Climate change and causal attribution: an overview

Alexis Hannart

1 November 2019

Definition

- *Attribution is the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of confidence.*

IPCC (2009)

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➡ Evidencing the causal influence of several factors

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IPCC (2009)

➡ Evidencing the causal influence of several factors

➡ Assigning a probability to a causal statement

« There is a 95% probability that human emissions are the dominant cause of the observed warming. »

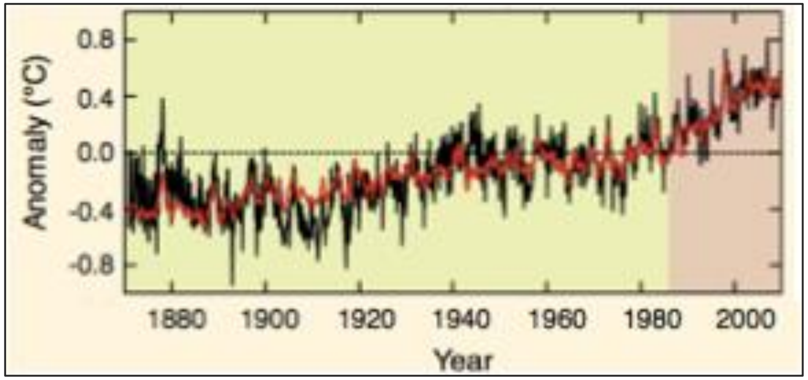
Definition

- *Attribution is the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of confidence.*

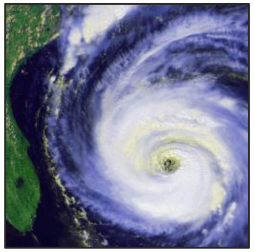
IPCC (2009)

→ Evidencing the causal influence of several factors

- Global long term trends
  - e.g. global warming



- Local extreme weather events
  - e.g. flood, hurricane…



Motivation

- Policy
  - Mitigation
  - Adaptation
- Liability
  - Legal responsibility
- Science
  - Improve understanding of underlying processes
- Awareness
  - Answer to general public and media

A typical media question to a climate scientist

Dr. Climate, was the event caused by climate change ?

A typical climate scientist answer

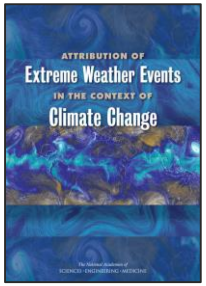
Dr. Climate, was the event caused by climate change ?

Ms. Journalist, I am afraid your question is ill-posed.

Indeed, climate change does not cause extreme events.

Instead, climate change can cause a change in the odds an event will or will not occur.

NAS 2016 report on attribution science



Another climate scientist answer

Great question !

Some events were indeed found not to be possible in a pre-industrial climate.

Therefore, we can actually say that climate change caused these events.

Possible next question

Is pre-industrial impossibility a strict requirement ?
What if the event is rare but still possible in a pre-industrial climate ?

So climate change is not a cause of such an event ?

A legitimate climate scientist question

Causal questions are tricky.
What should I say ?

Actually, what was causality
in the first place ?

Agenda

- Causality
- Case studies
- More causality

Two different problems

- Causal evidencing

A → B ?

- Causal discovery

? → B

? → ?

Two different problems

- Causal evidencing

A → B ?

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? → B

? → ?

Two different problems

- Causal evidencing

A → B ?

- A is usually :
  - human GHG emissions
  - human emissions (GHG, aerosols, ozone)
  - recent extensions into human climate engineering (SRM, CDR)
- B is usually:
  - short term extreme event
  - long term trend

Causality check-list

Can we come up with a list of simple conditions to determine whether or not A caused B ?

Causality fundamentals – 18th century

We define a cause to be an event followed by another, …

David Hume

Temporal precedence. ☑

… where if the first event had not been, the second never had existed, …

Counterfactual inconsistency. ☑

… and where all the events similar to the first are followed by events similar to the second.

Factual consistency. ☑

Causality check-list

- Temporal precedence. ☑
- Counterfactual inconsistency. ☑
- Factual consistency. ☑

Factual and counterfactual tests

Counterfactual inconsistency.

Earth as it would have been without A (counterfactual)

B never occurs.

Factual and counterfactual tests

Counterfactual inconsistency.

Earth as it would have been without A (counterfactual)

B never occurs.

Factual consistency.

Earth as it was with A (factual)

B always occurs.

Factual and counterfactual tests

Counterfactual inconsistency.

Earth as it would have been without A (counterfactual)

B rarely occurs.

Probability of B = p_0

Factual consistency.

Earth as it was with A (factual)

B (less) rarely occurs.

Probability of B = p_1

Causal calculus – 21st century

Causality has two facets: Necessary and Sufficient causation.

Judea Pearl

Necessary causation is similar to:

Counterfactual inconsistency. ☑

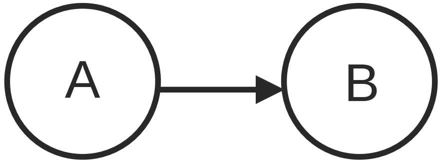
Sufficient causation is similar to:

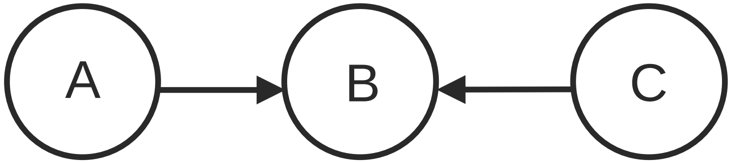
Factual consistency. ☑

Causal calculus – 21st century

Causality can be probabilized !

This can be done using a particular kind of probabilistic model called oriented graphical models.





Causal calculus – 21st century

Probabilities of necessary and sufficient causation can be derived easily using p_0 and p_1 !

Probability of necessary causation:

$$\mathrm{PN} = \max\{1 - \frac{p_0}{p_1}, 0\}$$

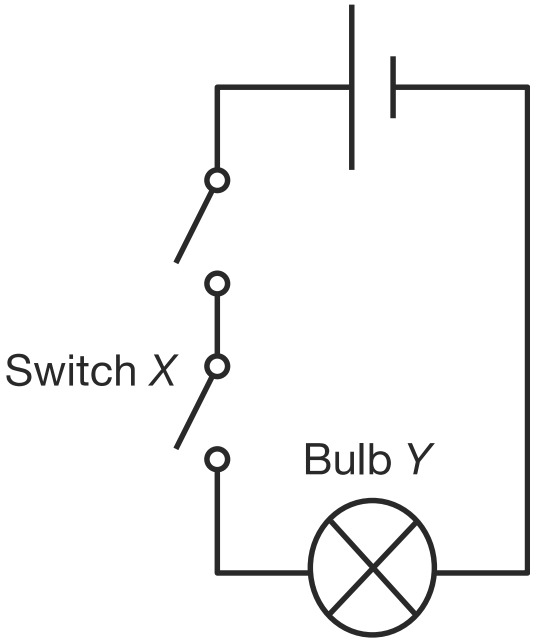
Probability of sufficient causation:

$$\mathrm{PS} = \max\{1 - \frac{1 - p_1}{1 - p_0}, 0\}$$

Causal calculus – 21st century

- **Probability of necessary causation** = probability that the effect is removed when the cause is turned off, conditional on the fact that the effect and the cause were initially present.

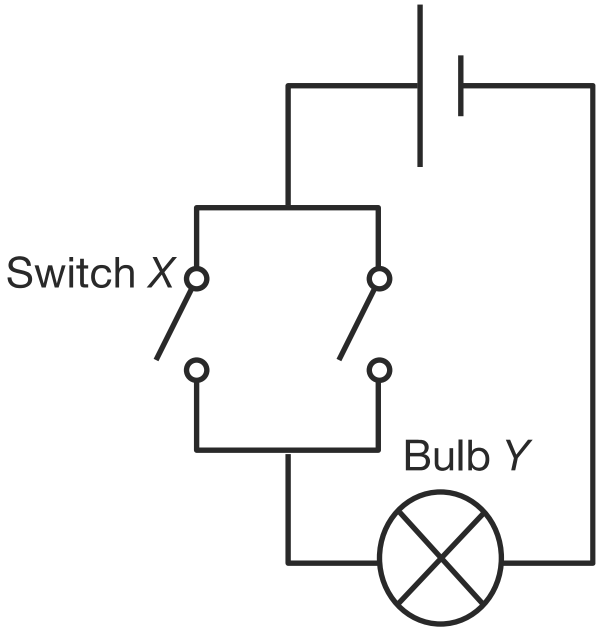
$$\mathrm{PN} = \max\{1 - \frac{p_0}{p_1}, 0\}$$



Causal calculus – 21st century

- **Probability of sufficient causation** = probability that the effect appears when the cause is turned on, conditional on the fact that the effect and the cause were initially absent.

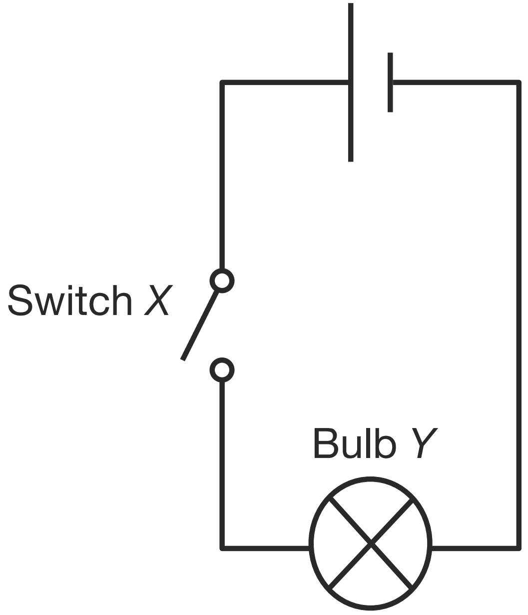
$$\mathrm{PS} = \max\{1 - \frac{1-p_1}{1-p_0}, 0\}$$



Causal calculus – 21st century

- **Probability of necessary and sufficient causation** = probability that the effect appears when the cause is turned on, conditional on the fact that the effect and the cause were initially absent.

