Dealing with uncertainties when detecting and attributing climate changes

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Thanks to Alexis Hannart & Aurelien Ribes & Francis Zwiers

ANR-DADA, ExtremeScope, LEFE-MULTI-RISK, Chavanah, A2C2


STATISTICS
Detection &
Attribution
CLIMATE

Detection & Attribution

Detection

Demonstrating that climate or a system affected by climate has changed in some defined statistical sense[1] without providing a reason for that change.

IPCC Good Practice Guidance Paper on Detection and Attribution, 2010

1. statistically usually, significant beyond what can be explained by internal (natural) variability alone

Examples of a "Detection" statement

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased."

IPCC-WG1-AR5 SPM

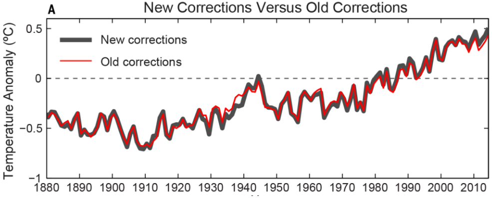


Fig. 2. Global (land and ocean) surface temperature anomaly time series with new analysis, old analysis, and with and without time-dependent bias corrections. (**A**) The new analysis (solid black) compared to the old analysis (red). (**B**) The new analysis (solid black) versus

Karl et al, 2015, Science

Attribution
Evaluating the relative contributions of multiple causal factors [2] to a change or event with an assignment of statistical confidence.

2. casual factors usually refer to external influences, which may be anthropogenic (GHGs, aerosols, ozone precursors, land use) and/or natural (volcanic eruptions, solar cycle modulations

Attribution

Evaluating the relative contributions of multiple causal factors [2] to a change or event with an assignment of statistical confidence.

Consequences

Need to assess wether the observed changes are

- consistent with the expected responses to external forcings
- inconsistent with alternative explanations

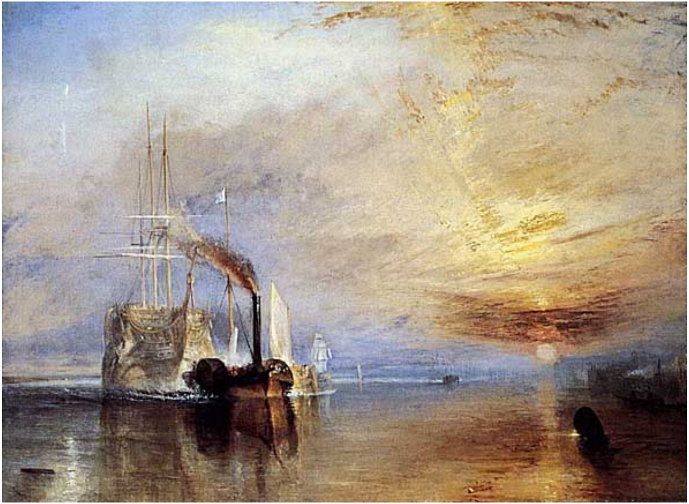
2. casual factors usually refer to external influences, which may be anthropogenic (GHGs, aerosols, ozone precursors, land use) and/or natural (volcanic eruptions, solar cycle modulations

Tambora 1815 (illustrations by G. & W.R. Harlin)


⇒ **Plutarch** noticed that the **eruption of Etna** in 44 B.C. attenuated the sunlight and caused crops to shrivel up in ancient Rome.

⇒ **Benjamin Franklin** suggested that the **Laki eruption** in Iceland in 1783 was related to the abnormally cold winter of 1783-1784.

Antropogenic forcings



Turner, The Fighting Temeraire - tugged to her Last Berth to be broken up : 1838-39

What do you need in D&A ?

