Using models and data to learn about the future of the climate

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What This Talk is About

- I will explain how climate change risk assessment cannot take place without statistics and probability.
- The focus of the talk will be on climate models and the importance of uncertainty quantification when climate projections are made using models.

Climate Change and Risk

(from John Elk III, lonelyplanet.com)

Risk

- We need probability/statistics to define and quantify risk.
- Risk associated with an action = expected cost (or "loss") for that action
  - "expected" means "on average"
    Sum over outcomes: probability of outcome$\times$ its cost
- For a particular policy, example of outcomes:
  - global sea level rise (2 metres? more? less ?)
  - strength of the Atlantic Meridional overturning circulation or "AMOC" (weakening? stable?)
- To study economic impacts: relate outcome to impact.
  Example: sea level rise of x metres will cost $ y.

Learning about Risk

- How do we learn about the probability of each outcome?
- What is probability of sea level rise of 2m. in 2100 if:
  - (A) Carbon emissions grow at same rate (“business as usual”)
  - (B) Carbon emissions are controlled by some policy
- Of particular interest: low probability-high impact events. For example sea level rise of 2 metres may be a relatively low probability event but extremely expensive.

Learning about Risk through Statistical Methods

Risk assessment based on climate projections should involve:

(1) Combining information from climate models and observations.

(2) Uncertainty quantification: for honest assessment of risk, critical to incorporate information about how certain or uncertain we are about various aspects of the climate projections.

Rigorous statistical methods have been/are being developed to address (1) and (2).

What is a Climate Model?

- Mathematical models that use a set of equations to describe climate processes. Because these equations are complicated, discretized on a grid and solved on computers $\Rightarrow$ in effect complex computer models.
- Equations combine physical laws for some processes and approximations for others. Approximations: due to computational constraints or because some processes are still not fully understood.

Climate Model Projections

- Projections: a climate model can be run into the future, for example the year 2100, in order to learn about future climate.
- These projections are subject to various uncertainties.

What Do We Mean by "Uncertainties?"

Types of uncertainty:

(1) Aleatoric: stochasticity (randomness) in the universe. Example: if we knew a coin was fair, still would not know if a particular toss would yield heads or tails.

(2) Epistemic: uncertainty regarding our knowledge. Example: the weight of a particular nickel is fixed but our knowledge about the weight is uncertain. If we knew the weights of 20 other nickels, we could make a better guess (reduced uncertainty).

Statistical models used to account for both.

Climate Model Uncertainties

- Model projections are uncertain as models can never fully describe the climate system.
- Boundary or initial condition uncertainty.
- "Forcings" uncertainty, e.g. uncertainty about emissions.
- Observations may have measurement errors, may not be available everywhere (interpolation uncertainty).
- **Parameter uncertainty**: parameters ("dials" in the computer model) may be uncertain. The value of the parameter may affect climate projections.

Consequences of Quantifying Uncertainty

Important:

- Uncertainty is not the same as not knowing.
- Uncertainty is not a reason for inaction (more on this in Mark Berliner's talk).
- Describing uncertainties carefully is central to the scientific enterprise."Without uncertainty quantification, it is easy to dismiss computer models." – A. O'Hagan.

A Statistical Challenge in Climate Science

Focus here on one important challenge:

- Characterizing values for unknown or uncertain parameters of a climate model is called **calibration.**
- Done by comparing climate model output (for various parameter values) to observations.

Statistical Methods

Bayesian inference is a useful approach:

- **Prior distribution** describes plausibility of various values of the parameters.
- **Probability model** (built using the climate model) connects parameters to observations.
- **Posterior distribution** describes plausibility of various values of the parameters using data.
- Summary: update prior using data $\rightarrow$ posterior.

Statistical modeling, theory and computing involved...

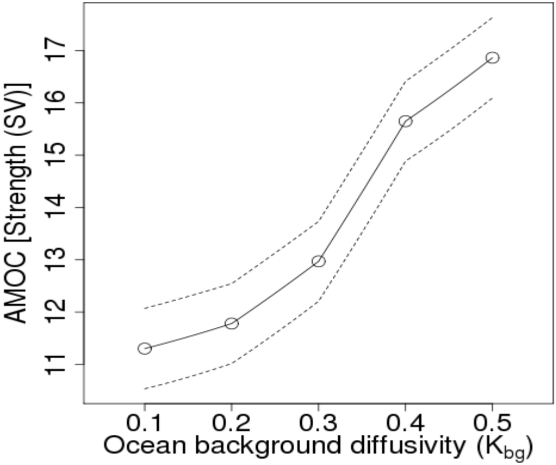
The AMOC and Climate Change

One concrete example:

- Atlantic Meridional Overturning Circulation (AMOC): AMOC heat transport makes a substantial contribution to the moderate climate of Europe (cf. Bryden et al., 2005)
- Any slowdown in the overturning circulation may have major implications for climate change
- AMOC projections may be made by climate models.

