The Hawkmoth Effect

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Abstract

The challenge of providing **actionable evidence** regarding future climate – evidence which can inform rational decisions – is limited by various constraints on the nature of the evidence that climate models (and modellers) are capable of providing. One such constraint is the Hawkmoth Effect: the structural instability property of most dynamical systems.

The dynamical-systems view and the statistical view of climate are somewhat different. Current statistical methods are limited by the need for simplifying assumptions in order to make the problem tractable. These assumptions must be made and justified outside the modelling framework. The dynamical-systems approach leads to a more cautious interpretation of modelled probabilities, with different ways to account for "unknown unknowns".

We consider some of the possible implications both for climate science and for climate policy, which should be based on good scientific evidence. Separating climate science from climate projection, and clarifying the underlying assumptions, are two good places to start.

Dynamics: Structural instability of complex dynamical systems

Complex systems do not generally have the mathematical property of **structural stability**. This is not a new result but its implications do not seem to be widely appreciated.

Real climate system R is modelled by equations M with error E: $R = M + E$

Real climate evolution r is modelled by solutions m with error e: $r = m + e$

Unless a system is proven to be structurally stable, if E is small it does *not* imply that e is small, or vice versa. Structural stability is proven only for a very restricted class of dynamical systems, with conditions which are certainly not satisfied by any form of climate simulation model. Thus, even when we improve the physics in a complex model, we may not necessarily improve the accuracy of the output.
This is the Hawkmoth Effect: a good approximation (small E) is not necessarily a good model in the sense of good predictive capability (small e).

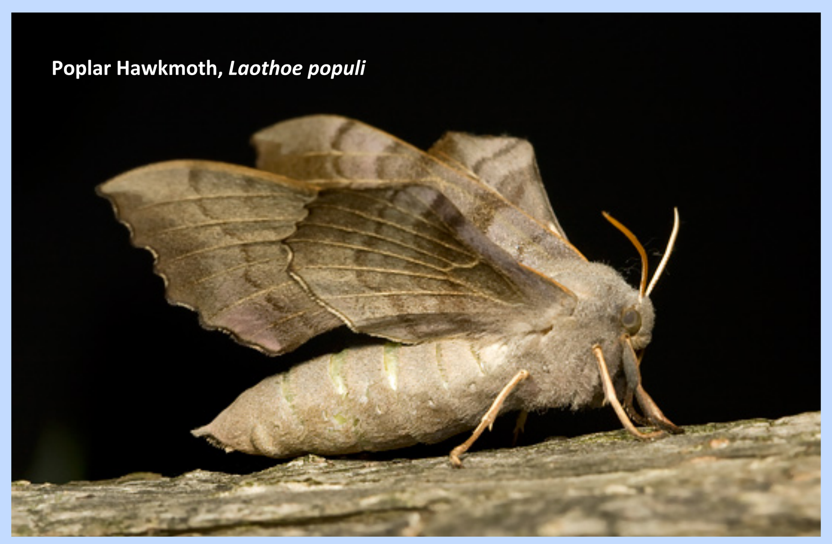
Statistics: Implicit assumptions of stability

Bayesian methods have become popular in climate model interpretation, and rely on the construction of **ensembles**: initial condition ensembles, perturbed parameter ensembles, and multi-model ensembles.

Probability distributions about model-variables of interest, such as the models' global mean temperature, are derived from these ensembles and are taken to represent probabilities about global mean temperature in the real world.

Several implicit assumptions have been made in taking this approach, on which the results are conditional. One assumption is that the model parameter-space is continuous, smoothly varying, and single-valued (see literature on **emulators**). The Hawkmoth Effect means that this assumption may not be safe, and as a prior assumption it should be quantified, in accordance with good Bayesian practice.

Another assumption is that the ensemble of models available provides a good estimate of the range of all possible model structures (see literature on **discrepancy**). Climate models share assumptions, language, developers, and even code. They cannot possibly be a meaningfully "random sample" of model space.



What is the Hawkmoth Effect?