$$\mathrm{PNS} = \max\{p_1 - p_0,\ 0\}$$



Causal calculus – 21st century

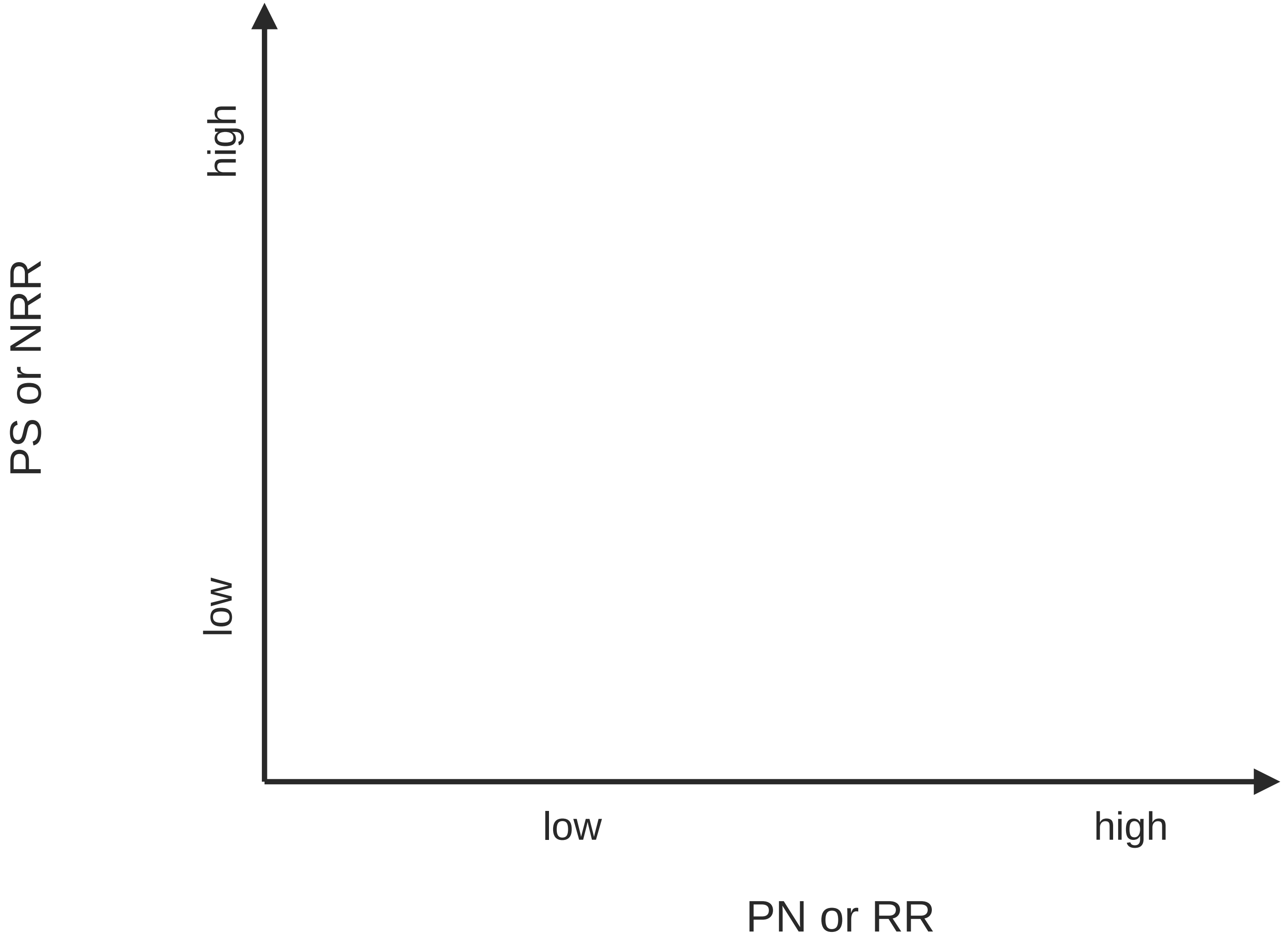
PN is an increasing function of the risk ratio

$$\text{PN} = \max\{1 - \frac{p_0}{p_1}, 0\} \quad \Leftrightarrow \quad \text{RR} = \frac{p_1}{p_0}$$

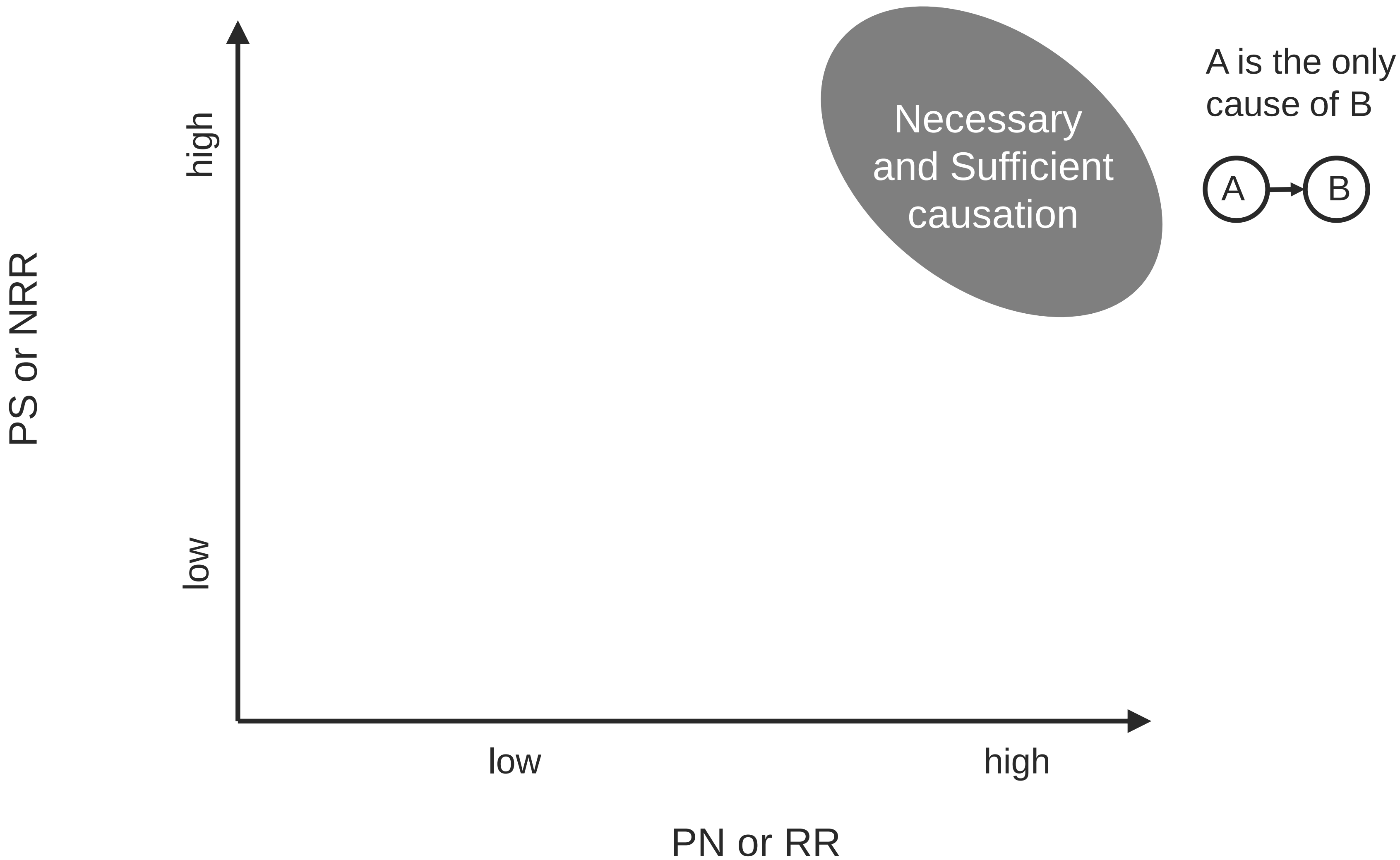
PS is an increasing function of the non-risk ratio

$$\text{PS} = \max\{1 - \frac{1 - p_1}{1 - p_0}, 0\} \quad \Leftrightarrow \quad \text{NRR} = \frac{1 - p_0}{1 - p_1}$$