Observations of climate indicators

Inhomogeneity in space and time (& reconstructions via proxies)

An estimate of external forcing

How external drivers of climate change have evolved before and during the period under investigation – e.g., GHG and solar radiation

A quantitative physically-based understanding

How external forcing might affect these climate indicators. – normally encapsulated in a physically-based model

An estimate of climate internal variability Σ

Frequently derived from a physically-based model

Classical assumptions

- Key forcings have been identified
- Signals are additive
- Noise is additive
- The large-scale patterns of response are correctly simulated by climate models
- Statistical inference schemes are efficient

Examples of a "Attribution" statement (e.g., see F. Zwiers' work)

Attribution results

TAR (2001)

– "most of the observed warming over the last 50 years is **likely** to have been due to the increase in greenhouse gas concentrations"

AR4 (2007)

– **likely** replaced with **very likely**
– "GHGs **likely** would have caused more warming than observed"

AR5 (2013)

– "It is **extremely likely** that human influence has been the dominant cause of the observed warming since the mid-20th century."
– "Greenhouse gases contributed a global mean surface warming **likely** to be in the range of 0.5°C to 1.3°C over the period 1951 to 2010 …"

Two classical statistical approaches in D&A

1- Linear regression techniques

One huge problem (from a stat and a decision making perspectives)

There is only one Earth !

One unique observation, ie. a very long vector (space $*$ time)

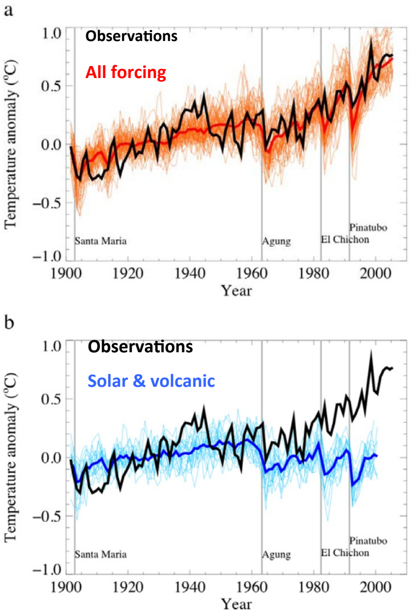
One huge problem (from a stat and a decision making perspectives)

There is only one Earth !

One unique observation, ie. a very long vector (space $*$ time)

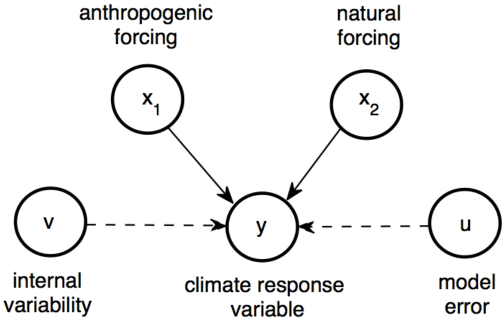
Methods based on learning from a large training set can't be easily applied

One key idea : use climate models to generate Earth's avatars



Source : Claudia Tebaldi

Summary


anthropogenic
forcing
natural
forcing
x1
x2
v
y
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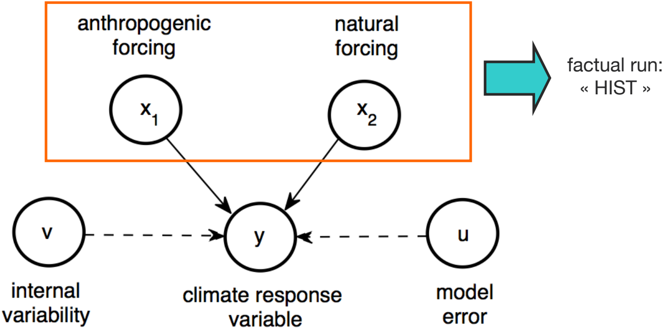
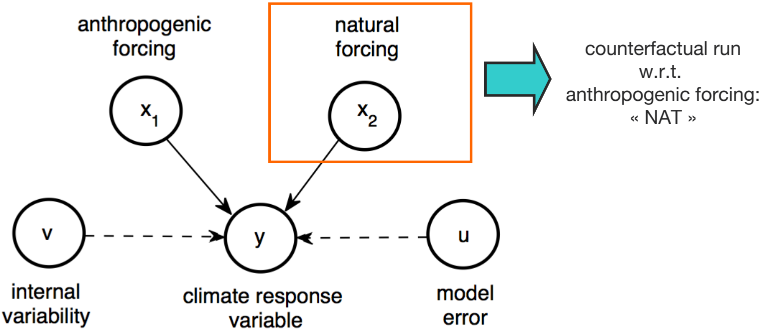
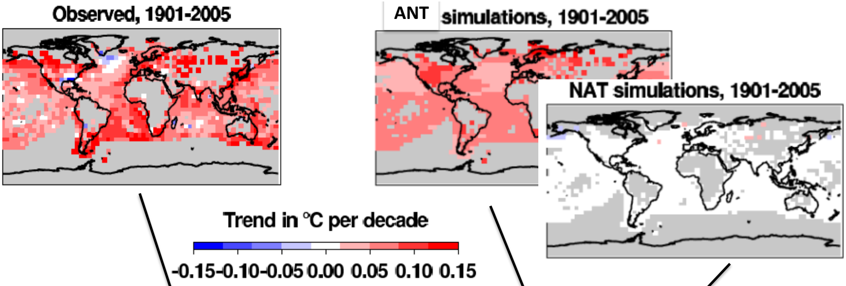
internal
variability
climate response
variable
model
error



