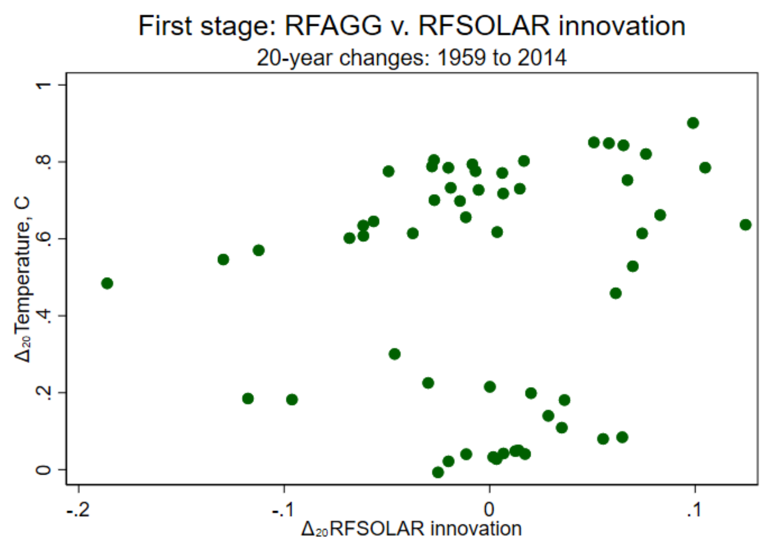


First stage scatterplots: 5, 10, 15, 20 year diffs - Solar

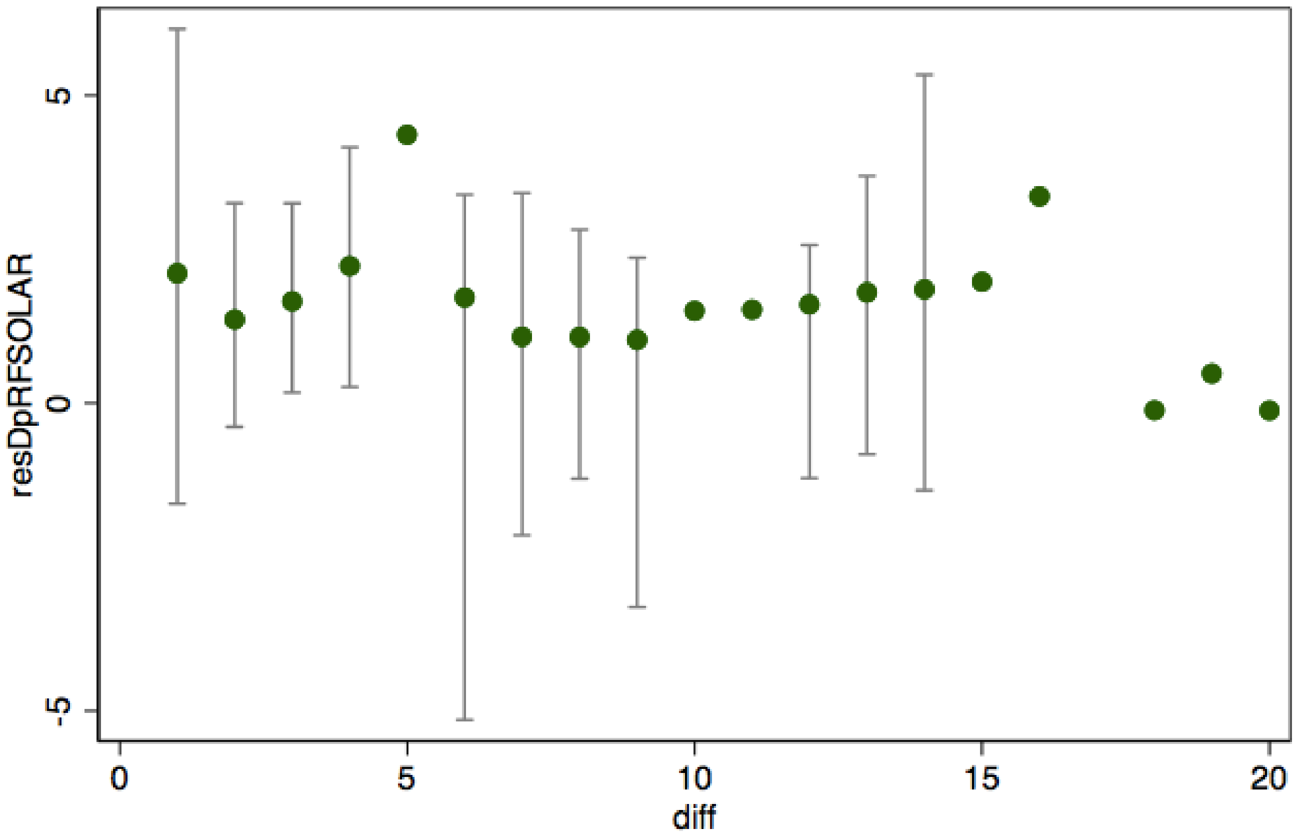








IV Results by horizon: IV = Solar



2SLS estimate and 95% HAR weak-IV robust CIs

IV:	RFSOLAR innovation
Control variable:	RF-Volcanic (stratospheric SOX)
Sample:	1959-2014