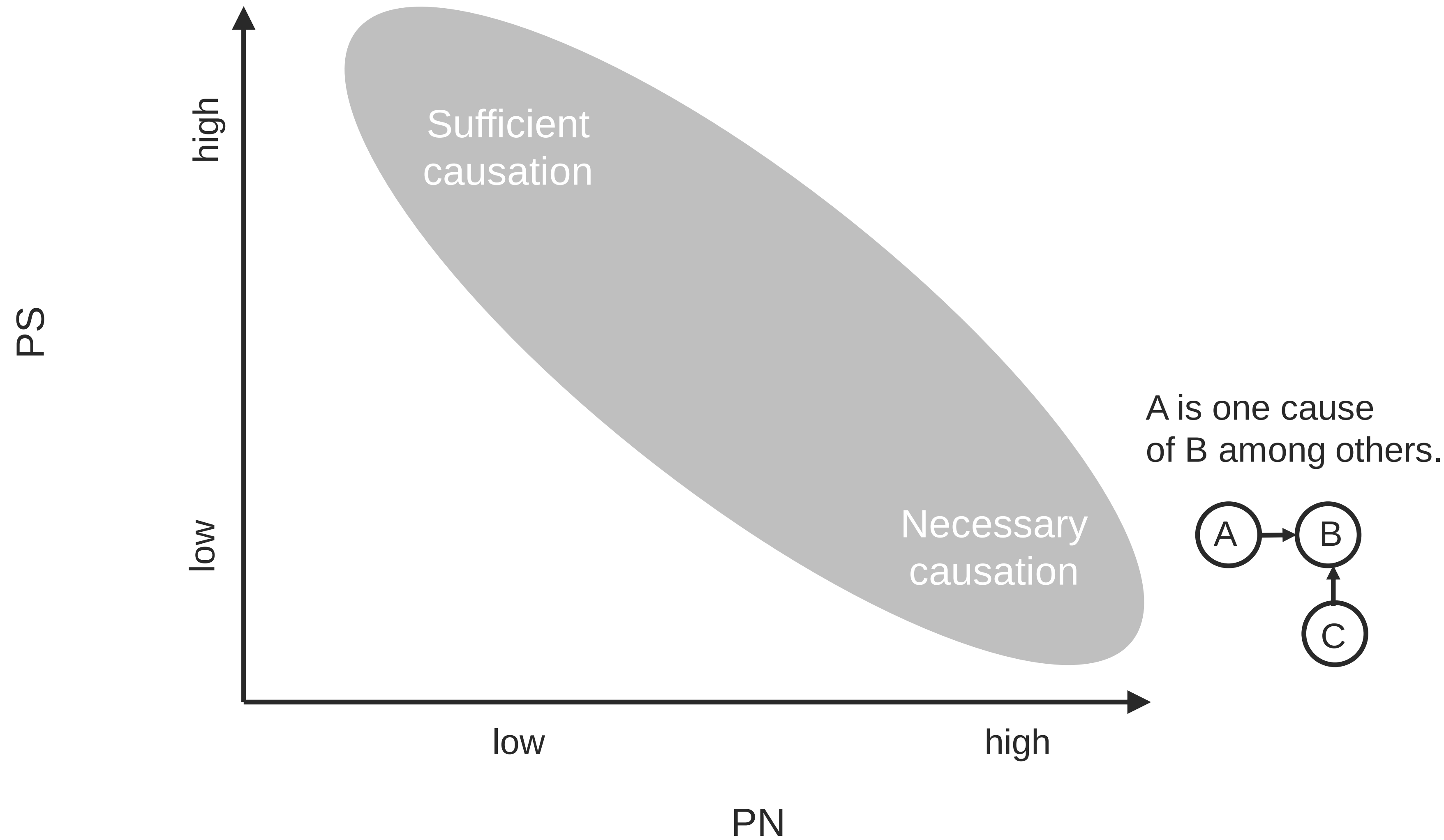
2D causality mapping



2D causality mapping



2D causality mapping



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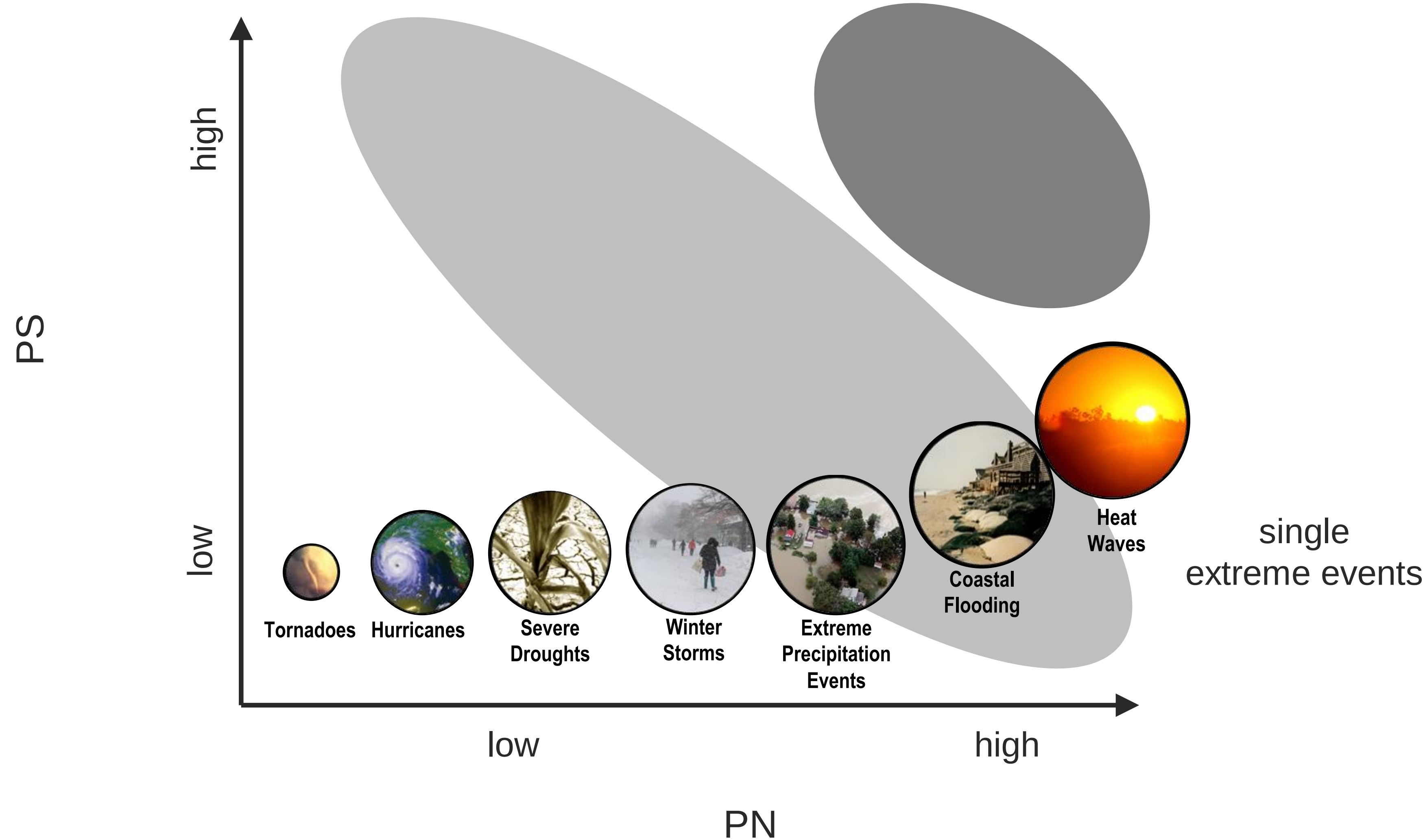
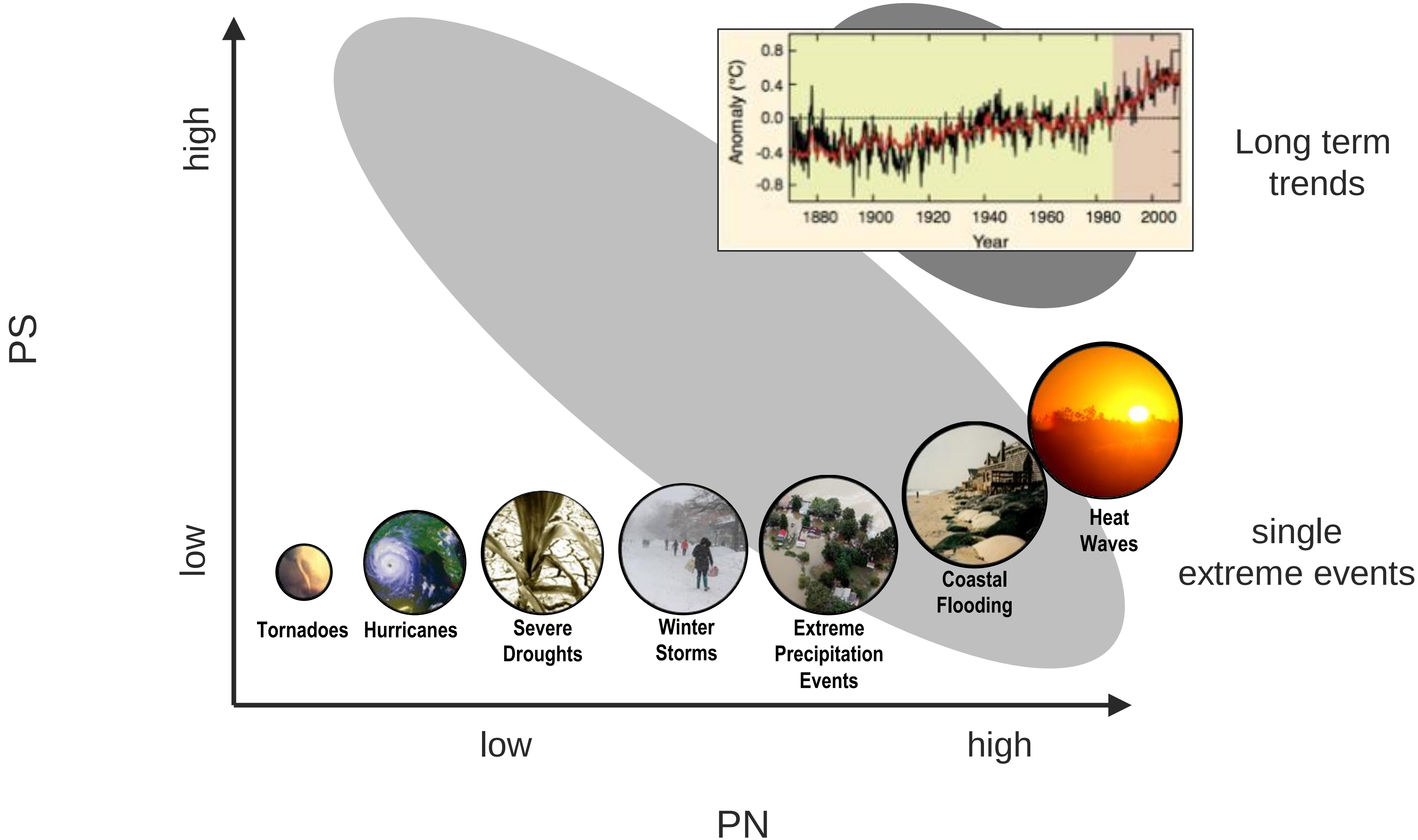


2D causality mapping



Agenda

- Causality
- Case studies
- More causality

Fort McMurray, Alberta, May 2016 wildfire

Kirchmeier-Young et al. 2017

Hypothetical causal chain

Human GHG emissions

<u>Factors involved in wildfires</u>

- ignition source
- available fuels
- weather conditions
- suppression efforts

- Fire occurrence
- Fire magnitude

Hypothetical causal chain

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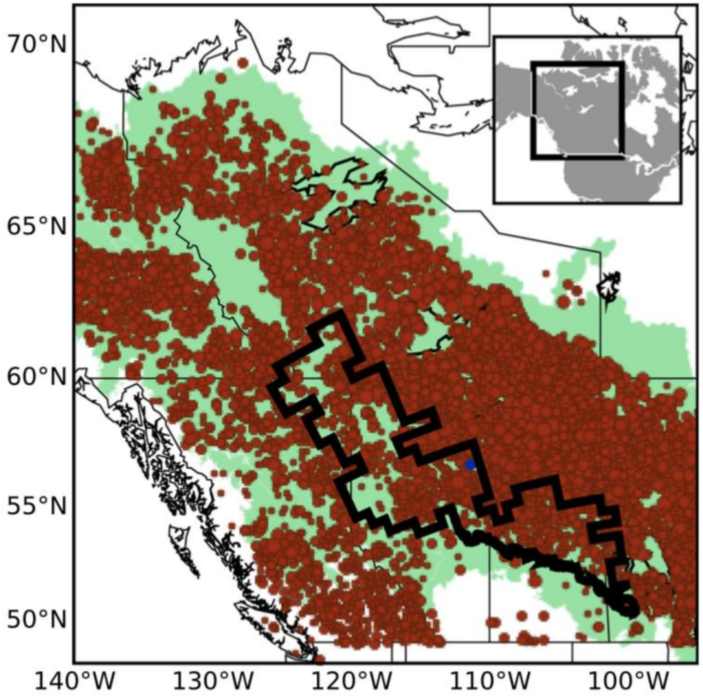
Canadian Forest Fire Weather Indexes

- Fine Fuels Moisture Code FFMC
- Duff Moisture Code DMC
- Drought Code DC
- Initial Spread Index ISI
- Buildup Index BUI
- Fire Weather Index FWI
- Daily Severity Rating DSR
- Surface Fuel Consumption SFC
- Rate of Spread ROS
- Head Fire Intensity HFI

Data

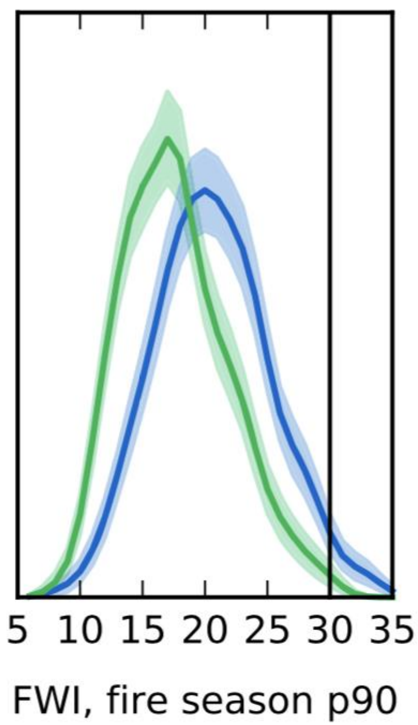
Wilfire occurrences
1980-2016



- Observations
  - Global Fire Weather Database
  - MERRA reanalysis 0.5°
  - 1980 to present

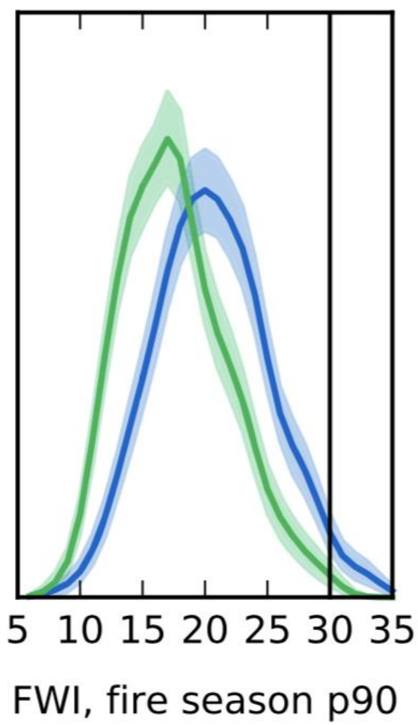
- Simulations
  - CanESM2 50 members ensemble
  - Resolution 2.8°
  - Historical NAT runs
  - Historical ALL runs
  - 1950 to 2020
  - Downscaled statistically to 0.5°
  - Multivariate bias correction

Results



- Blue: factual, green: counterfactual
- The factual and counterfactual PDFs of the FWI index differ
- The difference is most visible for large values of the index

Results



An event is usually defined based on a variable X exceeding a threshold u:

$$E = \{X > u\}$$

$$\left\{\begin{array}{l} p_0 \sim 0.02 \\ p_1 \sim 0.10 \\ RR \sim 5 \\ PN \sim 0.8 \\ PS \sim 0.07 \end{array}\right.$$

