Climate case study

Outline

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Introduction

This is the final report on the MUCM projects second case study. The purpose of the case studies is to provide exemplars of how MUCM methods can be applied in non-trivial problems. The MUCM Case Study 2 (CS2) has as its primary objective to explore the amount of CO_2 that can plausibly be added to the atmosphere without increasing global mean temperature (GMT) by more than 2°C in the period from the pre-industrial level (1800) to 2200. This is motivated by the concept of dangerous climate change. The objective of the 1992 United Nations Framework Convention on Climate Change (article 2) is to avoid dangerous climate change, although there is no official definition of what this means and therefore what level constitutes 'dangerous'. The target of limiting the global average temperature rise to 2°C above the pre-industrial level is often quoted and we use it as a benchmark, though the methods in CS2 are easily adapted for other targets.

Key points in the setup of the problem

- The primary interest is in the maximum GMT reached between 1800 and 2200. However, this doesn't really refer to the maximum GMT achieved in any one year, because this will be inflated by inter-annual variability. GMT is intended for this purpose to be a 'true' underlying mean temperature (i.e. we are looking at climate rather than weather).
- Different methods of measuring GMT could give appreciably different values, so it is usual to look not at absolute GMT but at the change in GMT from some baseline. For the purpose of CS2 we call this relative GMT (RGMT). RGMT is thought to be more meaningful, with different measurement techniques or definitions being much more consistent over RGMT than GMT. The baseline is defined as the average GMT between 1961 and 1990.
- The analysis will be based on the C-GOLDSTEIN simulator which is an intermediate

The challenge

How much CO_2 can we survive?

- How much CO_2 can we add to the atmosphere without increasing global mean temperature more than 2°C?
- Several ambiguities in this question
  - Obviously depends on time profile of CO_2 emissions
    - And on time horizon
  - Two degrees increase relative to what?
  - How to define and measure global mean temperature
- Even if we resolve those, how would we answer the question?
  - Need a simulator to predict the future
  - And much more besides!