anthropogenic forcing
natural forcing
x1
x2
factual run:
« HIST »
v
y
u
internal variability
climate response variable
model error


anthropogenic forcing
natural forcing
x1
x2
counterfactual run w.r.t. anthropogenic forcing: « NAT »
v
y
u
internal variability
climate response variable
model error

The basic regression scheme



$$\mathbf{Y}$$

$$\mathbf{X} = (\vec{x}_{ant}, \vec{x}_{nat})$$

$$\mathbf{Y} = \mathbf{X}\beta + \varepsilon$$

Gabi Hegerl's presentation at Geneva IPCC WG1/WG2 Meeting in Sept 2009

Ongoing research on regression schemes

Issues

- Estimation the internal variability (huge non-sparse covariance matrices)
- Dealing with climate model errors and GCM discrepancies
- Dealing with observational and forcing errors
- Dealing with extreme events

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- Dealing with observational and forcing errors
- Dealing with extreme events

Possible solutions

- Regularising covariance matrices
- Error-in-variable errors
- Taking advantage of multivariate extreme value theory (see Anthony's talk)

Two classical statistical approaches in D&A

1- Linear regression techniques

2- FAR (Fraction of Attributable Risk)

The FAR = the relative ratio of two probabilities, p_0 the probability of exceeding a threshold in a “world that might have been (no antropogenic forcings)” and p_1 the probability of exceeding the same threshold in a “world that it is”

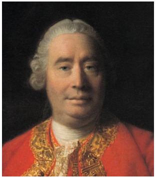
$$FAR = \frac{p_1 - p_0}{p_1}.$$

Example of an specific event, the 2003 summer heat wave over Europe (see Stott P. A., Stone D. A., Allen M. R. (2004). Human contribution to the European heatwave of 2003. Nature)

The cornerstone of causality: counterfactual definition

- D. Hume, *An Enquiry Concerning Human Understanding*,1748

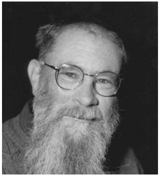
  « We may define a cause to be an object followed by another, where, if the first object had not been, the second never had existed. »



D. Hume, 18th century

- D. K. Lewis, *Counterfactuals*, 1973

  « We think of a cause as something that makes a difference, and the difference it makes must be a difference from what would have happened without it. Had it been absent, its effects would have been absent as well. »



D. Lewis, 20th century

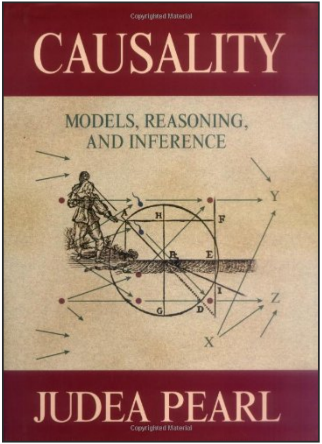
Coming slides : Hannart, A., Pearl J. Otto F., P. Naveau and M. Ghil. (BAMS, 2015). Counterfactual causality theory for the attribution of weather and climate-related events

Consolidation of a standard causality theory (1980-1990)