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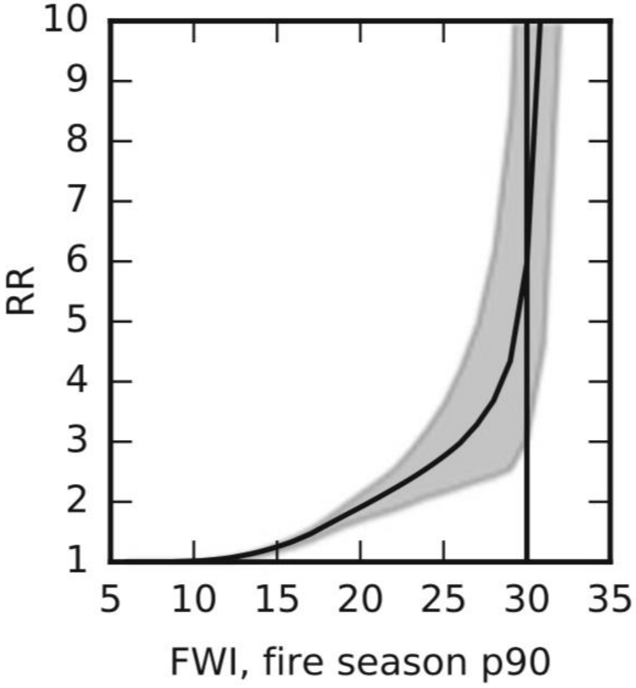

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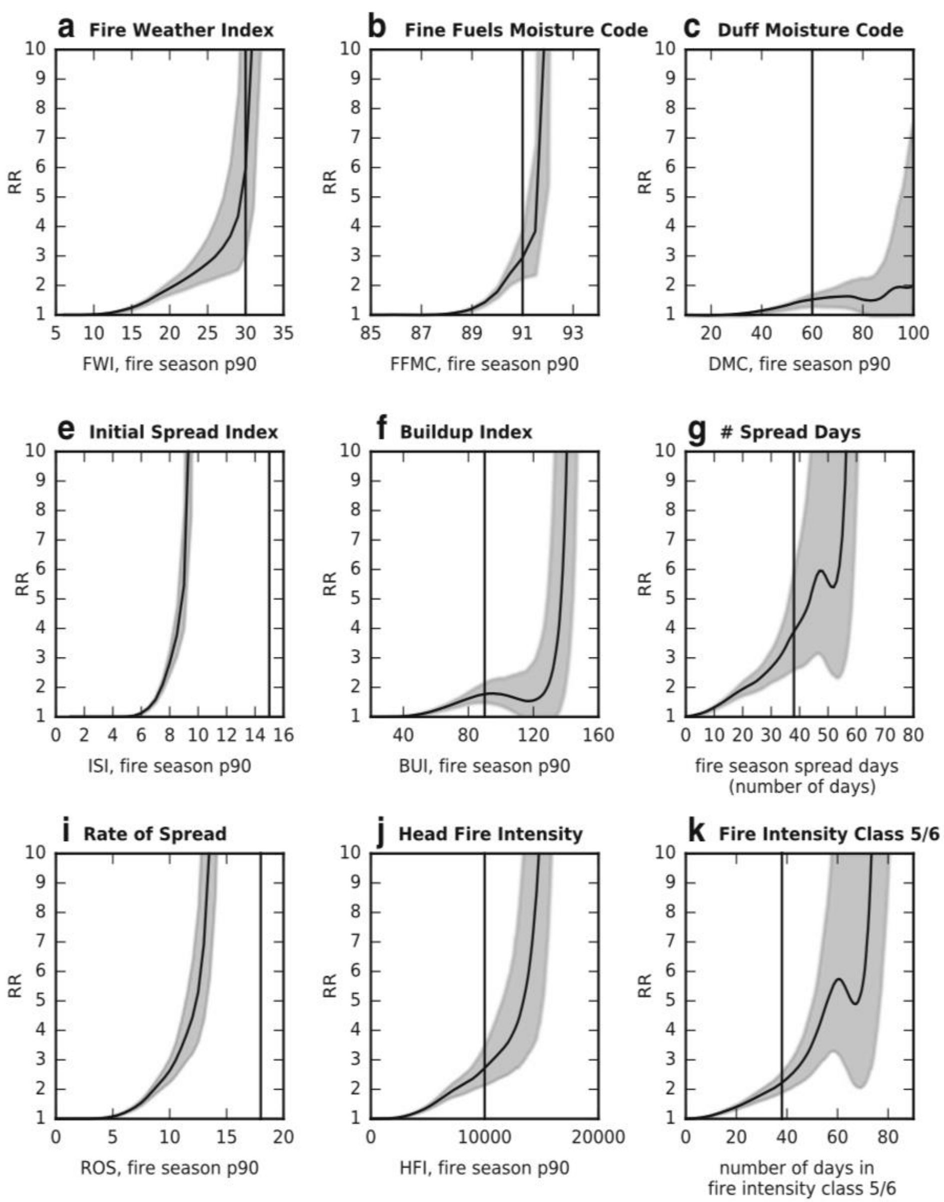

Risk Ratio

~ 2 to 7

A typical media question to a climate scientist

Dr. Climate, was the McMurray fire caused by human-induced climate change ?

Statements: the conventional way

Risk Ratio ~ 5

- « We can not say anything about whether or not human emissions were a cause of this particular wildfire.»
- « All we can say is that human emissions have made this type of event five times more likely. »

A possible answer based on previous considerations

We did observe an increase in the frequency of wildfires like this one over the past decades.

It is very likely that human emissions is the cause of this increase.

Regarding the McMurray fire, as a single extreme event, it has multiple necessary causes. None is sufficient.

More likely than not, human emissions is one of these necessary causes.

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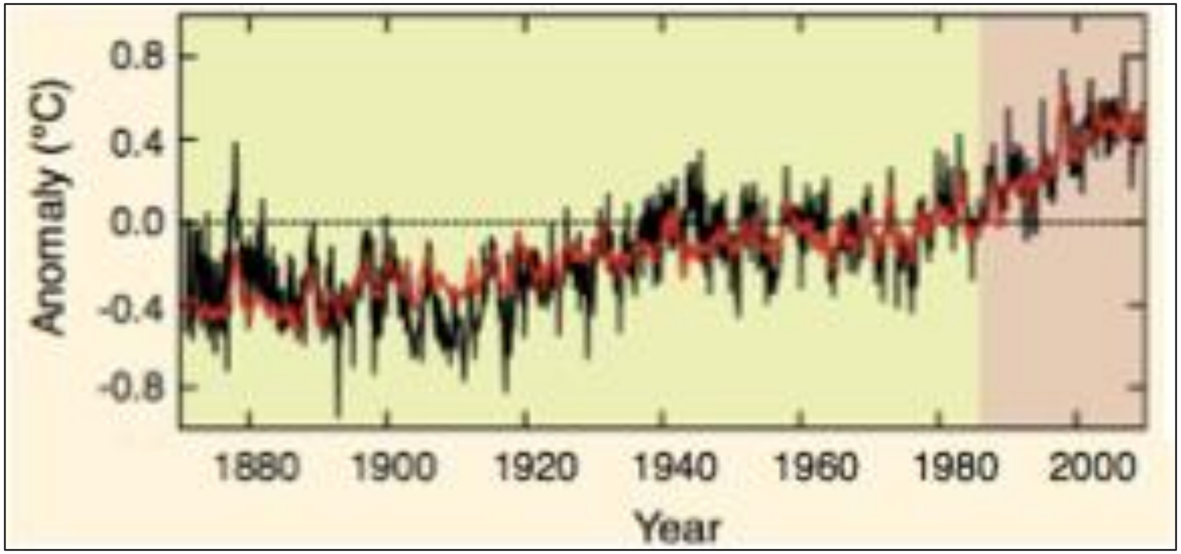
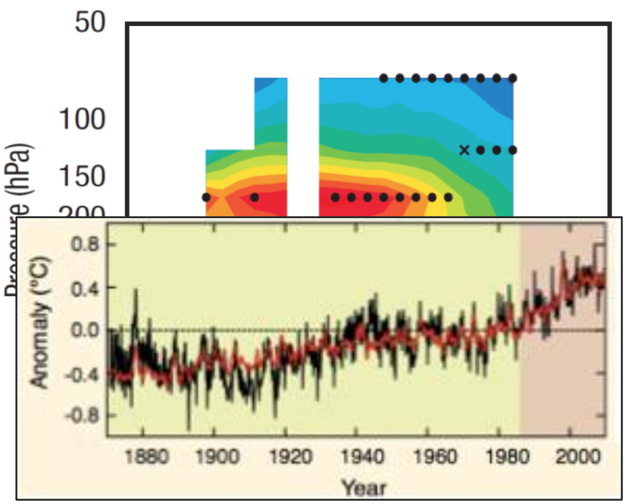
Global warming



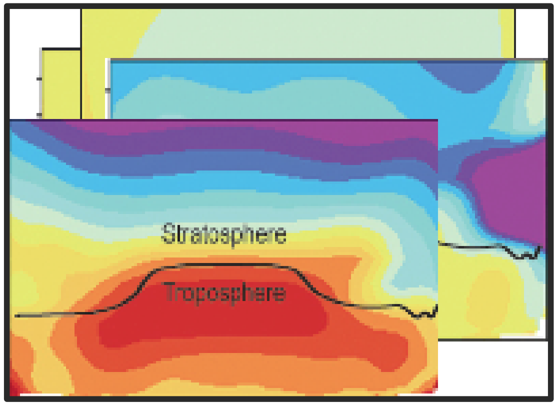
Conventional method for attributing trends

$$y = x\beta + \nu$$

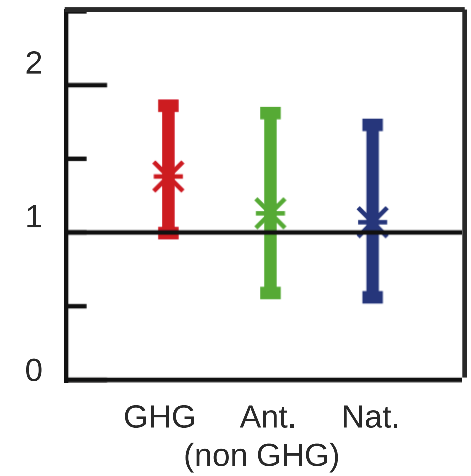
Observations



GCM patterns



Coefficients



Hasselmann 1993
Hegerl et al. 1996
Allen and Tett 1999
Allen and Stott 2003

Ribes et al. 2012
Hannart et al. 2014
Hannart 2016
Katzfuss et al. 2017
Hannart 2018b
More to come.

Defining an event

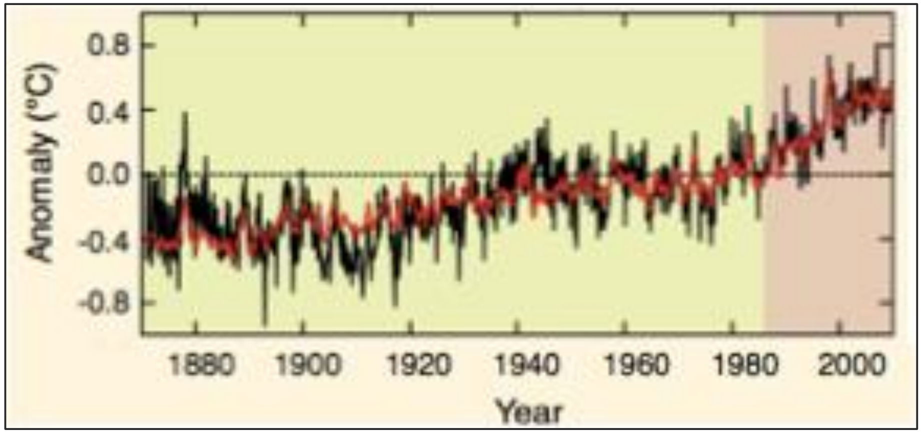
- An event is usually defined based on a variable X exceeding a threshold u:

$$E = \{X > u\}$$

Could this definition be used as well for long term climate trends?