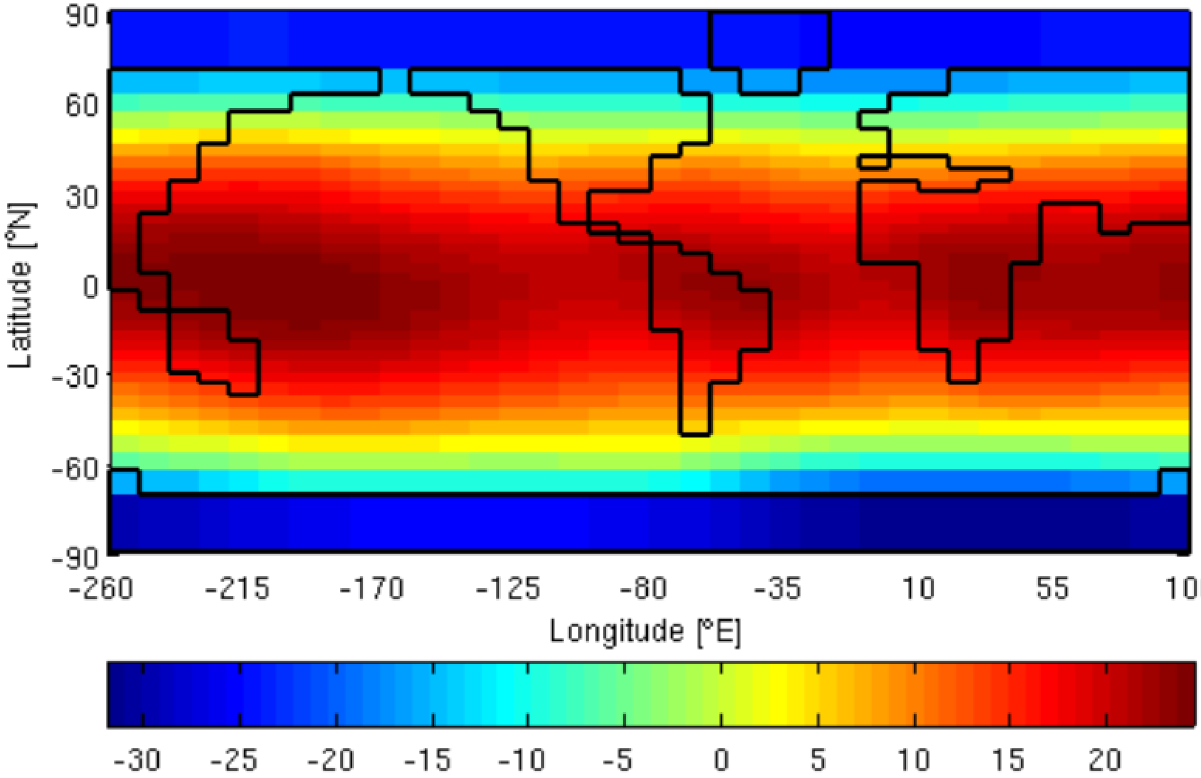
The simulator

- We use the C-Goldstein simulator
- Three coupled model components
  - GOLDSTEIN ocean model
  - An Energy Moisture Balance Model based on Uvic
  - A simple sea ice model
- Relatively low resolution
  - 36 x 36 x 8 ocean layers
  - 100 time-steps per year
- Spin-up to year 1800AD (3792 years of spin-up)
  - Then forced by historic CO_2 levels
    - From ice cores to 1957 then Mauna Loa to 2008

C-Goldstein inputs

- 18 inputs
  - All with uncertain values
- Need to allow for uncertainty in the analysis
- Last input has no effect except for future projections yielding significant warming

Input in C-GOLDSTEIN	Name in model	Default value
Ocean Drag Coefficient	adrag	2.5
CO2 radiative forcing	delf2x	5.77
Sea Ice Diffusivity	diffsic	2000
Width Atmospheric heat diff.	width	1.0
Slope Atmospheric heat diff.	slope	0.1
Ocean Horizontal diffusivity	diff1	2000
Solar Constant	solconst	1368
Threshold humidity profile	rmax	0.85
Meridional heat advection	betam1	0
scaling factor foratlantic to pacific moisture flux	sclfwf	1
Meridional moisture advection	betam2	0.4
Wind stress	scf	2.00
Zonal heat advection	betaz1	0
Zonal moisture advection	betaz2	0.4
Atmospheric Moisture Diffusivity	diffamp2	1e6,
Atmospheric heat diffusivity	diffamp1	5e6
Ocean Vertical diffusivity	diff2	1e-4
Sensitivity of Greenland Ice Sheet melt to warming	k_gis	0.01



Example of C-Goldstein output:
Surface air temperature in 2000
using default input values

The data

- We have historic data on global mean temperature
  - Decadal averages for each decade from 1850 to 2009
  - From HadCrut3
- These are to be used to calibrate the simulator
  - Thereby hopefully to reduce prediction uncertainty
- Note that the HadCrut3 data are actually values of the temperature “anomaly”