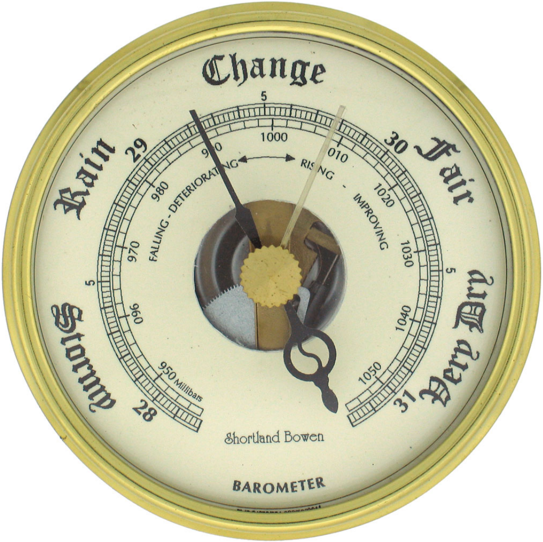
- Common theoretical corpus on causality
  - what does «X causes Y» mean ?
  - how does one evidence a causality link from data ?
  - philosophy, artificial intelligence, statistics.
  - statistics alone not enough - more concepts needed.

- J. Pearl (2000), *Causality: models, reasoning and inference*, Cambridge University Press.

- Turing Award 2004.



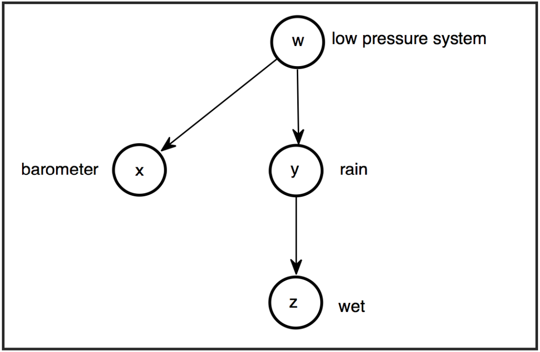
- Provides clear semantics and sound logic for causal reasoning.



Change
Rain
Fair
Stormy
Very Dry
29
30
28
31
1000
1010
1020
1030
1040
1050
980
970
960
950 Millibars
FALLING - DETERIORATING
RISING - IMPROVING
Shortland Bowen
BAROMETER

Oriented graphs

— visual representation of the conditional independence structure of a joint distribution



$$P(X, Y, Z, W) = P(W) \,.\, P(X \mid W) \,.\, P(Y \mid W) \,.\, P(Z \mid Y)$$

Interventional probability

- Limitation of oriented graphs
  - identifiability: several causal graphs are compatible with the same pdf (and hence with the same observations).

$$P(X,Y) = P(X)\,.\,P(Y \mid X) = P(Y)\,.\,P(X \mid Y)$$

$$X \rightarrow Y \qquad\qquad Y \rightarrow X$$

  - Need for disambiguation.

<u>experimentation</u>

Interventional probability

- New notion:
  - intervention $do(X=x)$
  - interventional probability $P(Y \mid do(X=x)) = P(Y_x)$

the probability of rain **forcing** the barometer to decrease,
in an experimental context in which the barometer is manipulated

$$P(Y \mid do(X=x)) \neq P(Y \mid X=x)$$

the probability of rain **knowing** that the barometer is decreasing,
in a non-experimental context in which the barometer evolution is left unconstrained

Fundamental difference : necessary and sufficient causation

- Definitions:
  - “*X is a necessary cause of Y*” means that X is required for Y to occur but that other factors might be required as well.
  - “*X is a sufficient cause of Y*” means that X always triggers Y but that Y may also occur for other reasons without requiring X.
- Examples:
  - clouds are a necessary cause of rain but not a sufficient one.
  - rain is a sufficient cause for the road being wet, but not a necessary one.

Fundamental difference : necessary and sufficient causation

- Definitions:
  - **Probability of necessary causality = PN** = the probability that the event Y would not have occurred in the absence of the event X given that both events Y and X did in fact occur.
  - **Probability of sufficient causation = PS** = the probability that Y would have occurred in the presence of X, given that Y and X did not occur.
- Formalization:

$$\begin{cases} \text{PN} =_{\text{def}} P(Y_0 = 0 \mid Y = 1, X = 1) \\ \text{PS} =_{\text{def}} P(Y_1 = 1 \mid Y = 0, X = 0) \\ \text{PNS} =_{\text{def}} P(Y_0 = 0, Y_1 = 1) \end{cases}$$