Does the word ‘event’ holds here as well ?

Global warming: what was the event?



$$E = \{X > u\}$$

For instance:

X = 1951-2010 warming
u = 0.2° C

Illustration: global warming

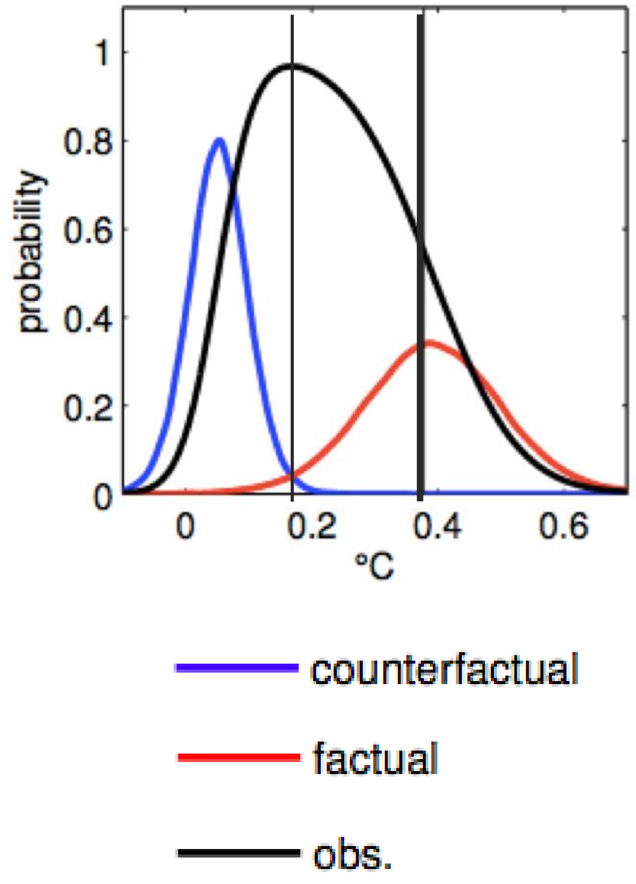
Computation of the PDF of the warming X from factual and counterfactual simulations.

Evaluation of p_0 and p_1

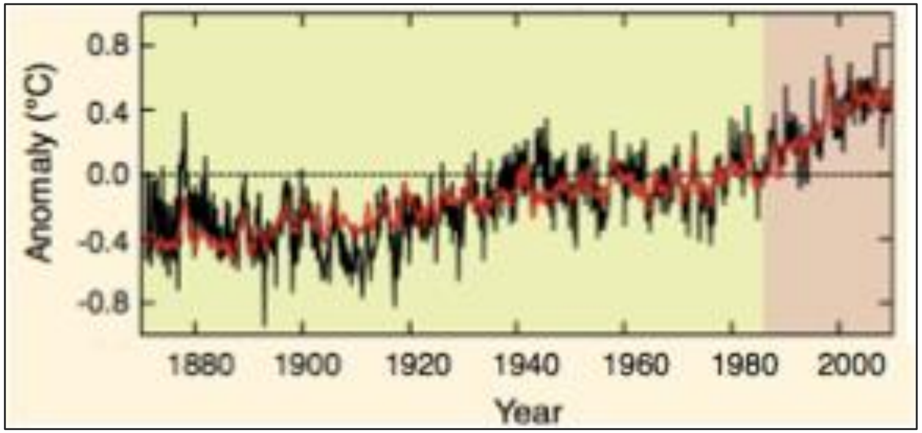
- $p_0 = 0.01$
- $p_1 = 0.99$

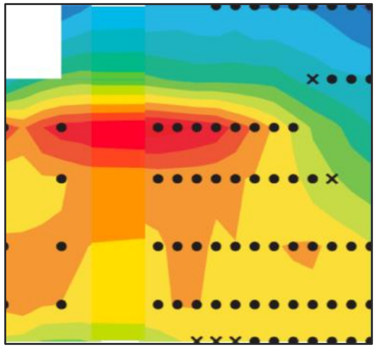
$PNS = p_1 - p_0 = 0.98$

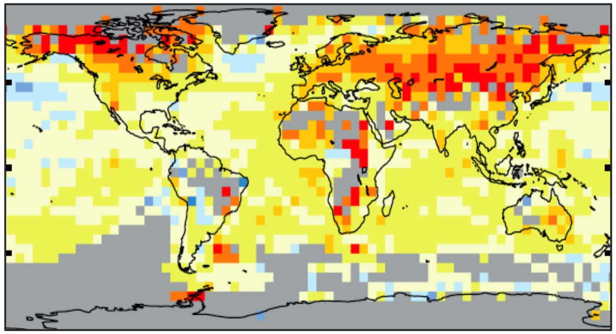
PDF of global warming
1951-2010



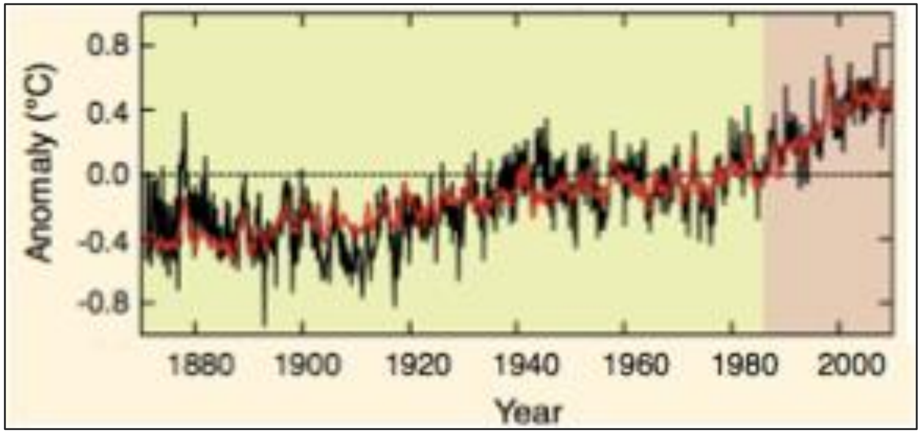
It is not just the trend, but also the patterns

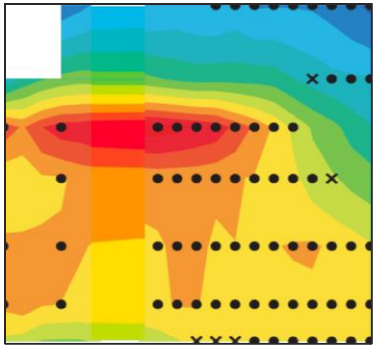


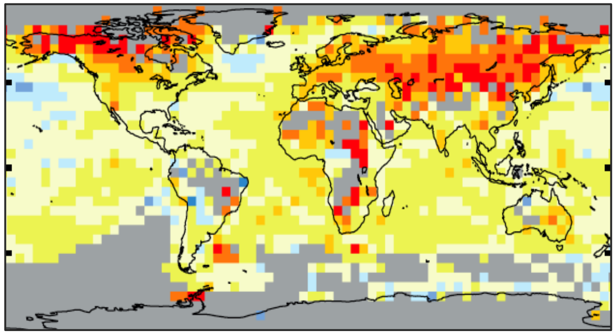




Trend and patterns: what was the event?

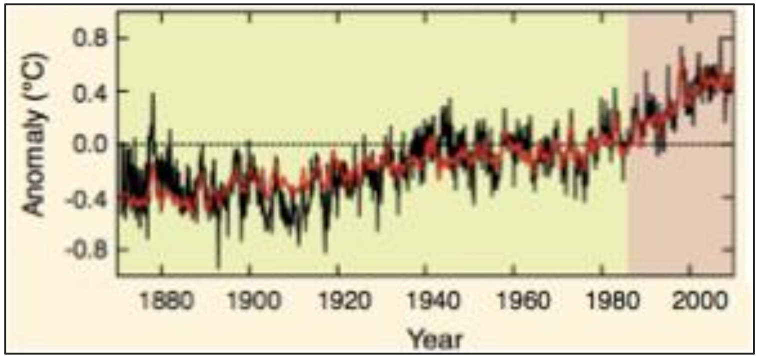


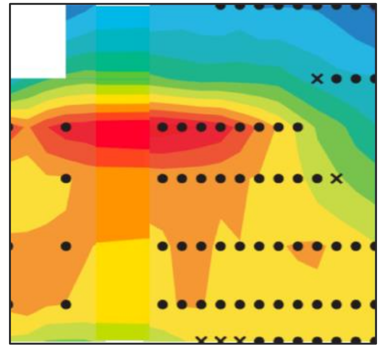


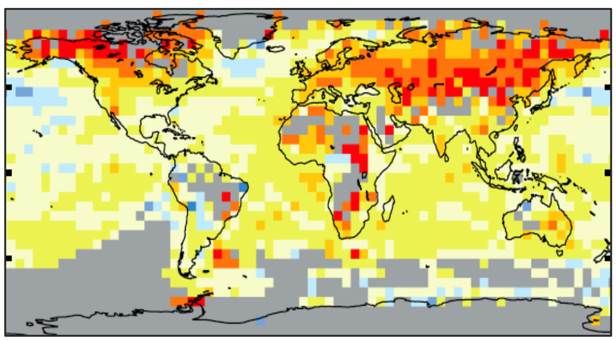


$$E = \{X > u\}$$

Event definition - Fingerprinting







$$y = (y_1, y_2, \ldots, y_d)$$

$$X = \phi^*(y)$$

Hannart and Naveau 2018

Results

Computation of the PDF of the optimal index X from factual and counterfactual simulations.