- Which brings us to the next slide

RGMT

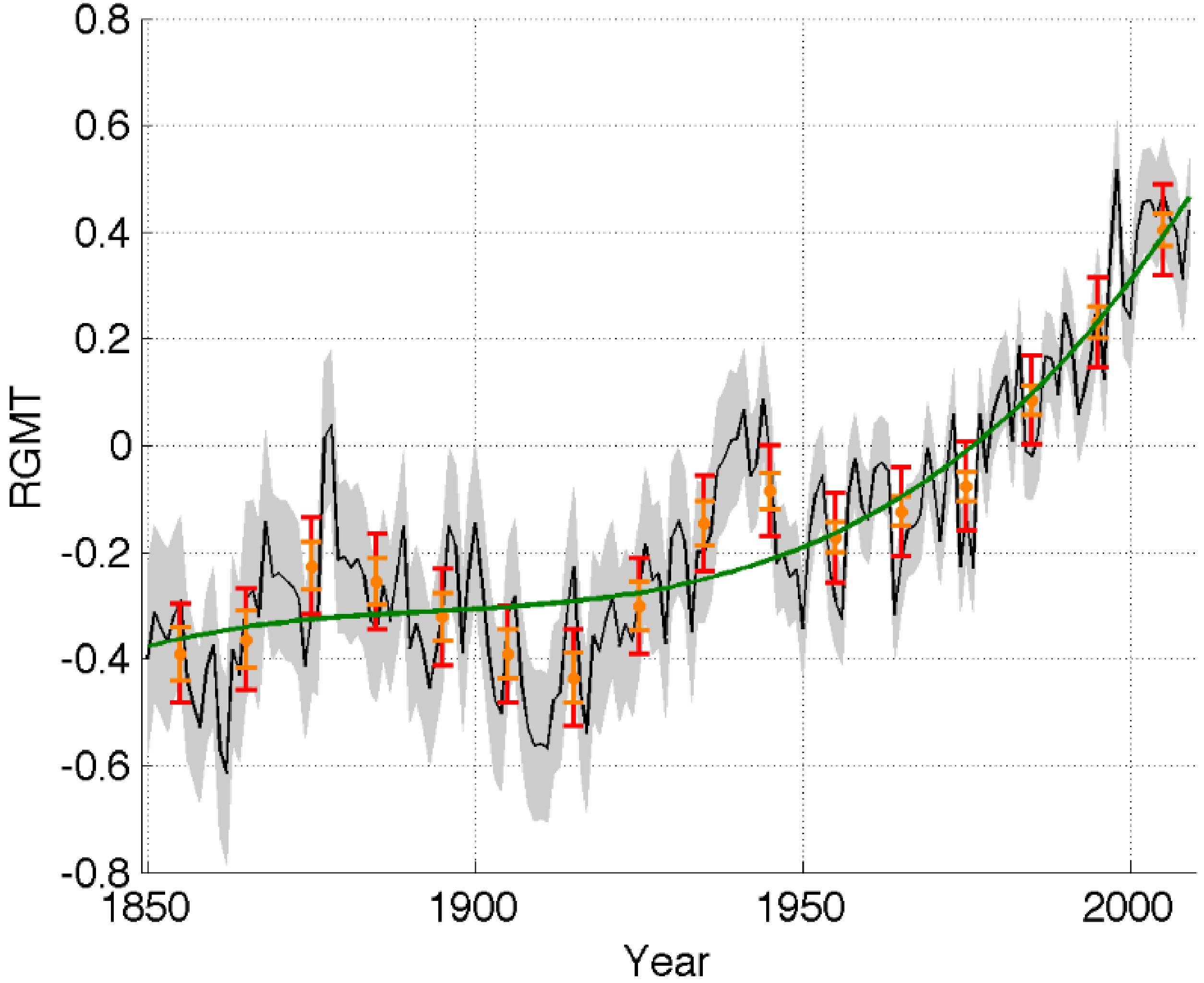
- Two issues around defining global mean temperature (GMT)

1. Attempts to measure or model it are subject to biases
   - It is generally argued that differences in GMT are more meaningful and robust
   - Hence our data are differences between observed GMT in a given year and the average over 1961-1990
   - We call this (observed) RGMT
     - Relative GMT
   - The output that we take from C-Goldstein for each decade is also converted to (simulated) RGMT
     - By subtracting average simulator output for 1961-1990

Weather versus climate

2. HadCrut3 data show substantial inter-annual variability
   - There is weather on top of underlying climate
   - C-Goldstein output is much smoother
     - Just climate
   - We assessed the inter-annual error variance by fitting a smooth cubic
   - And looking at decadal deviations from this line

- True RGMT is defined as underlying climate
  - Observed RGMT is true RGMT plus measurement *and* inter-annual (weather) error
  - Simulated RGMT is true RGMT plus input error *and* model discrepancy



- Black line and grey error bars = HadCrut3 and measurement error
- Green line = cubic fit
- Red decadal bars = measurement (orange) plus inter-annual error

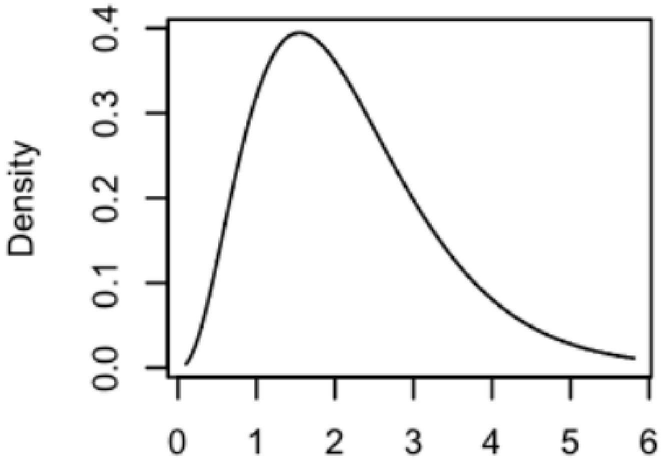
Target 2 degree rise

- The target of keeping with 2 degrees warming was defined as
  - Relative to pre-industrial temperature
  - For future up to year 2200
    - So max true RGMT should be less than (pre-industrial + 2)
- The objective was to assess the probability of achieving this target
  - For given future CO_2 emissions scenarios
  - Averaged with respect to all sources of uncertainty
    - After calibration to historic RGMT data
    - Including emulation uncertainty

