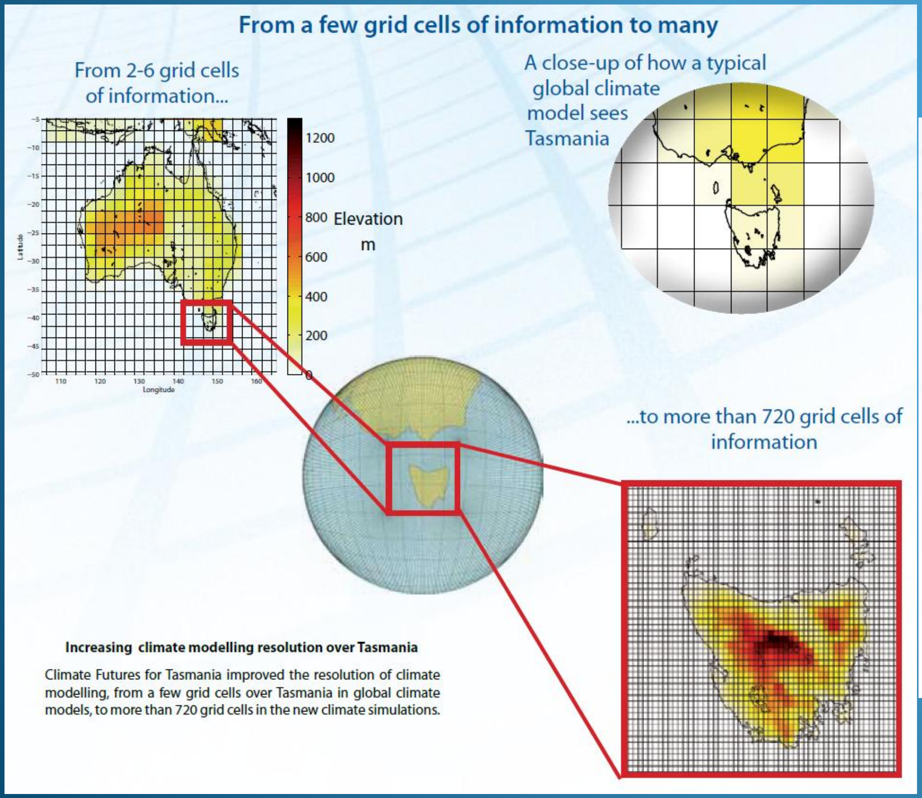
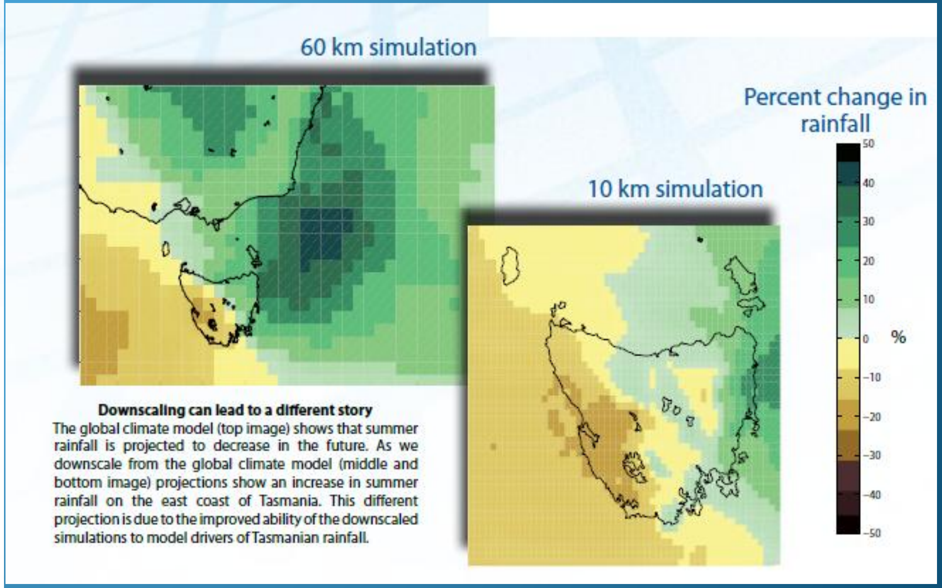
Lecture 16 - Climate Modeling Uncertainty



Increasing climate modelling resolution over Tasmania

Climate Futures for Tasmania improved the resolution of climate modelling, from a few grid cells over Tasmania in global climate models, to more than 720 grid cells in the new climate simulations.



Downscaling can lead to a different story

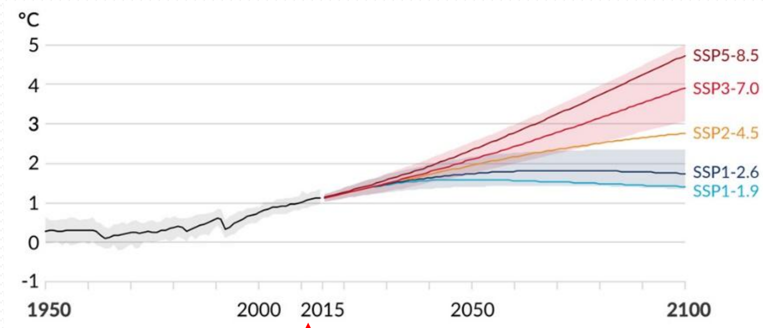
The global climate model (top image) shows that summer rainfall is projected to decrease in the future. As we downscale from the global climate model (middle and bottom image) projections show an increase in summer rainfall on the east coast of Tasmania. This different projection is due to the improved ability of the downscaled simulations to model drivers of Tasmanian rainfall.