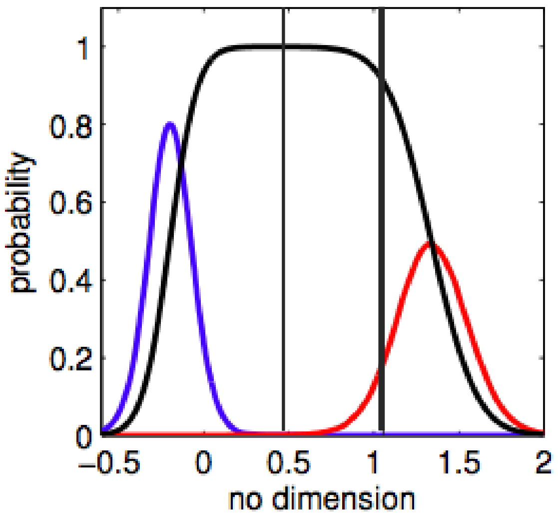
Selection of a threshold u defining the event of interest {X >u}

Evaluation of p_0 and p_1

- $p_0 = 0.00004$
- $p_1 = 0.99996$

PNS = $p_1 - p_0 = 0.9999$

PDF of optimal index



Agenda

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- More causality

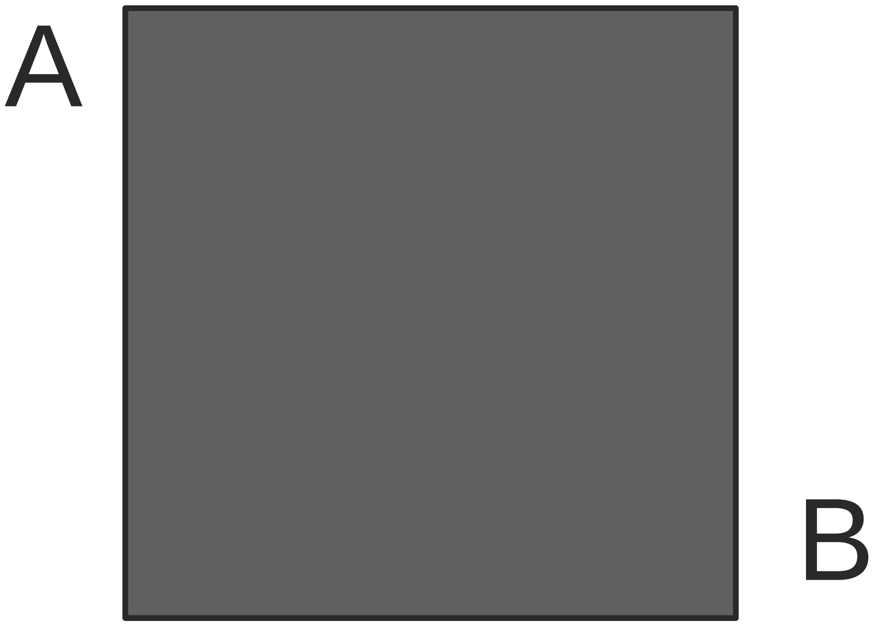
Causality check-list

Counterfactual inconsistency.

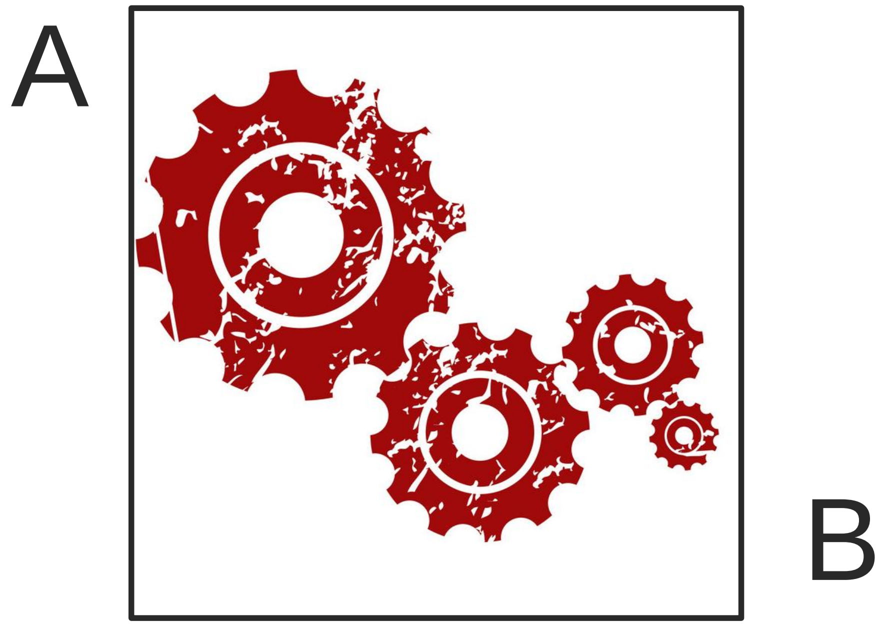
Factual consistency.

?

Which causal situation is most pleasant?



$p_1 = 0.99$
$p_0 = 0.01$



$p_1 = 0.99$
$p_0 = 0.01$

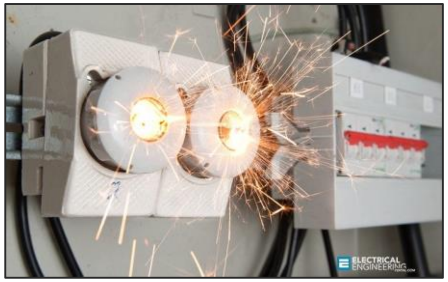
Causality check-list

- Counterfactual inconsistency. ☑
- Factual consistency. ☑
- Mechanistic understanding. ☑

Shepherd 2016
Williamson 2011
Ney 2009

Was the fire caused by the electrical fault ?

A



B

- Counterfactual inconsistency. ☑
- Factual consistency. ☐
- Mechanistic understanding. ☑

The electrical fault qualifies as a necessary cause.

Was the fire caused by atmospheric oxygen ?

A

B

Counterfactual inconsistency. ☑

Factual consistency. ☐

Mechanistic understanding. ☑

Was the fire caused by atmospheric oxygen ?

A

B

- Counterfactual inconsistency. ☑
- Factual consistency. ☐
- Mechanistic understanding. ☑

- Atmospheric oxygen does not qualify as a cause since its presence is always expected here.
- Lack of atypicality of A <u>in the context of the question</u>

Causality check-list

- Counterfactual inconsistency. ☑
- Factual consistency. ☑
- Mechanistic understanding. ☑
- Atypicality. ☑

Halpern and Hitchcock 2011
Knobe and Fraser 2008

Two different problems

- Causal evidencing

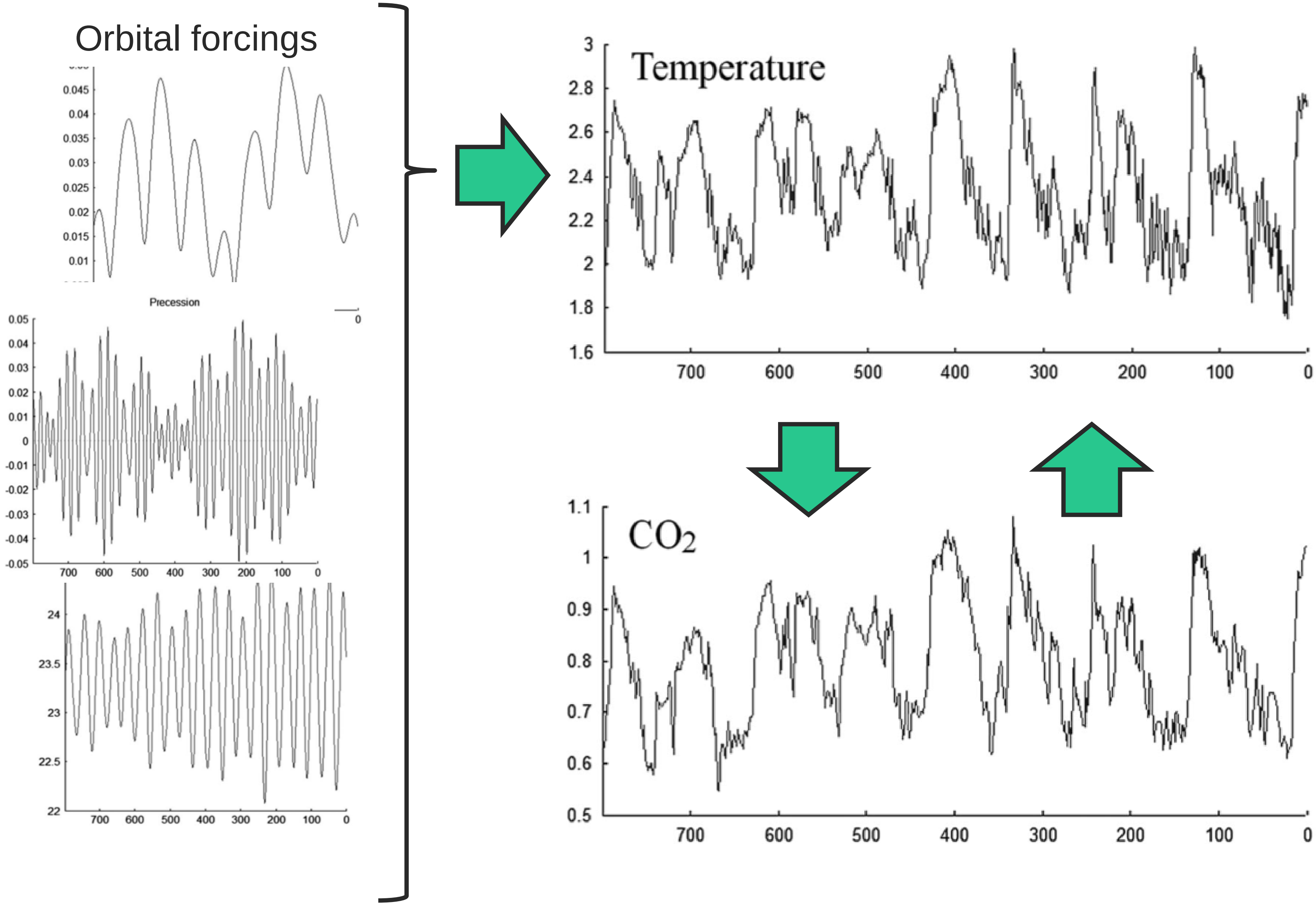
A ⇒ B ?

- Causal discovery

? ⇒ B

? ⇒ ?

Causal discovery – example



Granger approach – principle

Linear regression of past on present in observations

- Statistical formulation:
  - Vector Autoregressive model (VAR)
  - different order p (time) and dimension d (variables included)
  - different formulation of the noise component

$$\underbrace{A(L)}_{\substack{L\,=\,\text{lag}\\ \text{operator}}}\,\underbrace{y_t}_{\substack{\text{internal}\\ \text{variables}}} = \Lambda(L)\underbrace{d_t}_{\text{forcings}} + \underbrace{u_t}_{\text{noise}}$$

Granger approach – example

Table 5. Estimated matrix E with robust standard errors in parentheses

	Temp	CO_2	CH_4	Ice
Temp	-0.184^{***} (0.037)	0.090 (0.058)	0.038 (0.038)	-0.138^{**} (0.055)
CO_2	0.047^{***} (0.012)	-0.107^{***} (0.019)	-0.053^{***} (0.014)	-0.048^{**} (0.019)
CH_4	0.127^{***} (0.031)	0.026 (0.058)	-0.316^{***} (0.034)	-0.123^{**} (0.048)
Ice	-0.028^{**} (0.012)	-0.033^{*} (0.020)	-0.010 (0.012)	-0.121^{***} (0.018)

Table 6. 95% confidence intervals for 1-kyr changes (columns) following unit deviations from steady state (rows)

(a)	ΔTemp	ΔIce
CO_2	[−0.113, 0.974]	[−0.117, 0.004]
CH_4	[−0.078, 0.243]	[−0.026, 0.010]

(b)	ΔCO_2	ΔCH_4
Temp	[0.005, 0.015]	[0.030, 0.087]
Ice	[−0.050, −0.006]	[−0.281, −0.037]