Necessary and sufficient causation

- How to calculate PN, PS and PNS ?
  - difficult in general
  - closed formula under assumption of monotonicity
  - simplifies further under monotonicity and exogeneity:

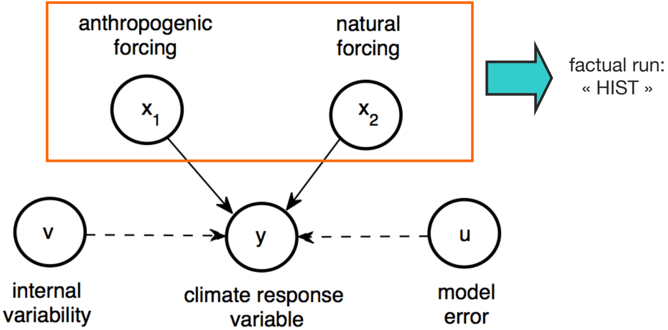
$$\mathrm{PN} = 1 - \frac{p_0}{p_1}, \ \mathrm{PS} = 1 - \frac{1-p_1}{1-p_0}, \ \mathrm{PNS} = p_1 - p_0$$

↓

FAR, « excess risk ratio »

Recall : The FAR = the relative ratio of two probabilities, p_0 the probability of exceeding a threshold in a “world that might have been (no antropogenic forcings)” and p_1 the probability of exceeding the same threshold in a “world that it is”

$$FAR = \frac{p_1 - p_0}{p_1}$$


anthropogenic forcing
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x_1
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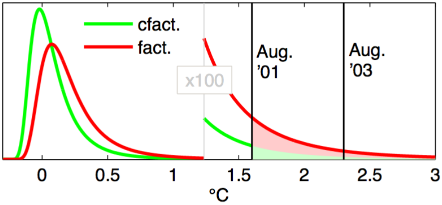
Revisiting the 2003 European heatwave with counterfactual theory

EVT extrapolation (GEV) based on HIST and NAT ensembles (Hadley center model)



p0 = 0.0008 (1/1250), p1 = 0.008 (1/125)

$p0 = 0.0008$ (1/1250), $p1 = 0.008$ (1/125)

PN = 0.9, PS = 0.0072, PNS = 0.0072

« CO_2 emissions are very likely to be a necessary cause, but are virtually certainly not a sufficient cause, of the 2003 heatwave. »

This highlights a distinctive feature of unusual events: several necessary causes may often be evidenced but rarely a sufficient one

- Which matters for event attribution: PN, PS or PNS ?

- The ex post perspective (judge) :
  - «who is to blame for the weather event that occurred ?»
  - insurance, compensation, loss and damage mechanisms (e.g. Warsaw 2013)
  - PN matters, not PS.

- The ex ante perspective (policy maker)
  - «what should be done today w.r.t. events that may occur in the future?»
  - PS matters for assessing the cost of inaction, PN for assessing the benefit of action.

- The dissemination perspective (media, IPCC)
  - PNS is a trade off between PN and PS.
  - good candidate for a single metric as it avoids explaining the distinction.

→ **PN, PS and PNS all matter**

Fraction of Attributable Risk (FAR)

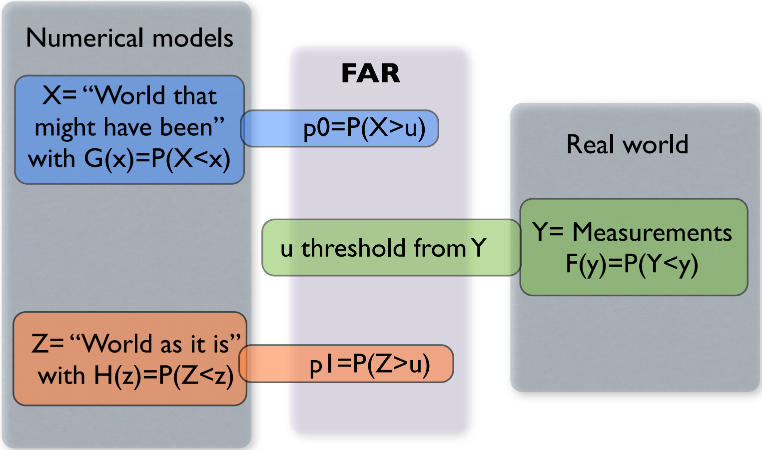
A relative ratio based on two probabilities