Today's Learning Outcomes

1. Know what spatial and temporal resolution refer to in climate models
2. Be able to briefly explain sources of error in climate models and projections
3. Be able to explain exponential growth and its relevance to climate change modeling

Climate Model Structure

Inputs are planetary energy budget variables



Ex. temperature

Orbital forcing

Solar forcing

Volcanic forcing

Land use forcing

Greenhouse gas forcing

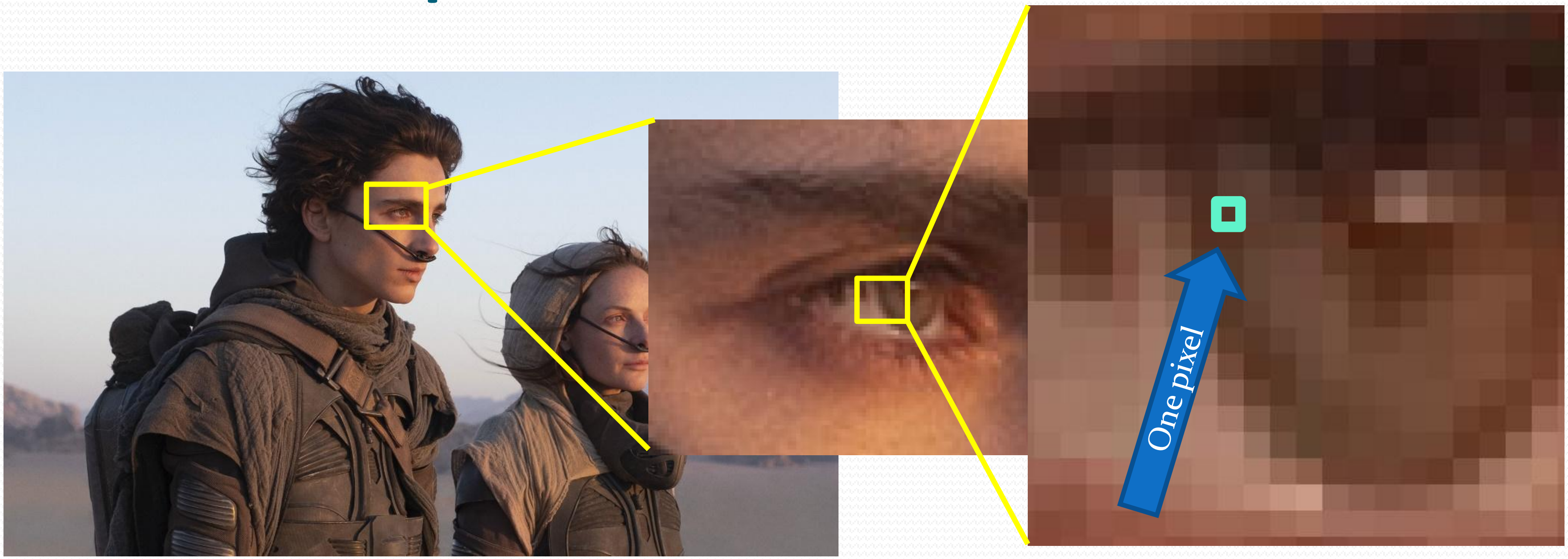
Global Climate Model

Expected Climate Outcomes

Generic Factors of Model Performance

- Spatial resolution (=resolution)
- Temporal resolution (=frame rate)
- Computing power (=processor speed)
- Mathematical model of underlying mechanisms (biology/chemistry/physics)

Spatial Resolution



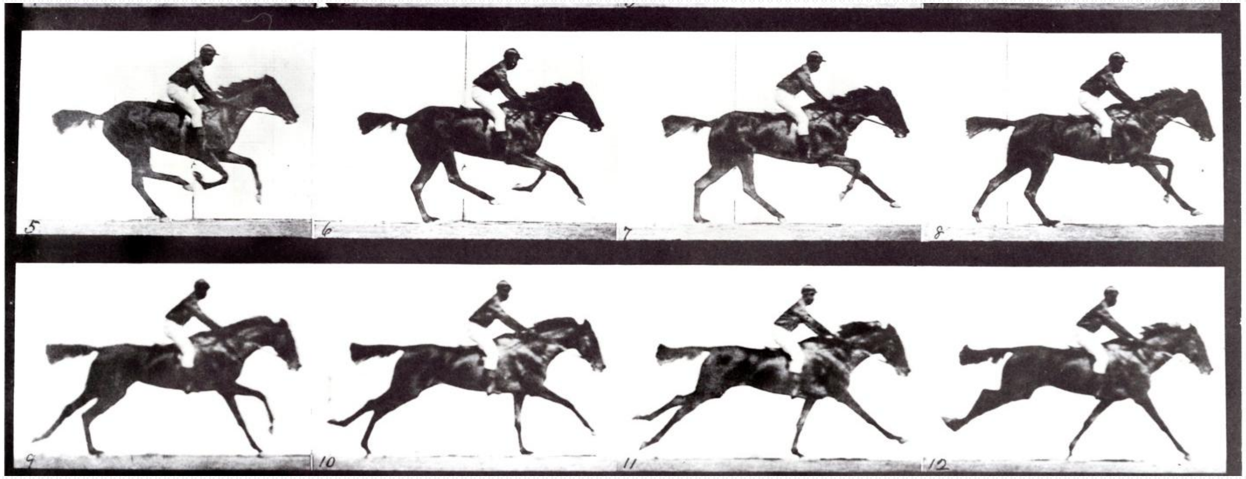
- Size of a model's base units for calculations (cell, pixel)
  - Each cell is assigned a value for each variable (color, wind velocity, wind direction, temperature, CO_2 ppm, etc.)

Spatial Resolution

- Higher resolution (= smaller cells/pixels) allows for smaller-scale details to be detected/modeled

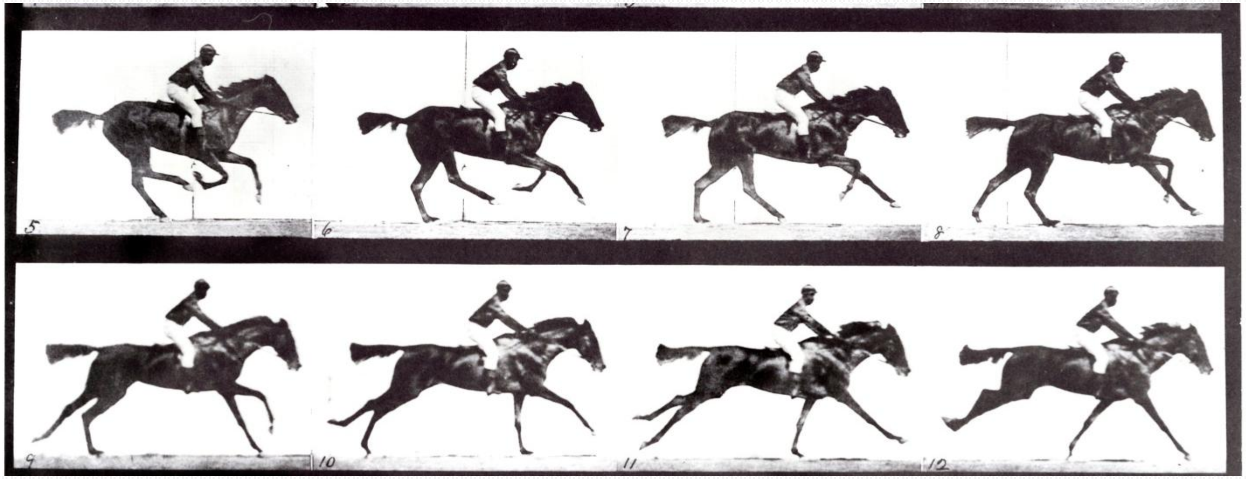
- Resolution often limited by the availability of data
  - i.e. variable with the lowest available resolution limits the level of detail