Elicitation

Parameter distributions

- Uncertainty about the 18 C-Goldstein inputs was characterised as probability distributions
  - True values *defined* to give best fit to historic RGMT
  - Obtained by eliciting judgements from 2 experts
  - Using the SHELF elicitation framework
    - http://tonyohagan.co.uk/academic/shelf
- E.g. Ocean Drag Coefficient
  - Default value = 2.5
  - Elicited range = [0.6, 4.4]
  - Distribution = Gamma(3.51, 1.62)



Model discrepancy

- Beliefs about discrepancy between C-Goldstein RGMT and true RGMT also elicited
  - From the same two experts
  - Defined for true values of inputs
  - Predicting ahead to year 2200
- Experts thought model discrepancy would grow with temperature
  - The higher the temperature, the further we get from where we can check the simulator against to reality
  - Simulator error will grow rapidly as we extrapolate
- Complex and difficult elicitation exercise
  - Details in toolkit

Analysis

Two emulators

We built two separate emulators

1. Emulation of the decadal simulated RGMT
   - As a function of 17 inputs
   - Multivariate GP emulator
   - Used for calibration against the historic temperature data
2. Emulation of future max simulated RGMT
   - Up to year 2200
   - As a function of 18 inputs and 3 scenario parameters
   - Used for assessing probability of staying under 2 degrees warming

The first emulator

- C-Goldstein takes about one hour to spin-up and run forward to 2008
- We ran it 256 times to create a training sample
- According to a complex design strategy – see the toolkit!
- After removing runs where no result or implausible results were obtained, we had 204 runs
- The multivariate emulator was built
- And validated on a further 79 (out of 100) simulator runs
- Validation was poor over the baseline period 1961-90 but otherwise good