The term "**butterfly effect**", coined by Ed Lorenz, has been surprisingly successful as a device for communication of one aspect of nonlinear dynamics, namely, sensitive dependence on initial conditions (dynamical instability), and has even made its way into popular culture. Dependence on initial conditions is a solved problem: initial condition ensembles are used to generate probabilities.

We use the term "**Hawkmoth Effect**" to refer to structural instability (see description above). A non-technical summary of the Hawkmoth Effect is that **"you can be arbitrarily close to the correct equations, but still not be close to the correct solutions"**.

The less media-friendly hawkmoth does not get as much attention as its celebrated butterfly cousin. However, it has greater consequences and is not yet accounted for by modern methods. Due to the Hawkmoth Effect, it is possible that even a good approximation to the equations of the climate system may not give probabilistic output which accurately reflects the future climate.

Climate decision-makers and climate model developers should take into account this possibility.

Conclusions

- The complex nature of the climate system presents a serious challenge for simulation-based decision support methods;
- We should not expect probability distributions generated in model-space to be directly relevant to the real world;
- Quantifying real probabilities requires expert judgement (subjective assessment) of the limits of model applicability and the relationship between model-variables and real-variables;
- Expert judgements about the fidelity of simulation models may differ, and will result in different future probabilities;
- Separating the role of simulation-for-understanding from that of simulation-for-decision-support would allow each community of simulation users to focus more on their own goals, with consequent improvements in each;
- Simulation-for-understanding should not be fettered by the need for simulations to "improve", as the Hawkmoth Effect implies that this may not always happen even when the physical process representations do improve;
- Simulation-for-decision-support should focus more on understanding and quantifying uncertainty and the limits to predictability (time and length scales), and should explicitly clarify uncertainties, including subjective probabilities of model inadequacy

Implications for climate decision-making

The essential criterion for model-derived information to be useful is that it must genuinely refer to the real world. Probabilities must be probabilities that are ascribed to real-world events, not simply the probability of something happening in the next model run.

Use of model-derived probability distributions for decision-making therefore needs to be approached with care. Caveats and conditions are often dropped or mislaid along the chain from modeller to decision-maker.

In particular, the implication that numerical answers can be provided and that uncertainty will reduce with more research may be counter-productive to the rational use of scientific evidence. For instance, we have a lot more understanding of the processes that contribute to climate sensitivity now that we did 30 years ago, but the range of uncertainty is remarkably little changed. Waiting for greater certainty in this instance is clearly counter-productive.

On the other hand, local/regional information for adaptation can be provided, but the statistical caveats and assumptions (first-order contributions to outputs) are often unclear. The opposite problem now holds, and care is needed to prevent decision-makers over-interpreting simulation probabilities as accurate real-world risks.

Implications for climate model development

The twin goals of climate model development are

- Better representations of physical processes ("simulation-for-understanding"); and
- Better representation of the future climate ("simulation-for-decision-support").

Experimental design for simulation models, such as the CMIP5 process, take these two goals into account, but we believe that more explicit separation would benefit both simulation-user communities.

Developing a set of models solely for physical understanding would remove the pressure for model results constantly to "improve", and allow more unfettered experimentation with processes.

Developing a set of models solely for decision support would allow a greater focus on quantifying adequacy for purpose, choosing relevant output variables and incorporating (model-informed) expert judgement into probabilistic statements about the real future climate.

There would be considerable interaction between the two sets of models, but they would have well-defined remits.

References

Frigg, R., Bradley, S., Du, H. and Smith, L.A. *Laplace's Demon and the Adventures of his Apprentices* forthcoming in Philosophy of Science.

Smith, L.A. and Petersen, A.C., (2014). *Variations on Reliability: Connecting Climate Predictions to Climate Policy*, forthcoming in Boumans, M., Hon, G. and Petersen, A.C. (ed.) Error and Uncertainty in Scientific Practice, London: Pickering & Chatto.

Thompson E. L. (2013). *Modelling North Atlantic Storms in a Changing Climate*, PhD thesis, Imperial College London.

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