Temporal Resolution



- Roughly equivalent to frame rate for videos (frames per second)
- Models proceed in steps, recalculating cell values with each step in time
  - Each step could be a year, month, week, day, minutes, etc.
- Climate models assume rates of movement are uniform going from one step to the next

Temporal Resolution

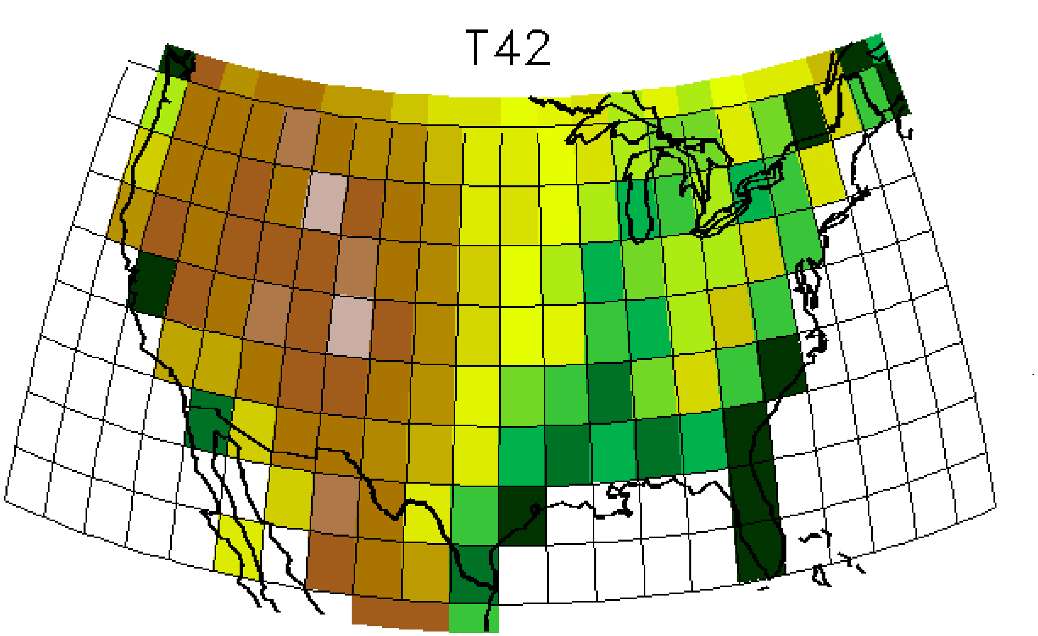


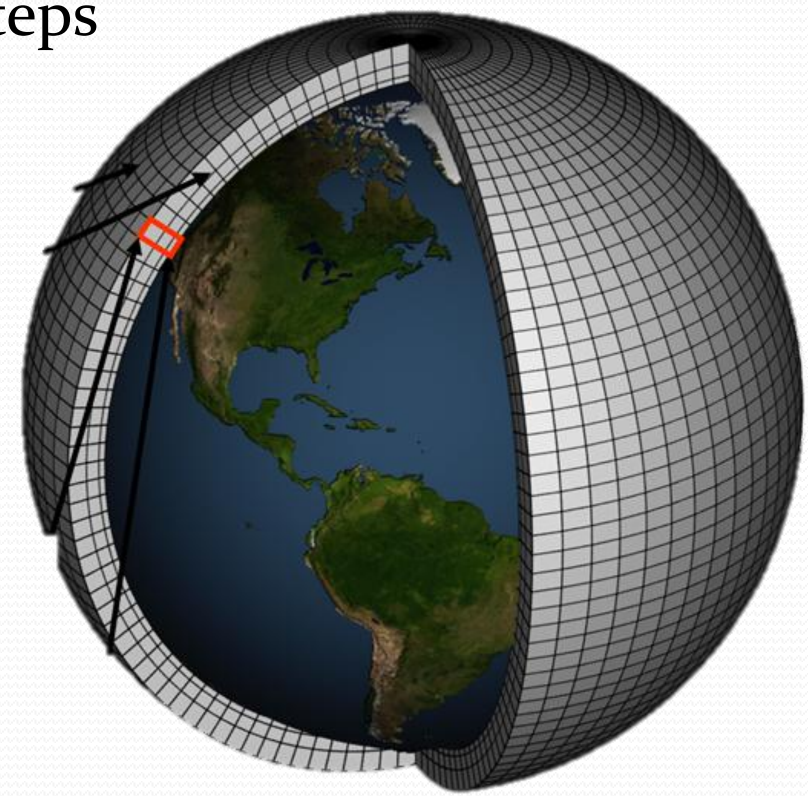
- Higher temporal resolution means each step represents a smaller amount of time
  - Able to capture smaller and short-term effects

- Constrained in climate models by underlying models and computing power
  - Short-term behaviors tend to be more chaotic (ex. weather)