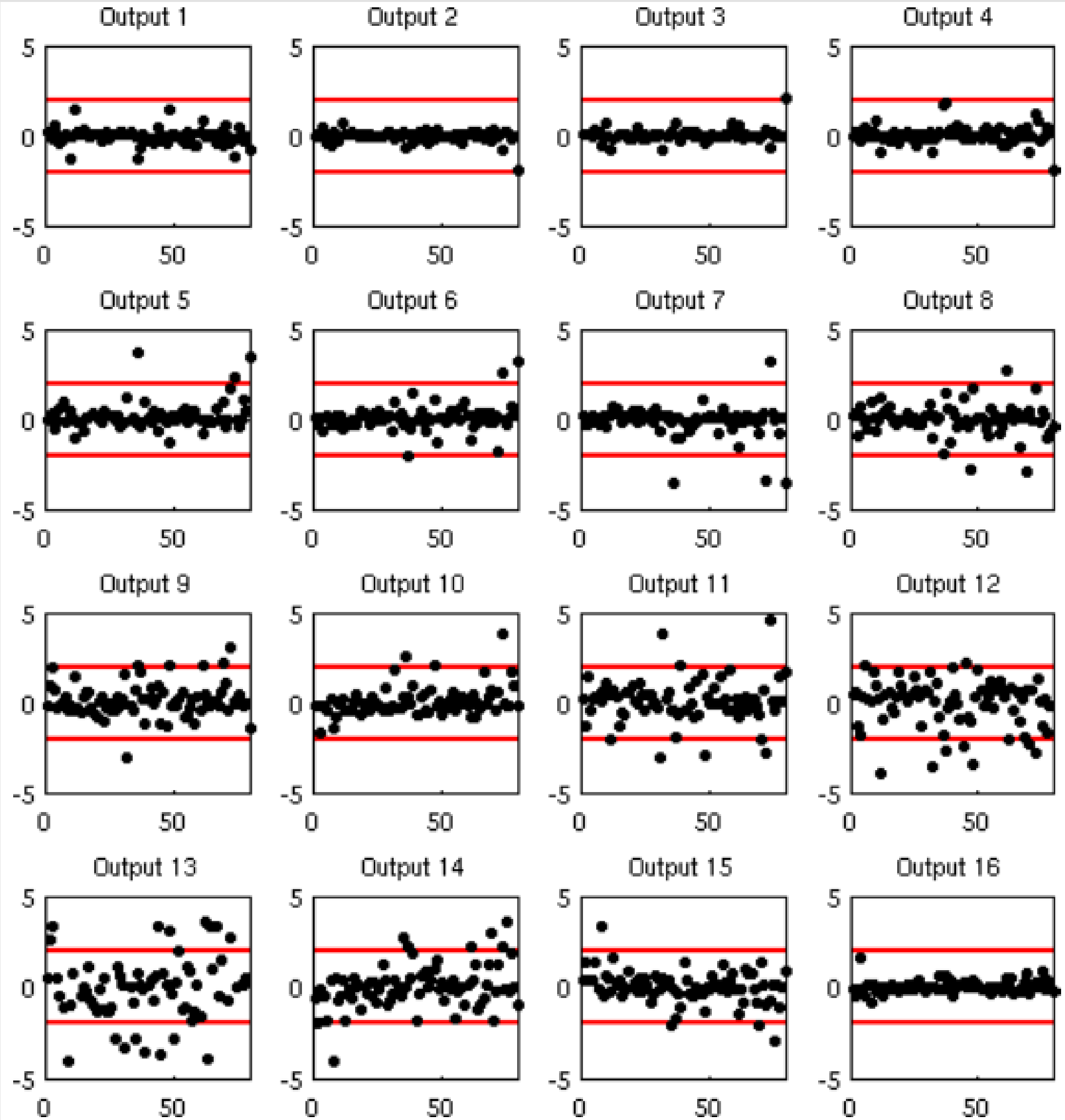
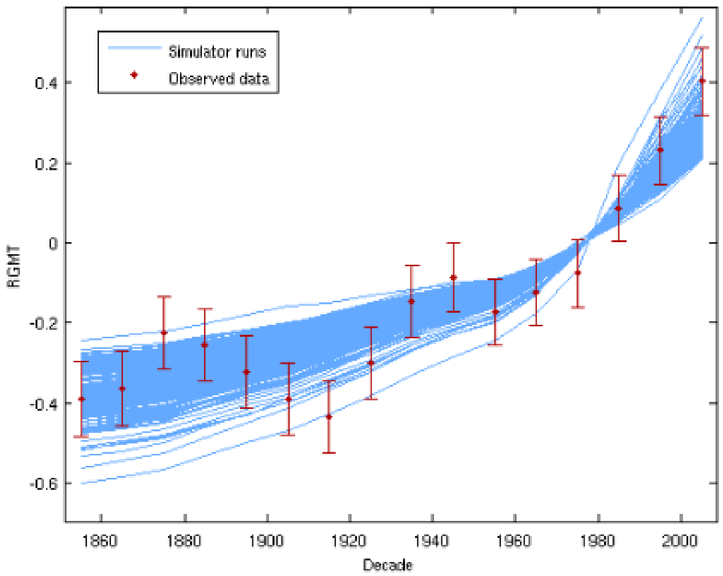


Figure 3c: marginal standardised errors (red lines correspond to 2 std. dev.)

- 95% of these standardised errors should lie within the red lines
- We see problems with outputs 12 to 14 (1960s to 80s)
- And results rather too good at the earliest and latest dates
- Partly the fault of multivariate GP

Calibration

- After allowing for model discrepancy, the decadal data provide little information about any of the input parameters
  - All training runs consistent with decadal data and the elicited discrepancy
- We do learn about the shape of the discrepancy
  - Calibration suggests it increases even faster with temperature
    - But this is largely coming from the final observations, and so may be unreliable

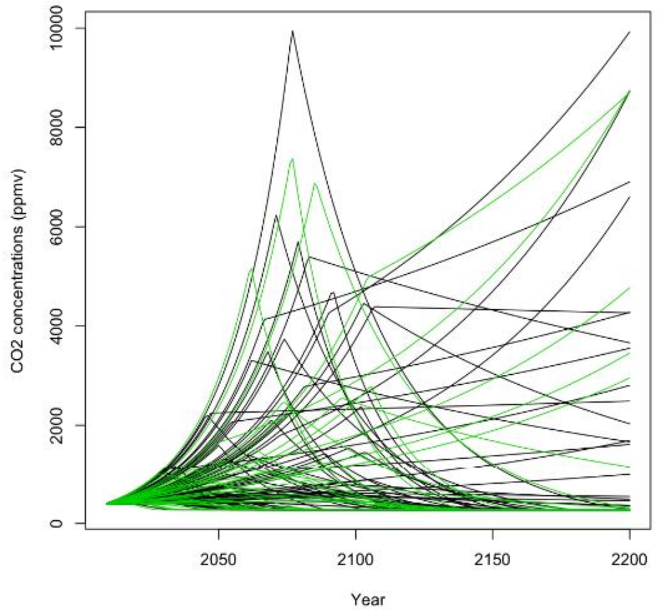


The second emulator – training runs

- Future scenarios for atmospheric CO_2 concentrations are governed by 3 parameters, t_1, dx and dy