Davidson et al. 2015

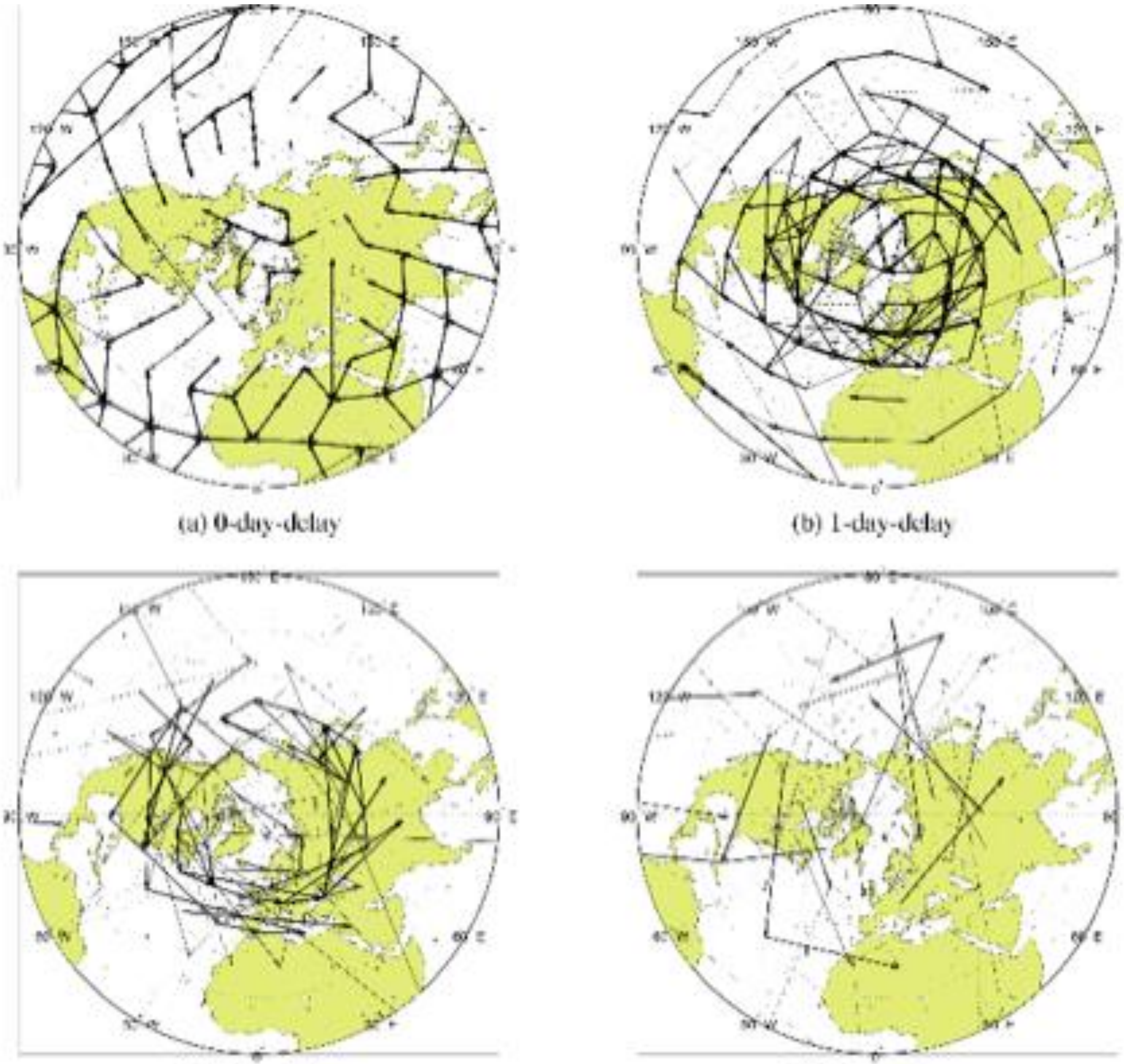
Tracking conditional independence in multivariate time series

Data:

- **500 mb geopotential height**
- NCEP/NCAR Reanalysis
- 1948-2011
- Results for winter (DJF months)
- Fekete grid

Shown here:

- Stereo-graphic projection (North)
- **Strongest direct connections for 0, 1, 2, 3 days.**



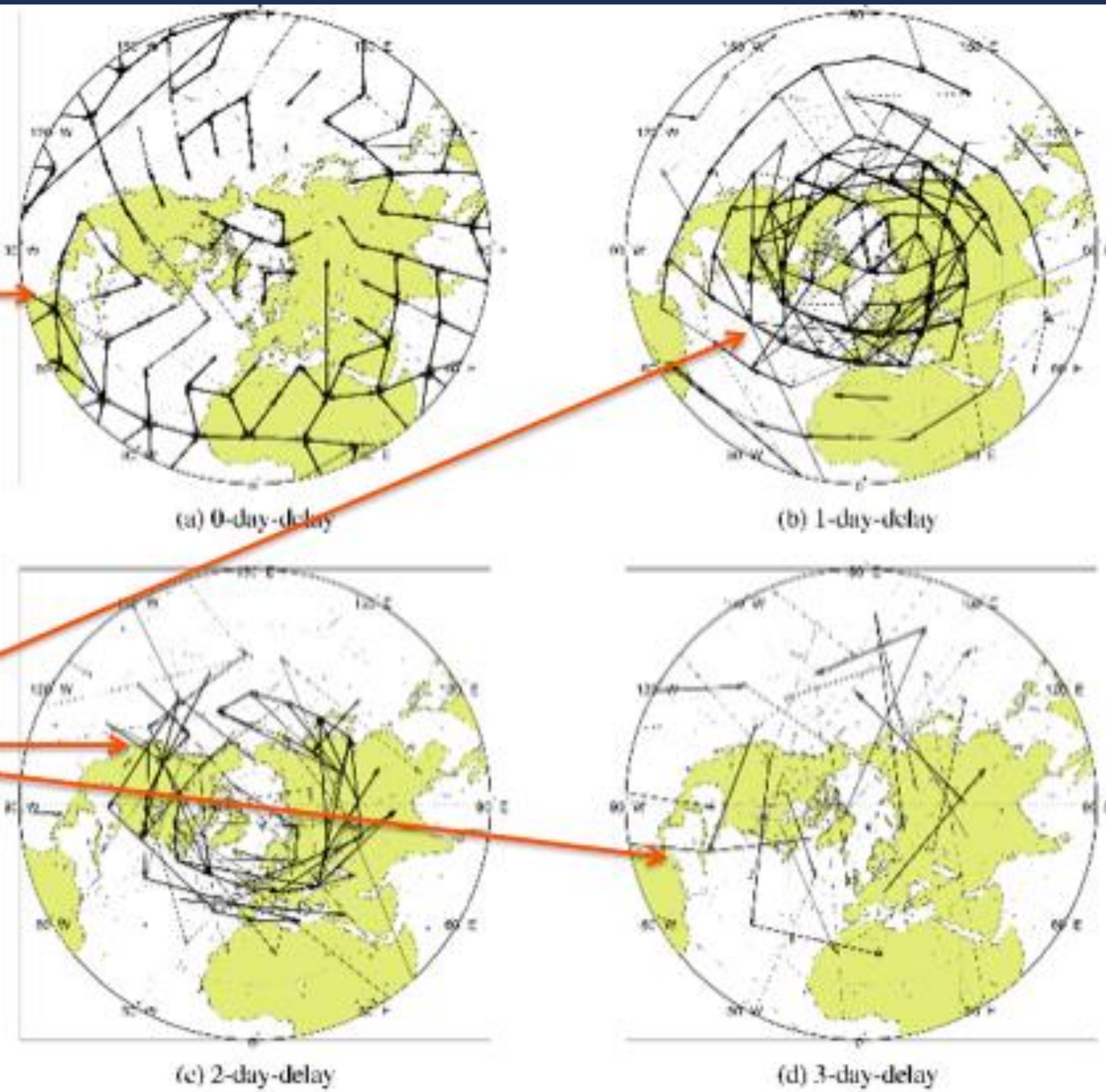
(a) 0-day-delay (b) 1-day-delay (c) 2-day-delay (d) 3-day-delay

Ebert Uphoff et al. 2012

Tracking conditional independence in multivariate time series

Due to dominant **diffusion** processes near equator

Due to **advection** processes (storm tracks)

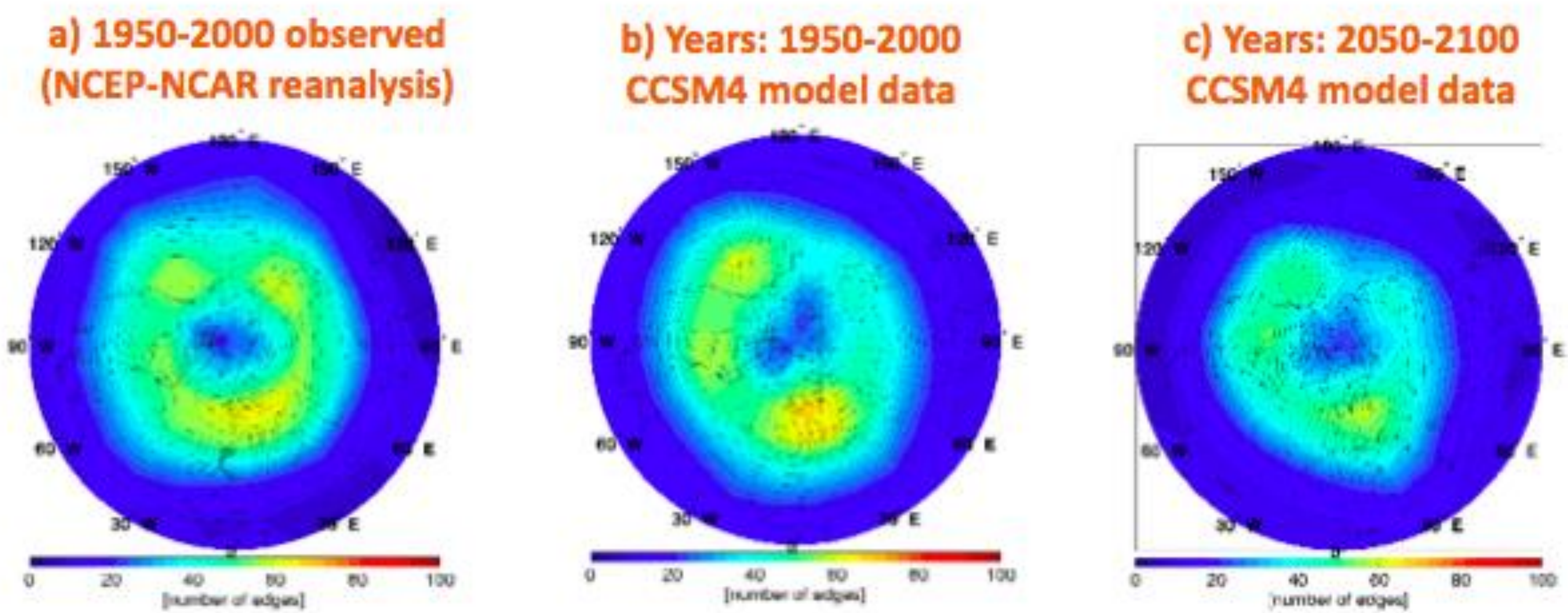


Ebert Uphoff et al. 2012

Example: tracking conditional independence in multivariate time series

Observations: In warmer climate

- information flow diminishes (hubs disappear)
- remaining hubs move poleward
- Consistent with literature: midlatitude storm tracks move poleward in warmer climate.
- We can now localize some of these effects!



Ebert Uphoff et al. 2014

Summary

- Causal theory provide useful probabilistic definitions to buttress attribution statements and unify methodology in the context of climate change.

- Four simple principles buttress most of causal attribution :
  - Counterfactual inconsistency,
  - Factual consistency,
  - Mechanistic understanding,
  - Atypicality.

Summary

- Counterfactual inconsistency and factual consistency require a modeling framework to perform numerical experiments.
- The modeling framework is also key to mechanistic understanding, and can be used for sensitivity analysis to help evidencing the causal chain.
- Atypicality could be discussed, in articulation with legal issues.
- Several methodological variations exist to implement these principles. More needs to be done.

