Causality in climate and hydrology

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We often see statements such as “90% of climate change is caused by X” and debates on whether the dominant cause of climate change is human activity, or the sun, or something else. However, in chaotic systems, it can be difficult to defend the meaning of such assertions, because if the “effect” occurs sufficiently later than the supposed “cause”, the relationship between the two is effectively lost because of the sensitivity of the “effect” to the initial conditions. In fact, although “A causes B” initially seems clear, closer examination of what it actually means reveals problems that have tortured philosophers for centuries. We review the meaning of causation in the context of hydroclimatology as well as its possible reformulation in probabilistic terms.

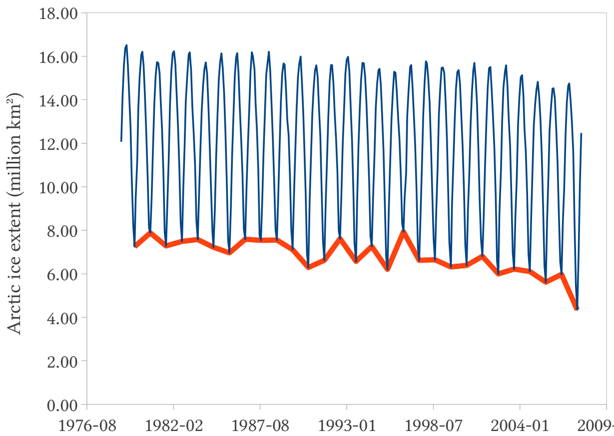

Figure 1: Arctic ice extent (also showing trend of annual minimums) (see bibliography for the source)

Figure 1 shows the variation of Arctic ice extent, as it is photographed by satellites. It increases in winter and decreases each summer. Now the minimum of each year shows a downward trend, which is what the fuss about melting polar ice is all about. Naturally, people ask why this happens. What is the cause of this downward trend? Some say it is carbon dioxide emissions; others that it is the Sun. But it is an almost universal belief that there must be a cause. This belief is called the doctrine of universal determinism, and examples of it can be seen in Figure 2. Some of the statements shown there even imply that the temperature change is a linear combination of its causes.

> “Climate only changes for a reason.”
>
> —Mark Serreze, U.S. National Snow and Ice Data Center, March 2011

> “[T]here remains a need to resolve which of the following statements is correct:
>
> Hypothesis 1: ... natural causes dominate climate variations ...
>
> Hypothesis 2...: ... the human influences are significant ...”
>
> —R. A. Pielke Sr. and 18 other scientists, November 2009

> “My assignment [of degree of belief] allows the anthropogenic influence to be as large as 70% and as small as 30% [of the observed temperature increase.]”
>
> —Judith Curry, September 2010

Figure 2: Statements implying causal determinism (for the sources, see bibliography)

In order to investigate whether causal determinism holds, we first have to ask ourselves what we mean by causation, and David Hume (1739) did that. What he discovered is that the whole meaning of causation is obscure. Explaining what “A causes B” means is difficult once you realize that “B is an effect of A” is a tautology. Hume thought that it does not have a physical meaning, but is only a fabrication of the human mind: he proposed that we get into the habit of saying that A is a cause of B when the following conditions hold:

1. A occurs before B;
2. A and B are proximate in space and time;
3. There is “constant conjunction” between A and B; that is, our experience tells us that B always follows A.

So if A is fire and B is heat, all three hold, so fire causes heat. Later several authors observed that, for example, when we say that a storm caused a flood, there is no “constant conjunction” between storms and floods, since there are storms that are not followed by floods. These authors have developed probabilistic theories of causation, because what the storm does is that it increases the probability of a flood occurring. Suppes (1970) proposed that A causes B if the following conditions hold:

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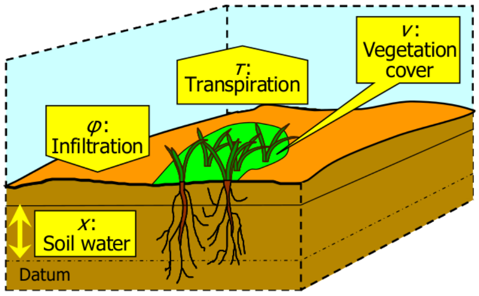
1. A occurs prior to B
2. $P(B|A) > P(B)$
3. There does not exist an event C prior to A such that $P(B|AC) = P(B|C)$

The last of these conditions is there to ensure that not every correlation is accounted of as causation.

Actually these rules are only a first approximation; they have some problems and need to be refined, but the refinements also have more subtle problems.

However, let's ignore all this, and let's pretend that we understand what we mean by causation. Assume we have the plot of land illustrated in Figure 3 (Koutsoyiannis, 2010), where it rains a certain, constant amount each



$$x_i = \min(x_{i-1} + \varphi - v_i \tau_p, \alpha)$$

$$v_i = \frac{\max(1+(x_{i-1}/\beta)^3, 1)\, v_{i-1}}{\max(1-(x_{i-1}/\beta)^3, 1) + (x_{i-1}/\beta)^3 v_{i-1}}$$

Parameters:

α = 750 mm

β = 100 mm

Forcings:

φ = 250 mm

Figure 3: A toy model which can produce trends without a cause

year. It is partly covered by vegetation, which transpires water, which it gets from the soil water. If in a year the level of the soil water is high, the vegetation cover increases, resulting in more transpiration, and the level of water goes down; this results in decreasing vegetation, and so on. This extremely simple toy model is stationary and has constant "forcings" (constant amount of rainfall/infiltration each year). Now when we give it some initial conditions and run it for, say, one hundred years, we see (Figure 4) that the water table goes up and down, but the minimums have a downward trend, except in the last few years where it is reversed. What is the cause of this trend, when the model is stationary and the "forcings" are constant? What's more, the model is chaotic; we run it again, rounding the initial conditions to the nearest millimetre, and, as we see in the picture, the trend in this case vanishes.

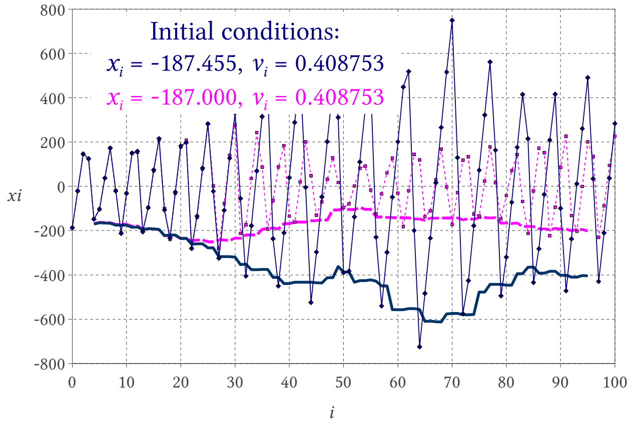


Figure 4: Two runs of the toy model (also showing trend of minimums)

The conclusion is that we should be careful when we talk about causes, and that trends and shifts do not necessarily imply non-stationarity or a change in forcings: they can just happen.

Sources and selected bibliography

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