$$PN = FAR = \frac{p_1 - p_0}{p_1}.$$

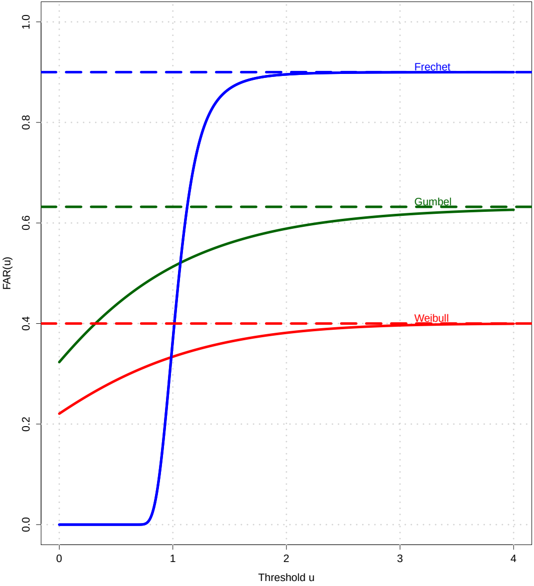
where p_0 the probability of exceeding a threshold in a “world that might have been (no antropogenic forcings)” and p_1 the probability of exceeding the same threshold in a “world that it is”

How to define an event？

How to define an event ? UK school, $FAR(u) = 1 - P(X > u)/P(Z > u)$

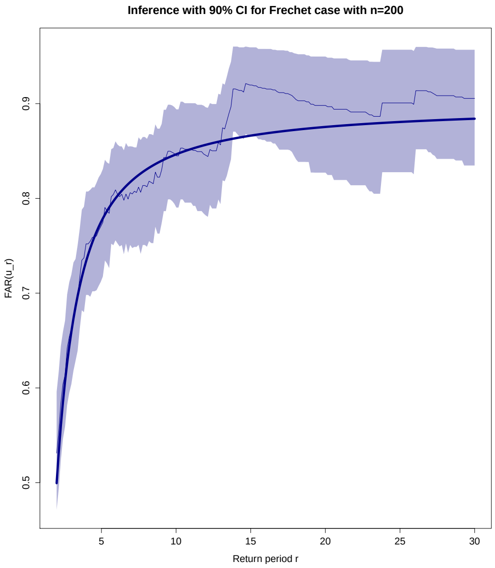


FAR and Extreme Value Theory



Inference of $FAR(u) = 1 - P(X > u)/P(Z > u)$

Empirical approach with a lot of numerical runs

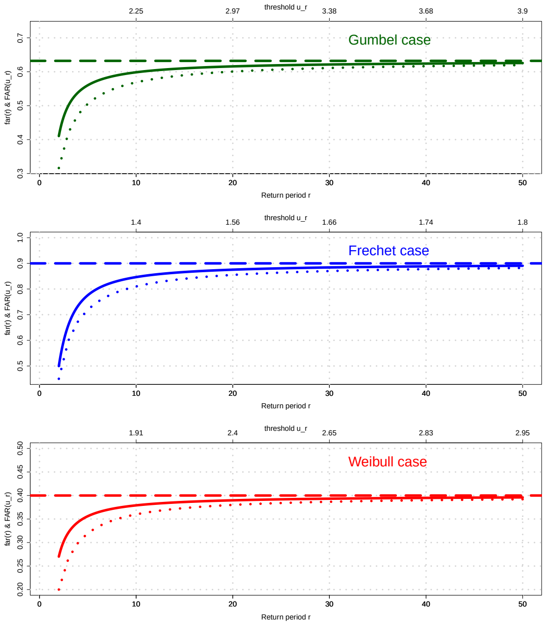


How to define an event ?