Global Resolution

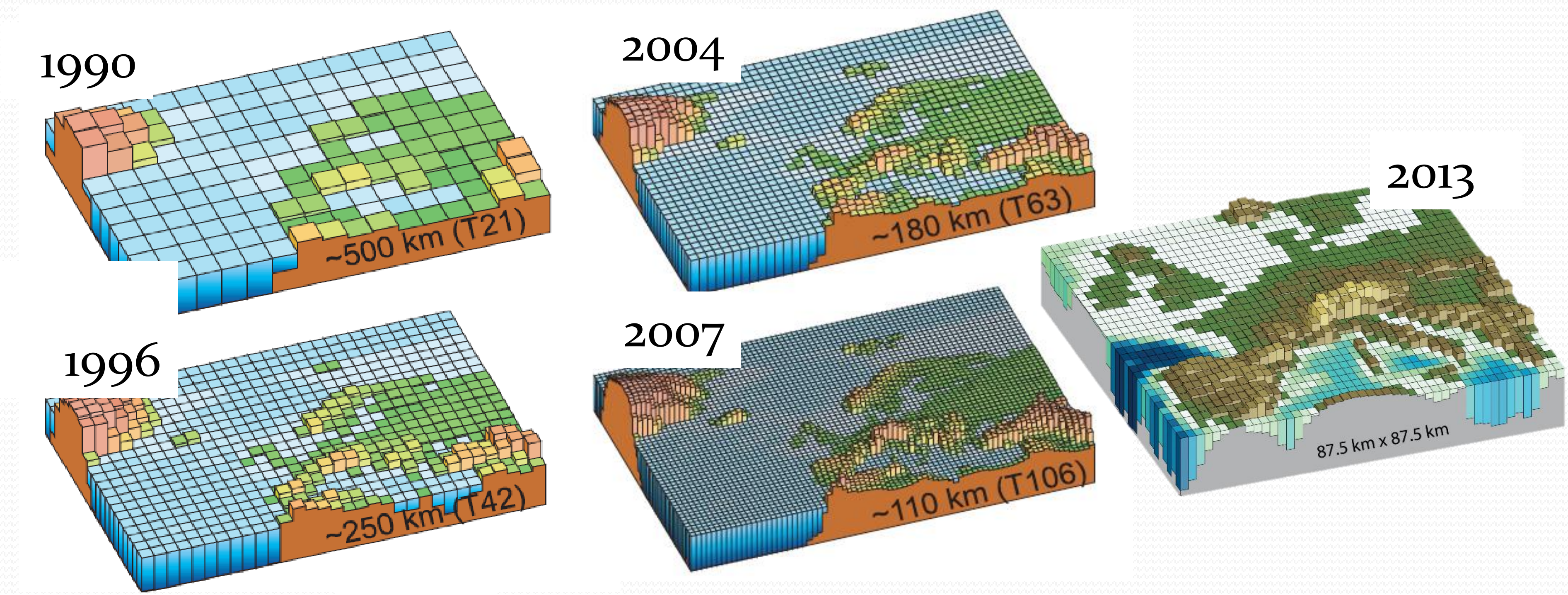
- Climate models divide the world up into uniform pixels (or voxels in 3D) that are the basic units of operation of the model, and model changes values for each cells for many different variables between time steps





Global Resolution Improvement

- Spatial and temporal resolution have both increased dramatically over the past 30+ years, mostly thanks to computing power increases



Computing Power

- Higher spatial resolution means storing more data since each cell gets assigned values for variables of interest and more calculation between steps
- Higher temporal resolution means more calculation overall since what used to be one step might now be five
- Scaling up either or both requires enormous processing power

Example Computing Power

- Dr. Yifan Cheng ran a climate model of Alaska with a spatial resolution of ~4km per cell (very high)
- Required 300,000 CPU hours per model year
- x30 years simulation = 9,000,000 CPU hours!
  - Usually run multiple simulations for a single study

Computing Cluster

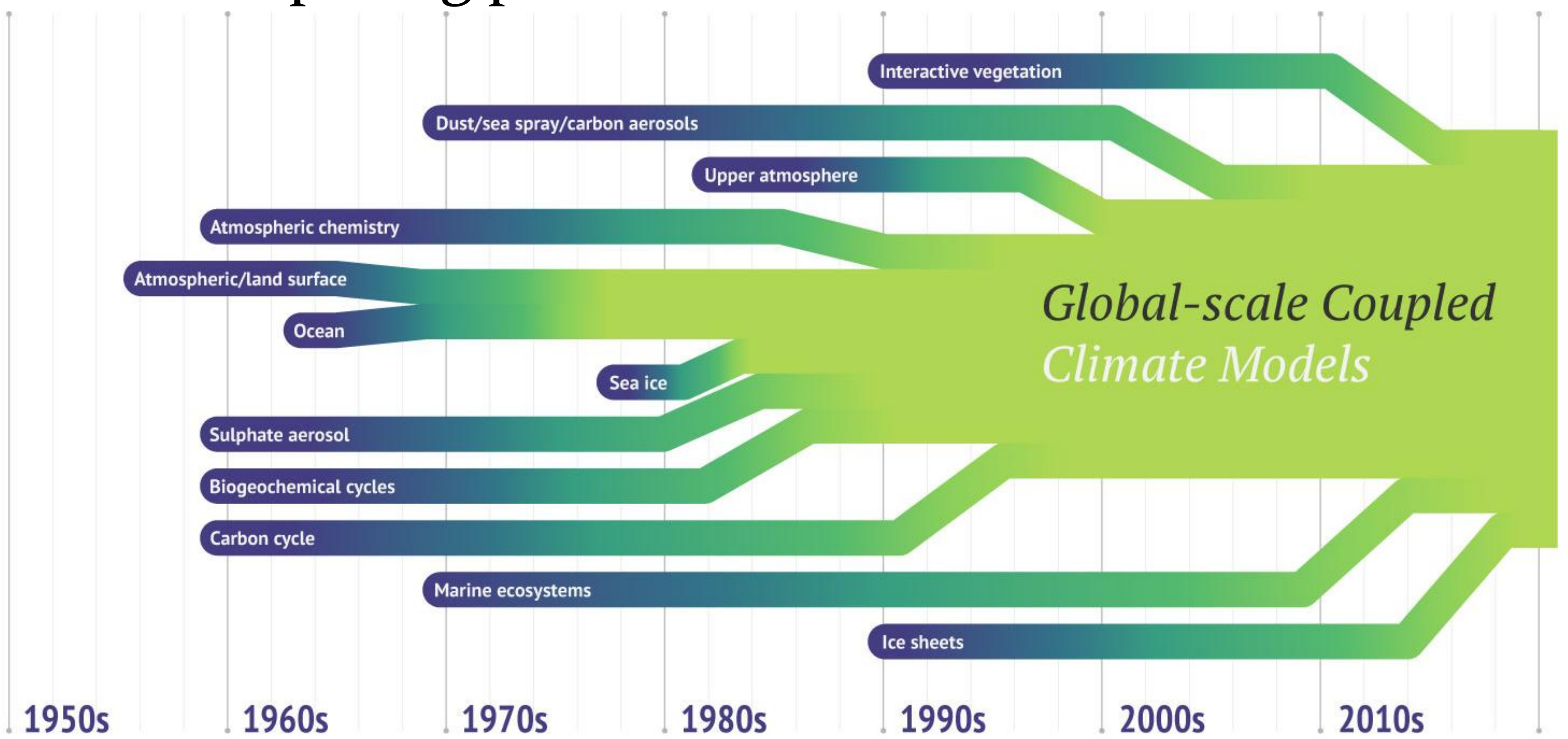
- Huge number of processors working in parallel to make many tens of millions of calculations for each time step