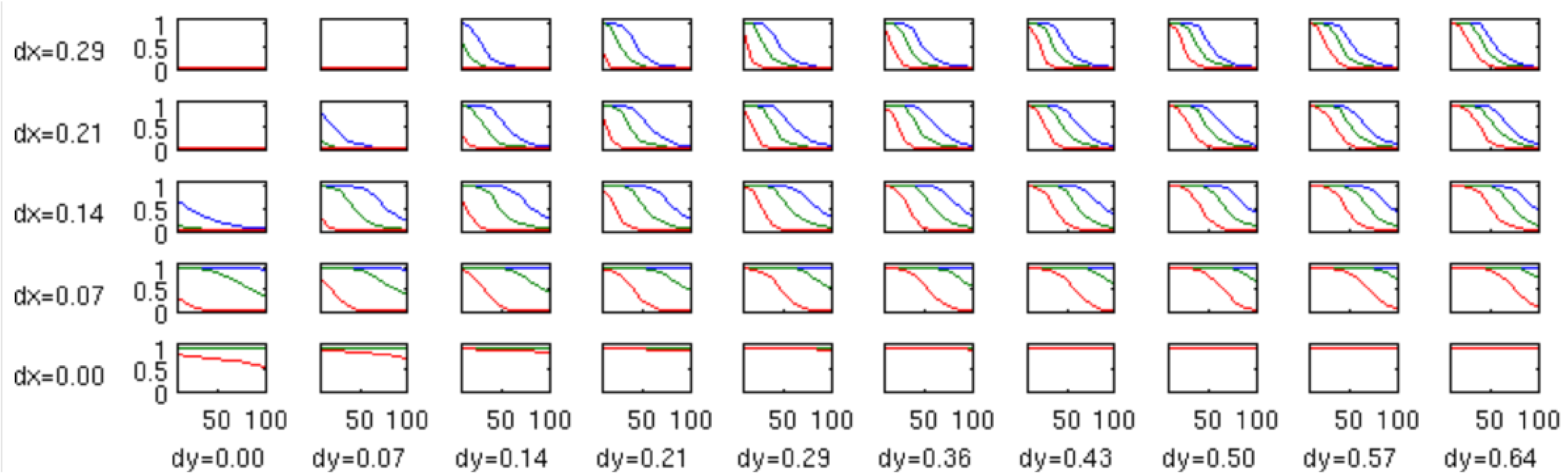
$$C = \begin{cases} C_0(1+dx)^t & \text{for } t < t_1 \\ C_0(1+dx)^t(1-dy)^{(t-t_1)} & \text{for } t \geq t_1 \end{cases}$$

- Each of the original spin-ups was run forward to 2200 with 64 combinations of these 3 parameters
  - Black lines
- Validation spin-ups were run forward with 30 combinations
  - Green lines



Computing probabilities of target

- The second emulator was built for the max RGMT output
  - And validated well
  - Particularly well when temperature rise was smaller
- Probability of true RGMT rise staying below a specific threshold
  - Computed by averaging emulator predicted probabilities
  - Averaged over the sample of calibrated parameter values
  - Allowing for discrepancy and emulation uncertainties
- Calculation can be done for any (t_1, dx, dy) and any threshold
  - We used 2, 4 and 6 degrees



- Red lines are for 2 degrees warming
  - Green for 4 degrees and blue for 6
- Each frame shows probability as a function of t_1
  - Chance of staying under 2 degrees decreases the later we act
  - And the faster we increase CO_2 before acting
  - And the slower we decrease thereafter
- That's as expected of course, but now we have quantitative assessments of the chance

Conclusions

- We can now see just how early and how hard we must act on CO_2 emissions
  - In order to have a good chance of staying under 2 degrees
- Lots of caveats, of course
  - In particular, it’s dependent on the expert elicitation of C-Goldstein model discrepancy
    - We have very little data to check those judgements
  - But nobody has attempted to include that factor before
    - This is pioneering work!
- Emulation was crucial
  - Even for a moderate complexity model like C-Goldstein