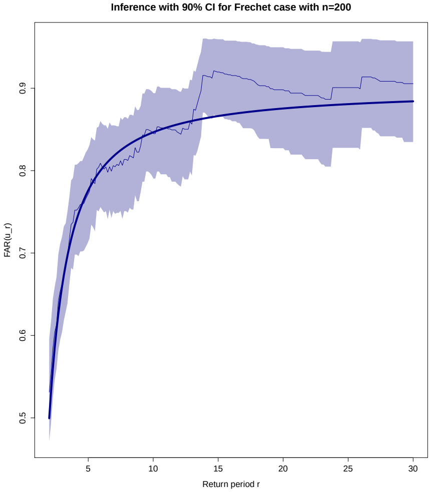
$$far(r) = 1 - \frac{\mathbb{P}(X^{(r)} > \max(X^{(1)}, \ldots, X^{(r-1)}))}{\mathbb{P}(Z^{(r)} > \max(X^{(1)}, \ldots, X^{(r-1)}))},$$

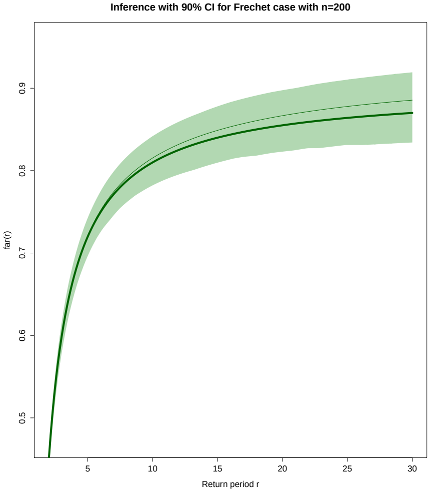
where r represents a return period in years.

Alternative FAR : $far(r) = 1 - \frac{1}{r\mathbb{P}(Z^{(r)} > \max(X^{(1)}, \ldots, X^{(r-1)}))}$



FAR, far and Extreme Value Theory





Conclusions

Summary

- Causality
- Uncertainties (natural variability, model errors, large dimension, etc)
- Defining extreme events, FAR and Extreme Value Theory

Future work

- How to reduce unclear statements about “events” ? about causality ?
- How to link numerical models and observations ?
- How to infer a ratio of two small probabilities (zero divided by zero) ?
- How to deal with the non-stationarity ?

Coming events (see blog “Beyond the hill”)

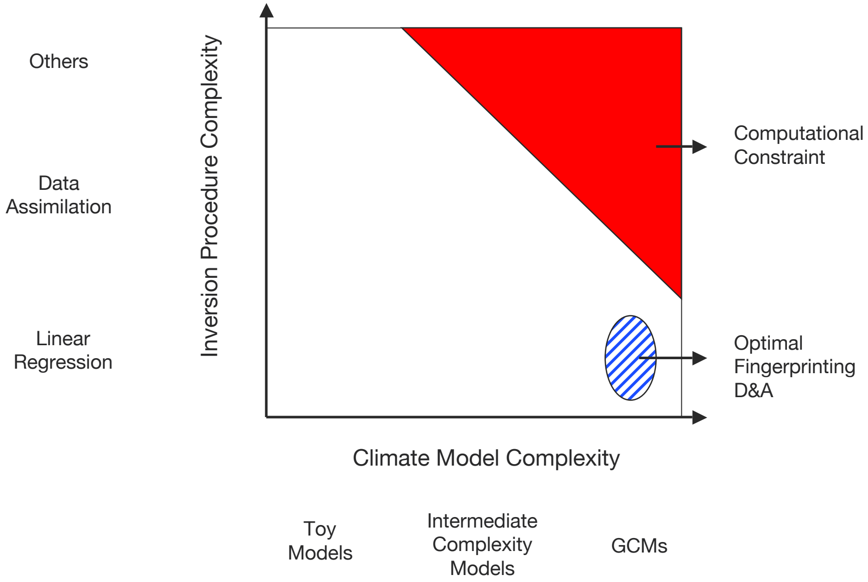
- EVA (Extreme Value Analysis), Michigan, June 15-19, 2015
- Statistical and mathematical tools for the study of climate extremes, Nov 9-13 2015, Cargese, Corsica
- Summer School on Extreme value modeling and water resources,Lyon June 13-24 2016.