Underlying Mechanisms

- No amount of computing power, spatial, or temporal resolution matters if there's no good understanding of how the system works
- Need to have a mathematical models of processes which can be translated into a computer to calculate
- In climate there are many connected systems occurring simultaneously which are considered
  - The more parts of the system modeled the more accurate the model as a whole should become

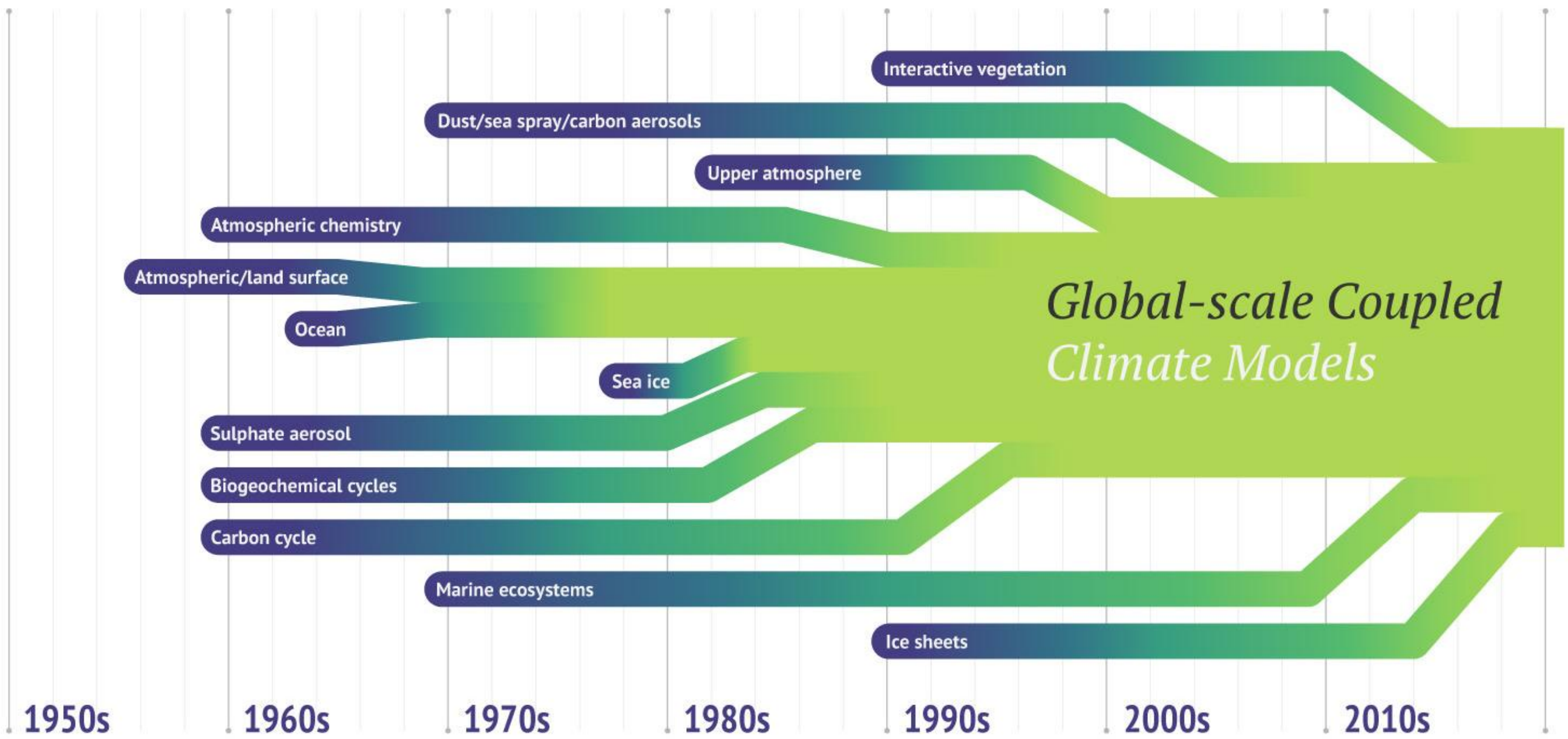
Underlying Mechanisms

- The # of climate systems models incorporate into each cell has increased dramatically as our understanding and computing power have allowed



Underlying Mechanisms

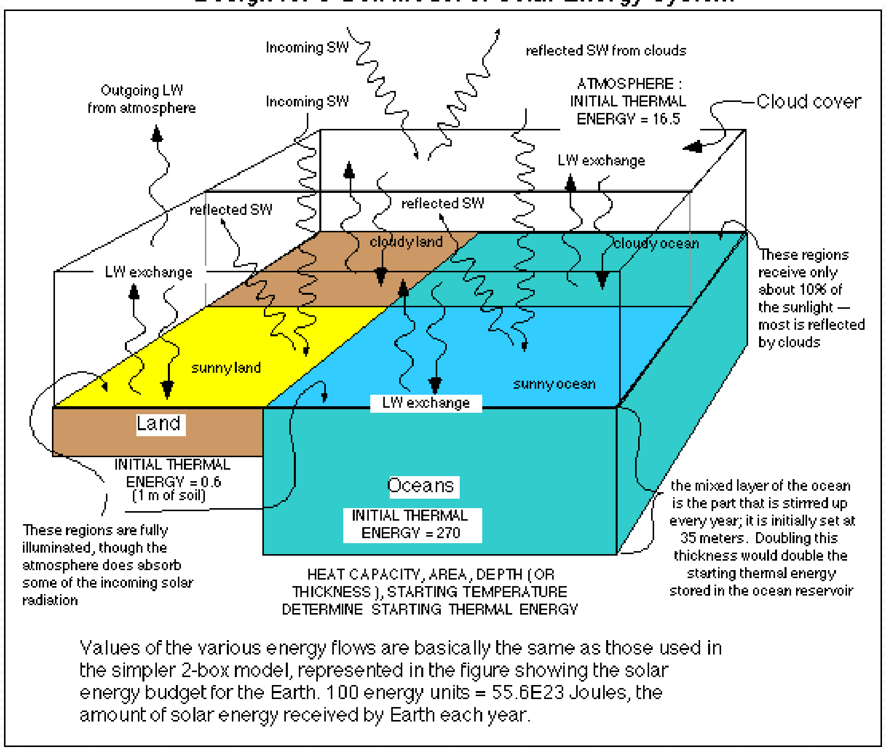
- Mathematical models in climate systems are often modular (models each part separately) and then linked with another mathematical relationship