Thank you

Event definition - Fingerprinting

- Event of interest:

$$\{\phi^*(y) > u^*\}$$

- Define the event optimally w.r.t. PNS:

$$\begin{aligned}(\phi^*, u^*) &= \text{argmax}_{u,\phi}\ \text{PNS}(\{\phi(y) > u\}) \\ &= \text{argmax}_{u,\phi}\ p_1(\phi(y) > u) - p_0(\phi(y) > u)\end{aligned}$$

- Standard classification problem. A solution is:

$$\begin{cases}\phi^*(y) = \log f_1(y) - \log f_0(y) \\ u^* = 0\end{cases}$$

Event definition - Fingerprinting

Gaussian setting:

$$f_0(y) = \mathcal{N}(y \mid \mu_0, \mathbf{\Sigma})$$

$$f_1(y) = \mathcal{N}(y \mid \mu_1, \mathbf{\Sigma})$$

$$\phi^*(y) = (\mu_1 - \mu_0)'\mathbf{\Sigma}^{-1} y$$

Event definition - Fingerprinting

Gaussian setting:

$$f_0(y) = \mathcal{N}(y \mid \mu_0, \boldsymbol{\Sigma})$$

$$f_1(y) = \mathcal{N}(y \mid \mu_1, \boldsymbol{\Sigma})$$

$$\phi^*(y) = (\mu_1 - \mu_0)' \boldsymbol{\Sigma}^{-1} y$$

$$\phi^* = \boldsymbol{\Sigma}^{-1}(\mu_1 - \mu_0) = \sum_{i=1}^{d} \left[\frac{(\mu_1 - \mu_0)' \mathrm{v}_i}{\lambda_i} \right] . \mathrm{v}_i$$

Event definition - Fingerprinting

Gaussian linear regression setting:

$$f_0(y) = \mathcal{N}(y \mid \boldsymbol{x}\beta_0, \boldsymbol{\Sigma})$$

$$f_1(y) = \mathcal{N}(y \mid \boldsymbol{x}\beta_1, \boldsymbol{\Sigma})$$

$$\phi^*(y) = \quad \cdots$$

Was the wildfire caused by human GHG emissions?

A

B

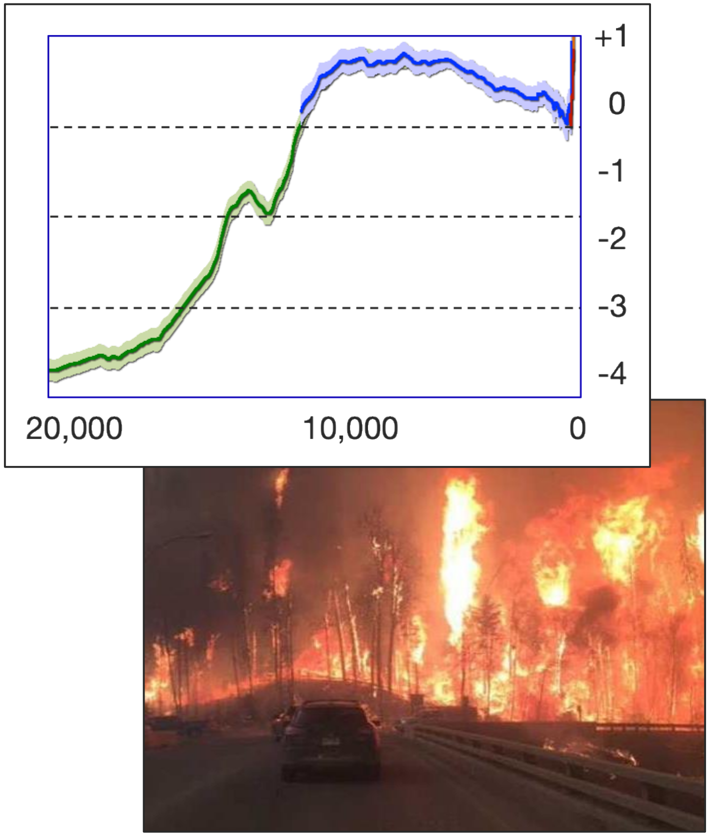
- Counterfactual inconsistency.
- Factual consistency.
- Mechanistic understanding.

- Is A atypical <u>in the context of the question?</u>
- Debatable.

Was the wildfire caused by the last deglaciation?

A

B



- Counterfactual inconsistency. ☑
- Factual consistency. ☐
- Mechanistic understanding. ☑

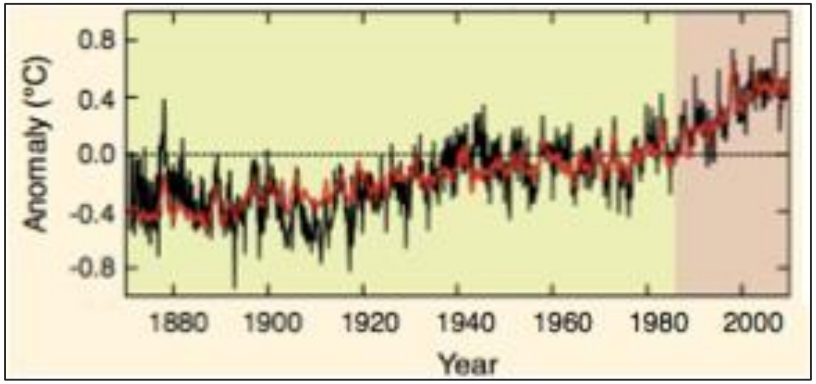
Is A atypical <u>in the context of the question?</u>

No.

Was global warming caused by human GHG emissions?

A

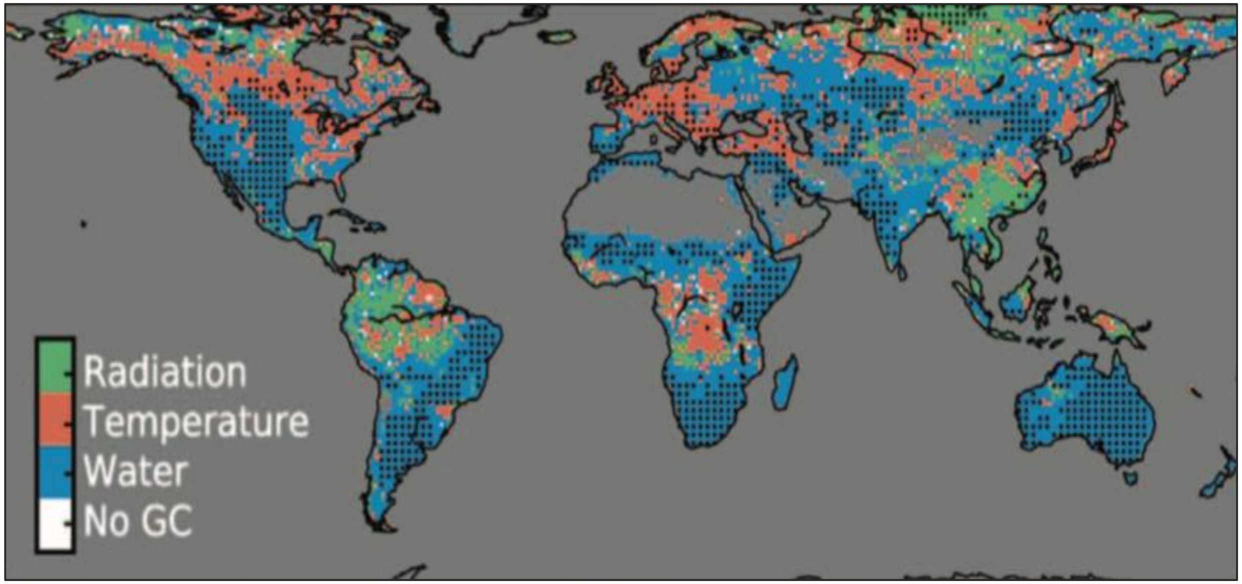
B



- Counterfactual inconsistency. ☑
- Factual consistency. ☐
- Mechanistic understanding. ☑

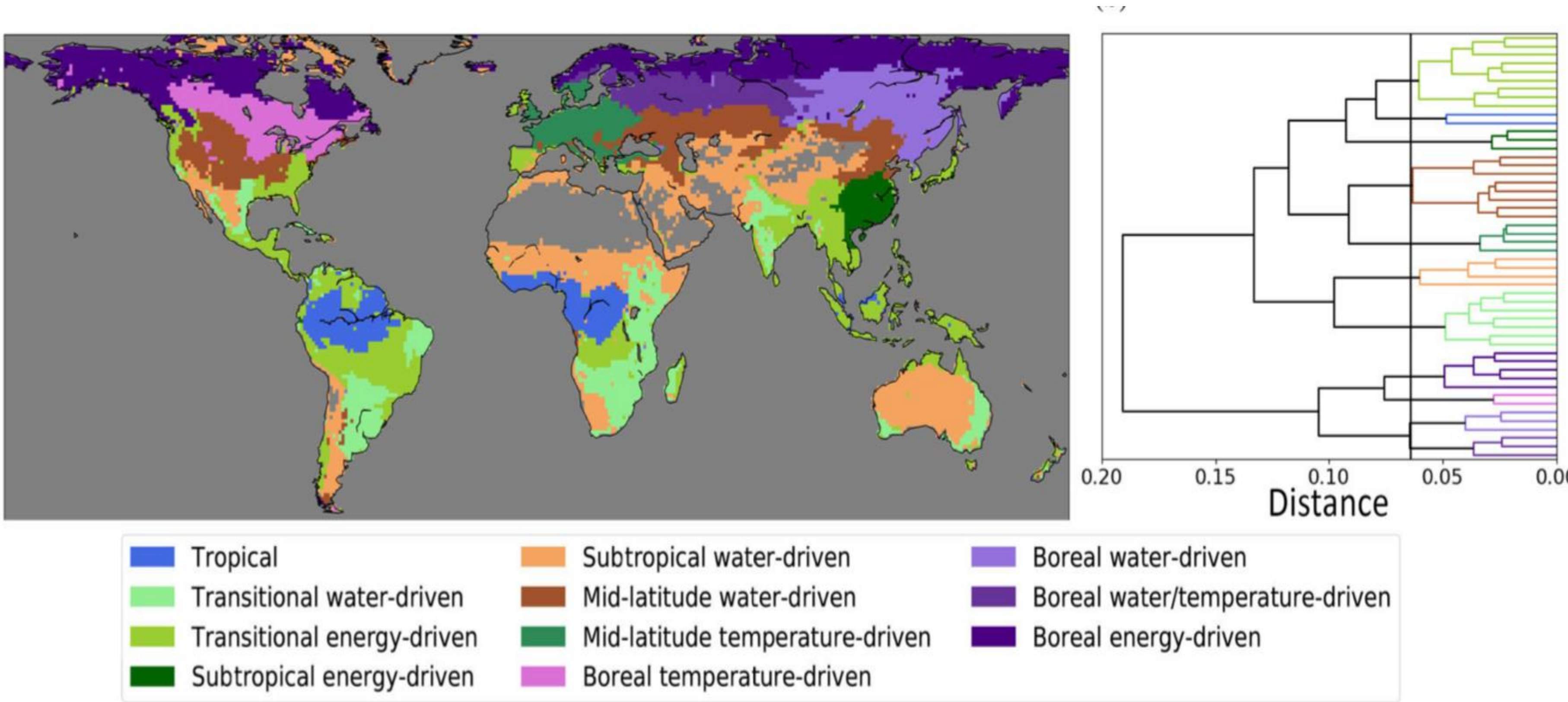
- Is A atypical <u>in the context of the question?</u>
- Yes.

Nonlinear Granger causal classification



Pappagianopoulou et al. 2017

Nonlinear Granger causal classification



Pappagianopoulou et al. 2018