A few articles

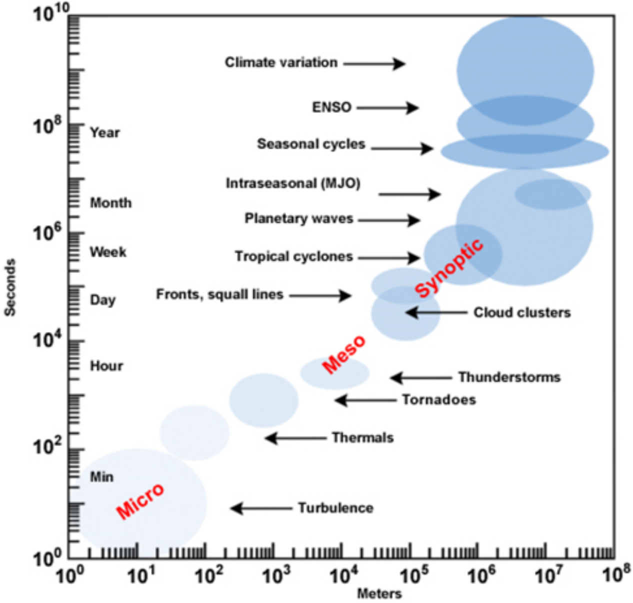
- Coming up special issue on D&A in “Weather and Climate Extremes”
- Hannart, A., et al. 2015 : Causal counterfactual theory for the attribution of weather and climate-related events. Bull. Amer. Meteor. Soc. In press.
- Hannart A. and P. Naveau. Estimating high dimensional covariance matrices : a new look at the Gaussian conjugate framework (Journal of Multivariate Analysis, 2015).
- Hannart, A., A. Ribes, and P. Naveau (2014), Optimal fingerprinting under multiple sources of uncertainty, Geophys. Res. Lett..
- Naveau, P., Guillou, A. and Rietsch, T. (2014), A non-parametric entropy-based approach to detect changes in climate extremes. Journal of the Royal Statistical Society : Series B (Statistical Methodology).

From the Far side (G. Larson)

Big data : statistical versus numerical models



Spatial and temporal scales in weather and climate



Interventional probability

- Property:
  - Exogeneity: X exogenous if X has no parents
  - in this case:

$$P(Y \mid do(X = x)) = P(Y \mid X = x)$$

Necessary and sufficient causation

- How to calculate PN, PS and PNS ?
  - difficult in general.
  - closed formula under the assumption of monotonicity:

$$\begin{cases} \text{PN} = 1 - \frac{p_0}{p_1} + \frac{p_0 - P(Y_0=1)}{P(X=1,Y=1)} \\ \text{PS} = 1 - \frac{1-p_1}{1-p_0} - \frac{p_1 - P(Y_1=1)}{P(X=0,Y=0)} \\ \text{PNS} = P(Y_1 = 1) - P(Y_0 = 1) \end{cases}$$

where:
p1 = P(Y=1 I X = 1) : factual probability of the event
p0 = P(Y=1 I X = 0) : counterfactual probability of the event

Necessary and sufficient causation

- The judge perspective:
  - defendant A shot a gun at random in a seemingly desert place.
  - B stood one kilometer away and was unluckily hit right in between the eyes.
  - PN ~ 1, PS ~ 0.
  - but A is an obvious culprit for the death of B from a legal perspective.
  - only PN matters here, PS does not.

- The policy-maker perspective:
  - what is the best policy to achieve a given objective ? (say, reducing accidental gunshot mortality)
    - prohibiting guns sales => PN = .., PS ~ 1
    - restricting guns sales => PN = .., PS = …
    - better informing gun owners on safety => PN = .., PS = …
  - both PN and PS matter to assess efficiency.

- *« It is very likely (>90%) that CO_2 emissions have increased the frequency of occurrence of 2003-like heatwaves by a factor at least two »*

$$\neq$$

- *« CO_2 emissions are very likely to be a necessary cause of the 2003 heatwave. »*

Event attribution - summary

- *« Have CO_2 emissions caused the 2003 European heatwave? »*

- The answer is greatly affected by:
  - how one defines the event « 2003 European heatwave »,
  - what is the temporal focus of the question,
  - whether causality is understood in a necessary or sufficient sense.

⇨ **Precise causal answers about climate events critically require precise causal questions.**

Observed change in surface temperature 1901–2012