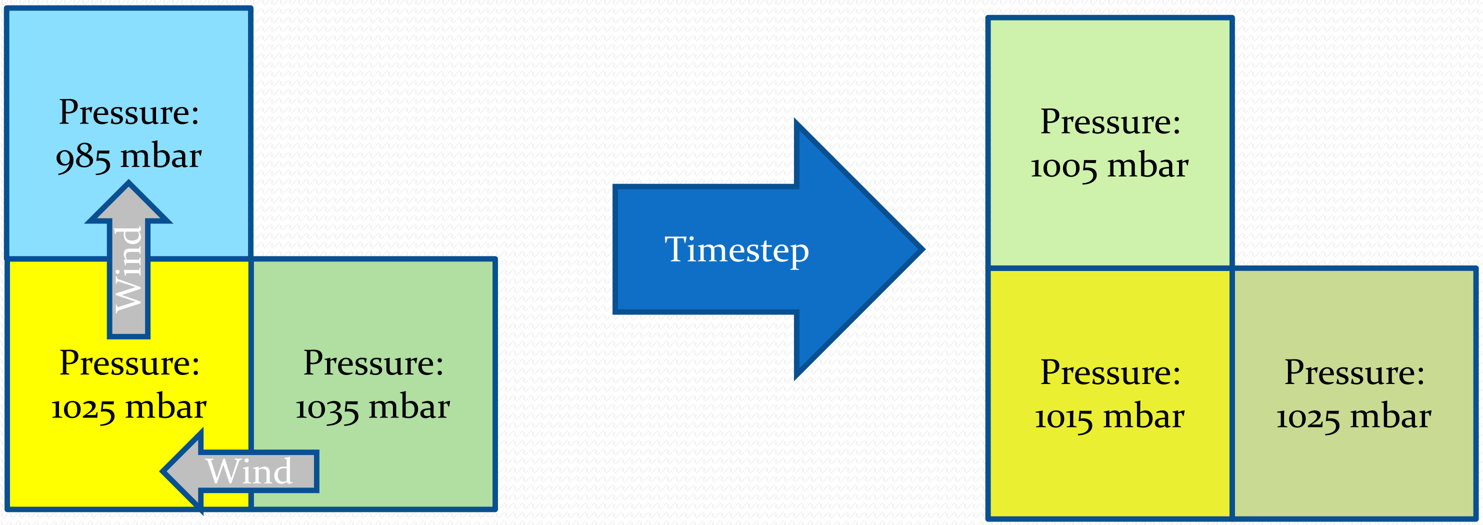
Variables & Equations in Climate Models

- Surface air temperature, sea surface temperature, deep sea temperature, atmospheric pressure, CO_2 ppm, CH_4 ppm, ozone, aerosol concentration, ice extent, precipitation, etc. **and** all the linkages (= transfer or matter or energy) among these factors

Design for 3-Box Model of Solar Energy System



Model cells in the grids only act upon their neighbors



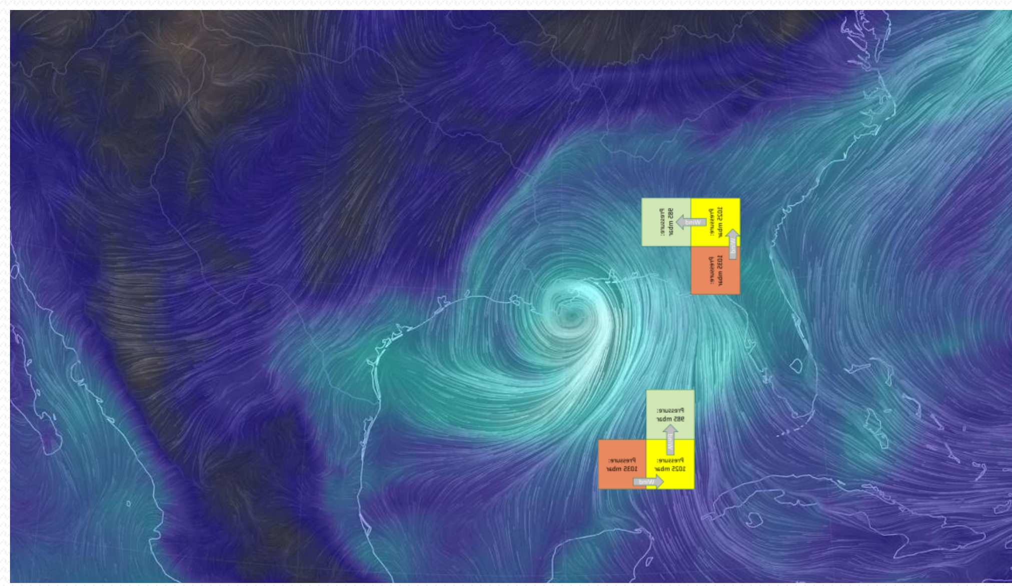
Well-known, uncontroversial physical or chemical equations govern the transfer of material and energy (e.g. water, heat, air) between grid cells.