Estimates of TCR-*h*

Method	Instruments	Diff (h)	Estimate	95% CI	First-stage F	Sample
OLS (Levels)	--	--	**1.5**		--	1860-2014
DOLS	--	--	**1.6**	(1.5, 1.7)		1860-2014
DOLS	--	--	**1.4**	(1.2, 1.6)		1959-2014
IV	RFSUN, RFCO2-Cars (k=2)	15	**1.1**	(.8, 1.4)	24.9	1959-2014
IV	RFSUN, RFCO2-Cars (k=2)	20	**1.2**	(1.1, 1.4)	41.5	1959-2014
IV	RFCO2-Anth + RFSOX-Anth	10	**1.5**	(0.6, 2.6)	329.8	1959-2014
IV	RFCO2-Anth + RFSOX-Anth	15	**1.7**	(1.1, 2.5)	327.8	1959-2014
IV	RFCO2-Anth + RFSOX-Anth	20	**2.1**	(1.1, 5.1)	136.9	1959-2014

First-stage *F*'s are HAR. TCR-*h* is TCR estimated using *h*-differences IV. IV confidence intervals for *k*=1 are HAR-AR; for *k*=2 are HAR-strong-instrument. Temperature series is Hadley-4. IPCC-AR5 range for TCR is 1-2.5.

Some related work

Spatial-temporal

Atak, Linton, and Xiao, *J. Econometrics* (2011)
Bau, McInerny, and Stein, *Environmetrics* (2016)
Castruccio and Stein, *Ann. Appl. Stat.* (2013)
Chang et. al. (2016)

Longer data sets (500 year; paleo)

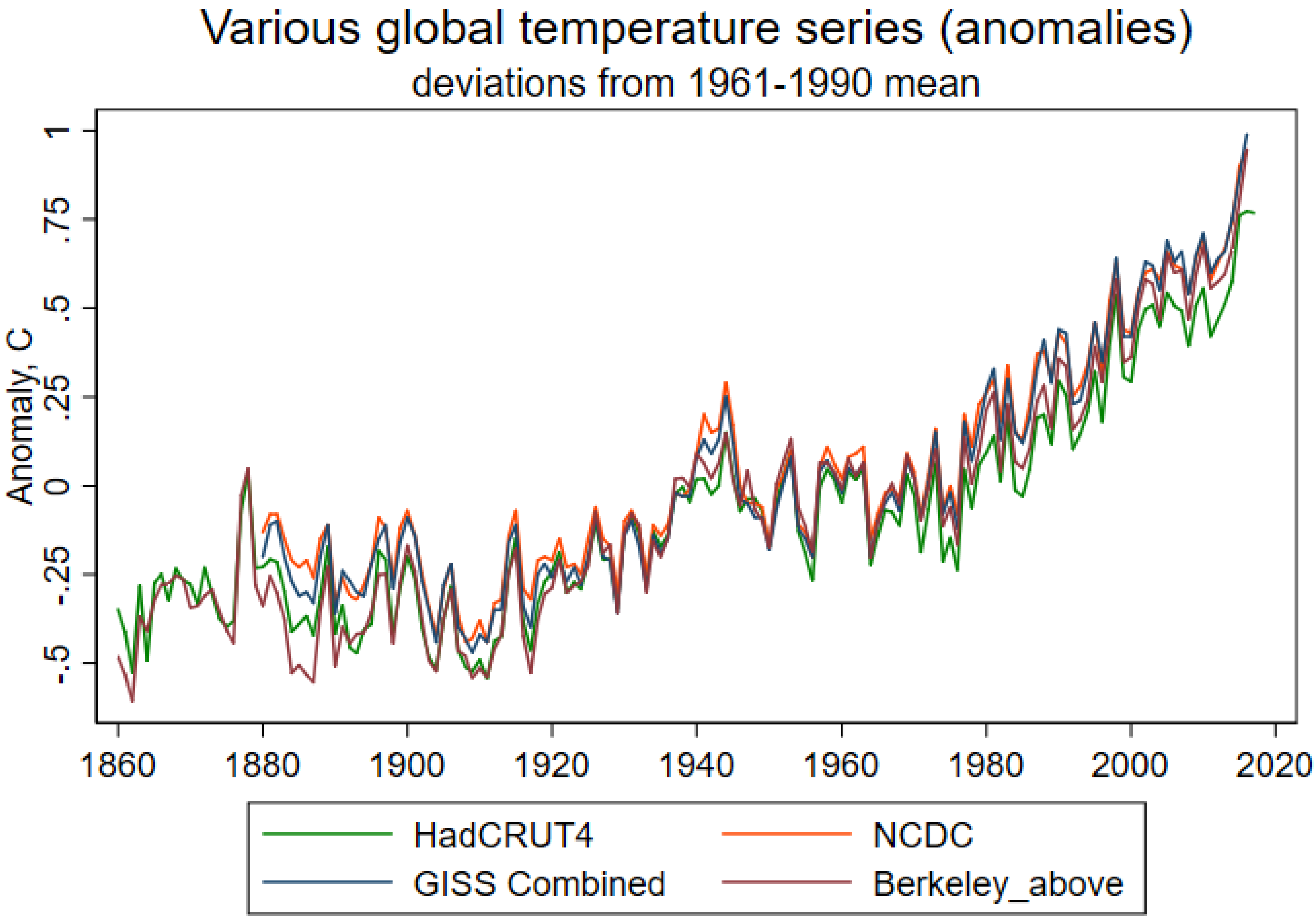
Dergiades and Kaufmann, *J Env Econ Mgt* (2016)
Davidson, Stephenson, Turasie, *Environmetrics* (2016)
Kaufmann and Pretis, ms, (2017)

ECS/TCR

Storelvmo, Leirvik, Johmann, Phillips, *Nature Geoscience* (2016)

Additional Slides

The temperature measurement debate



Radiative Forcing