The Hawkmoth Effect

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Abstract

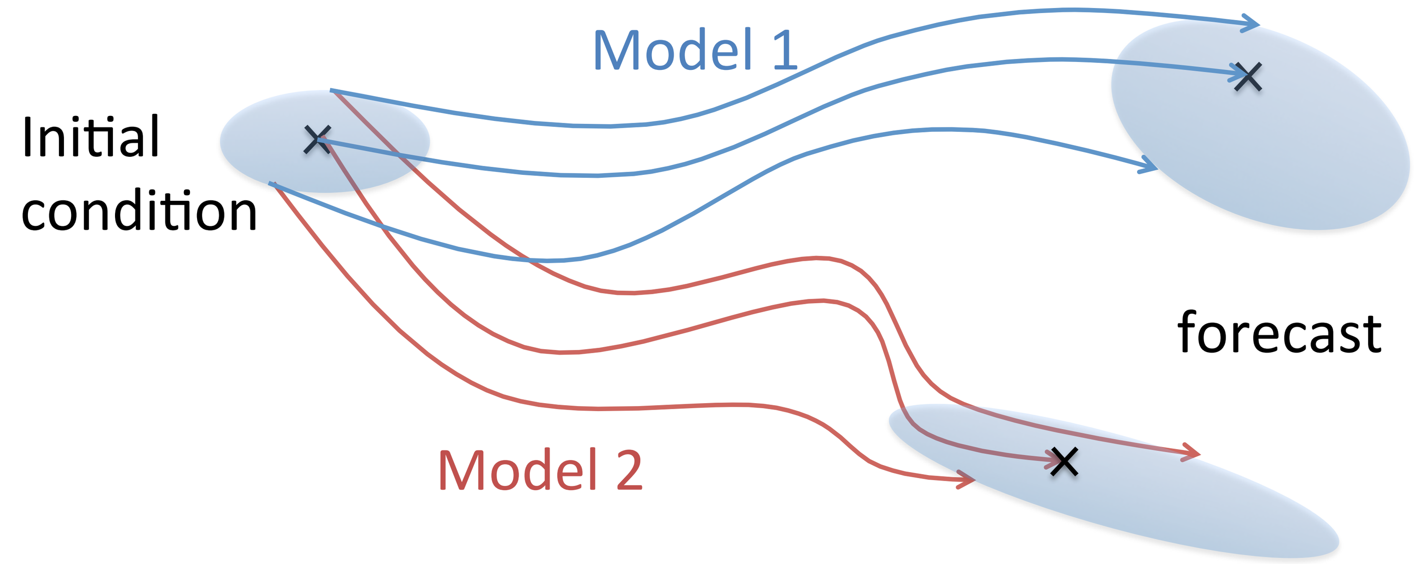
The challenge of providing **actionable evidence** regarding future climate – evidence which can inform rational decisions – is limited by constraints on the nature of the evidence that climate models (and modellers) are capable of providing. One such constraint is the Hawkmoth Effect: a structural instability property of 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 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 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 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 are not widely appreciated.



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. 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. 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.


Poplar Hawkmoth, *Laothoe populi*

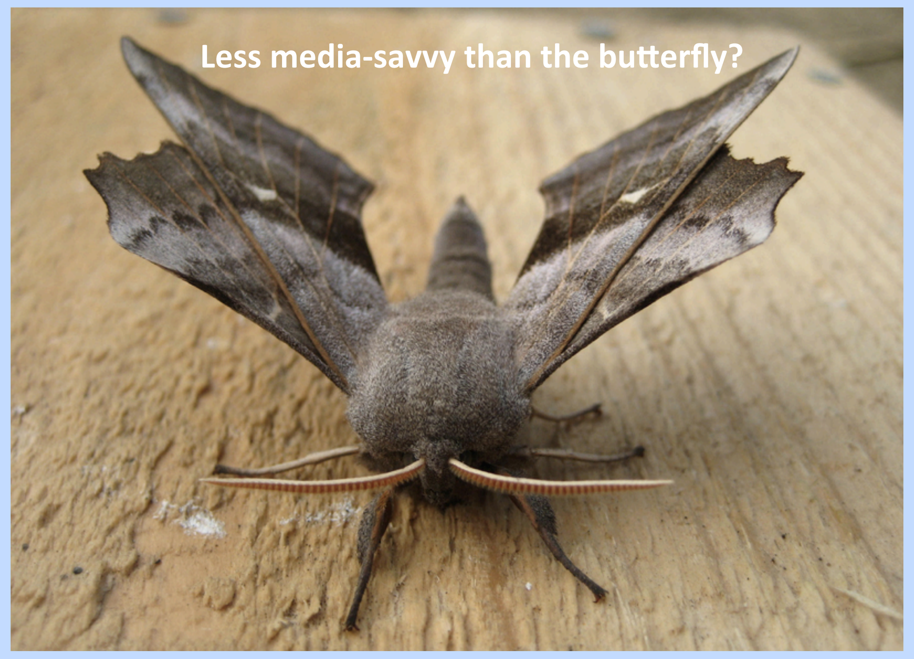
What is the Hawkmoth Effect?

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. The problem is easily solved using probabilistic forecasts.

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 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 output which accurately reflects the future climate.

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


Less media-savvy than the butterfly?

Implications for climate decision-making

Useful information 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 climate-model-derived climate 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 detrimental to the rational use of scientific evidence. Waiting for greater certainty or more detail may be 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 and separate remits.

Conclusions

- The complex nature of the climate system presents a serious challenge for simulation-based decision support methods;
- Quantifying real (not just model) 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

References

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