A major source of uncertainty about the AMOC is due to uncertainty about $\mathbf{K_{bg}}$: model parameter that quantifies the intensity of vertical mixing in the ocean.

AMOC and Model Parameter $\mathbf{K_{bg}}$

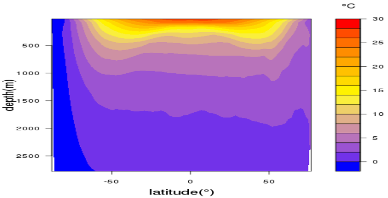


Learning about $\mathbf{K_{bg}}$

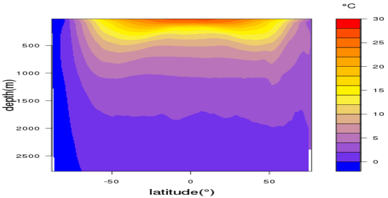
- Two sources of indirect information:
  - **Observations** of ocean temperatures.
  - **Climate model output** at different values of $\mathbf{K_{bg}}$ from University of Victoria (**UVic**) Earth System Climate Model (Weaver et. al., 2001).
- Models with different $\mathbf{K_{bg}}$ values result in markedly different ocean temperatures. Comparing observations to model output allows us to learn about $\mathbf{K_{bg}}$.

Ocean Temperatures

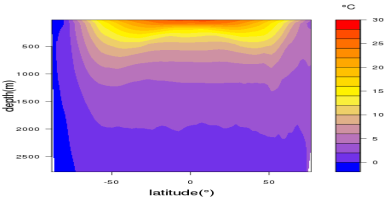
K_{bg} of 0.1



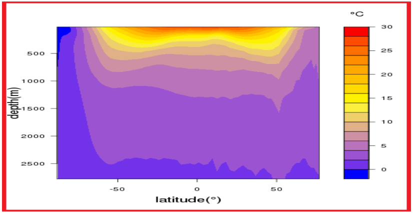
K_{bg} of 0.2



K_{bg} of 0.3

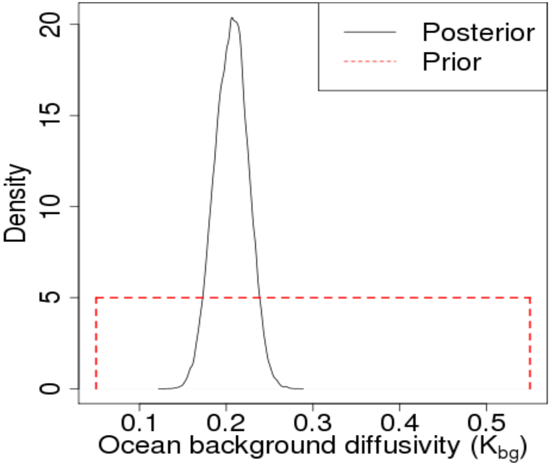


Observations

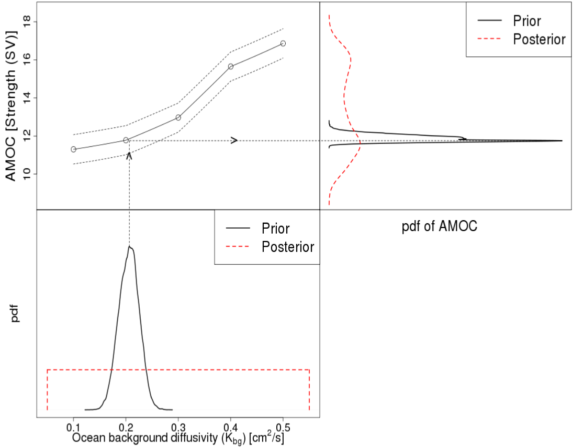


(2D versions of 3D data)

Results for K_{bg} Inference



MOC Projections for 2100 Using Inferred $\mathbf{K_{bg}}$



Concluding Thoughts

- Quantifying uncertainties is central to the scientific enterprise and is crucial when studying climate model projections.
- **Caveats** in illustrative example: only described a few uncertainties. Many others! This is ongoing work...
- Powerful modern statistical techniques can sometimes *reduce* uncertainties about climate projections. Useful for policy makers.
- Without probability and statistics, it is not possible to quantify risk. Without risk assessment, it is impossible to formulate sound policy. To assess costs we also need to connect model projections to economic impacts.

Collaborators

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- Sham Bhat, Los Alamos National Laboratories

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