Incompressible Navier–Stokes equations *(convective form)*

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} - \nu \nabla^2 \mathbf{u} = -\frac{1}{\rho}\nabla p + \mathbf{g}.$$

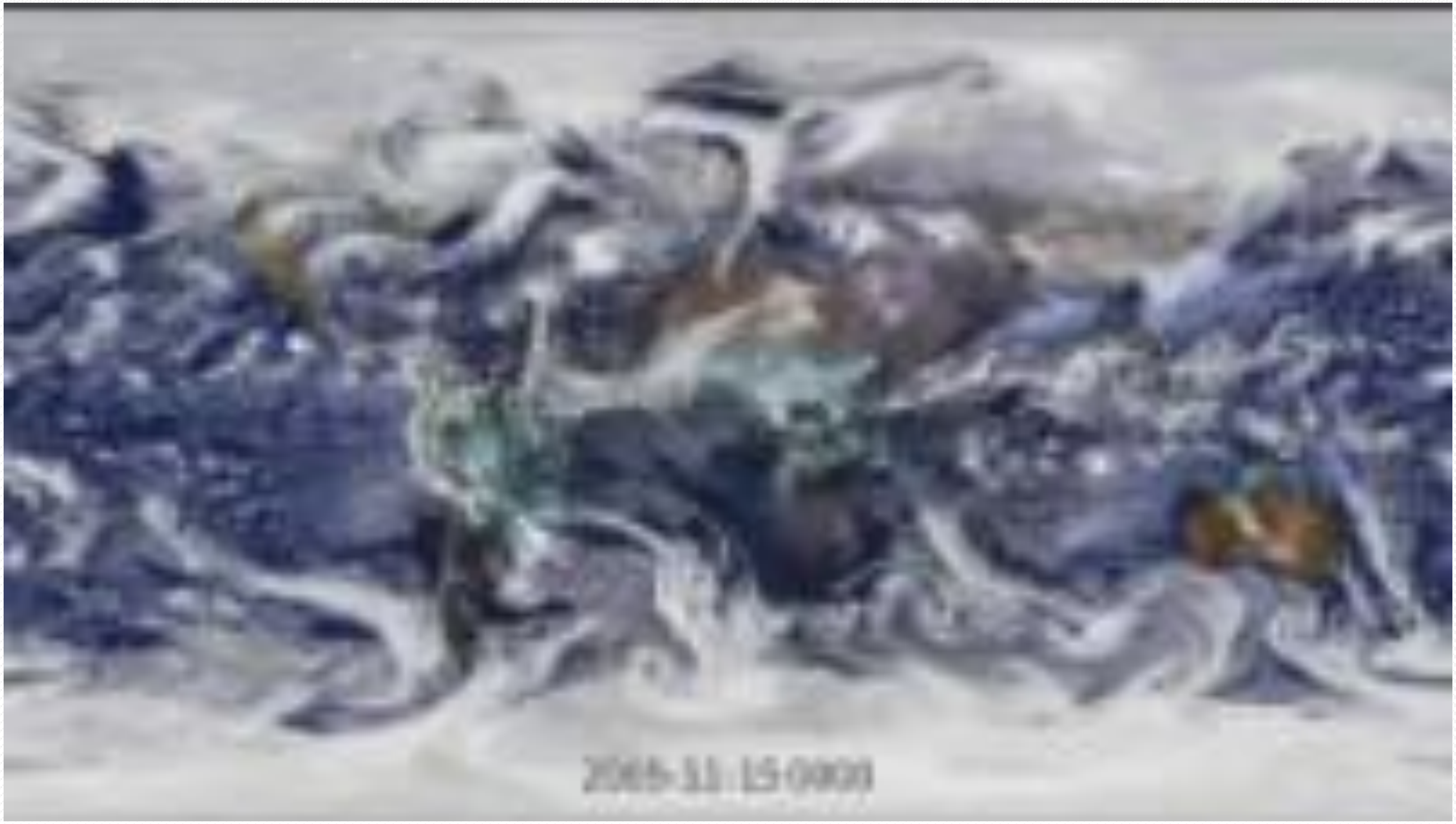
Emergent Properties

- Emergent properties are parts of a system that only emerge at a certain level and not below
  - The whole is more than the sum of its parts
  - Example: the human consciousness is an emergent property of nerve cells, not predictable from examining individual cells



- Climate emergent property example
  - Hurricanes from air pressure differences between cells

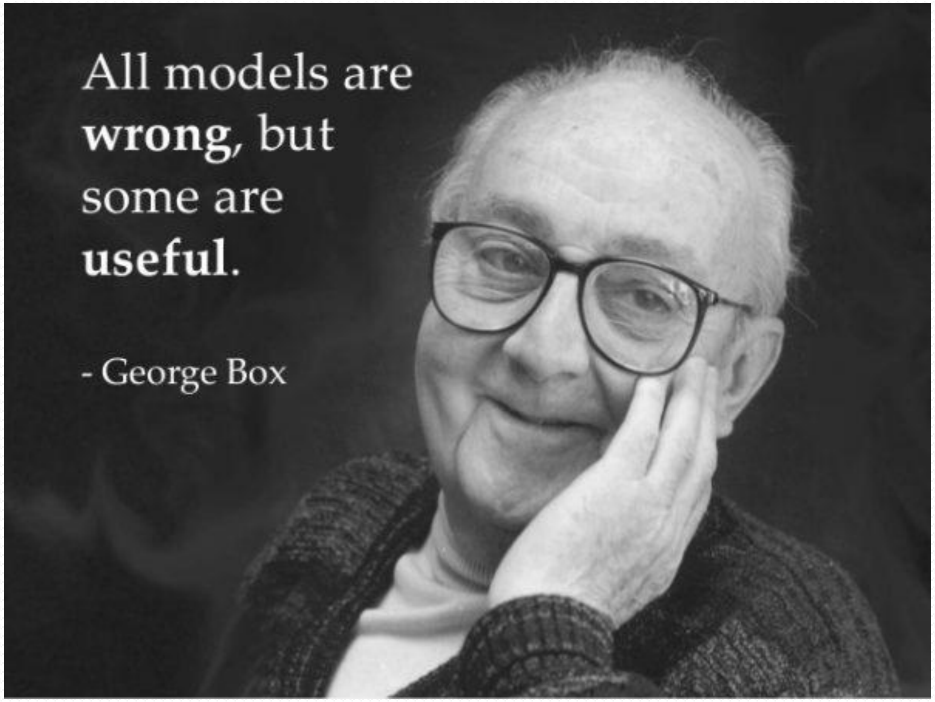
Climate models simulate a possible future global weather, which is certainly not correct.



It's the ***statistics of that weather***, the climate, that we want the models to get right

Averaging Models

- Every model involves choices about what is important versus ignorable
  - What are the best ways to arrive at approximate solutions?
- Individual models are good, but imperfect



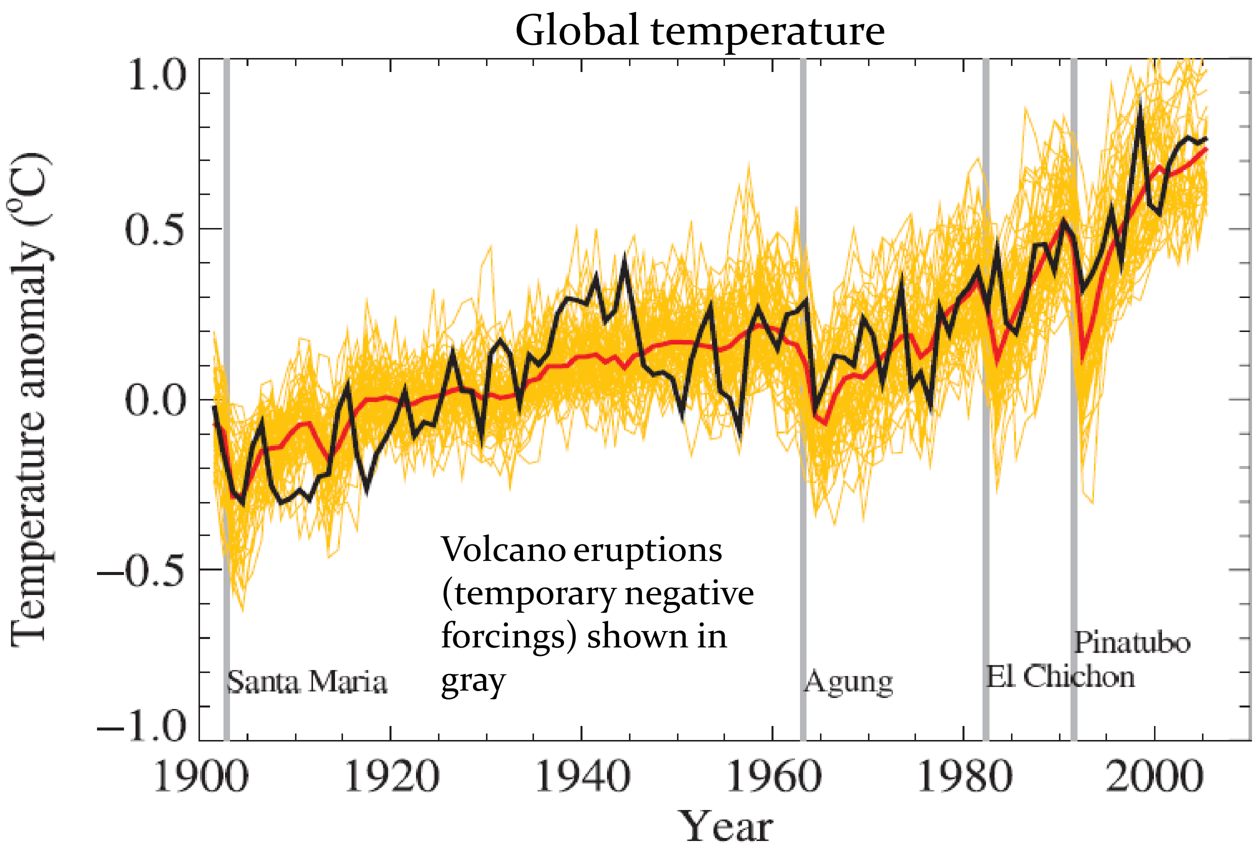
Averaging Models

- The **average** results of multiple climate models are much closer to actual observations over time than any single model is

- We do not know which model is most accurate (probably many are best under different scenarios) but the average gives us our best fit to the data available
  - Having a really good model for the ocean's might mean having to use a simplified equation for how the atmosphere and the oceans link

Averaging Models

- There's a wide spread of possible temperature values at each time-step between models but the average is closest to correct



Individual climate models

Average of all models

Observations

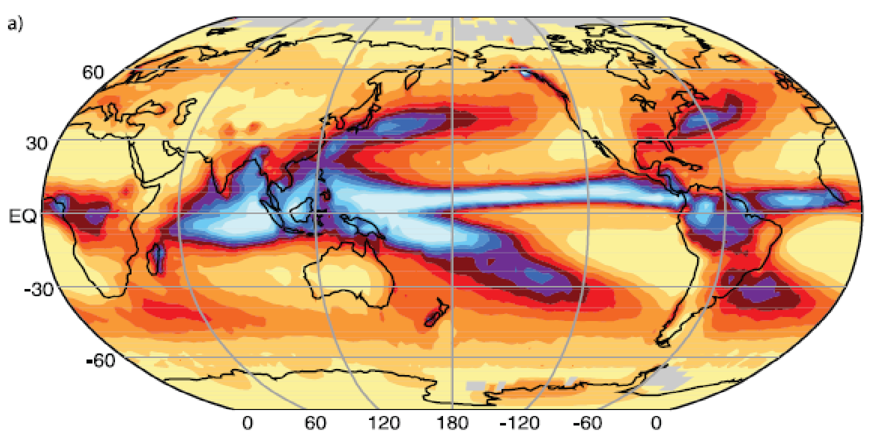
[This is the whole premise of 538]

Validating Models

Climate model results must be compared to today's observations first

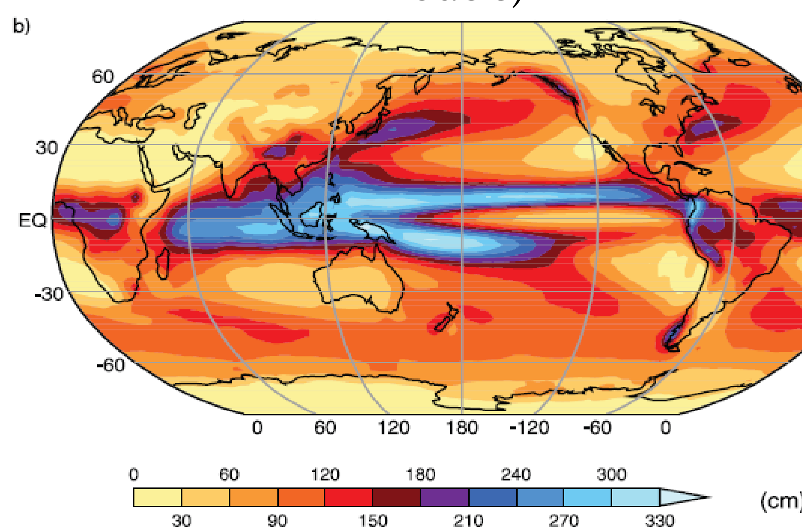
Once we know a climate model is reliable, we can trust it to predict the future

Observed rainfall



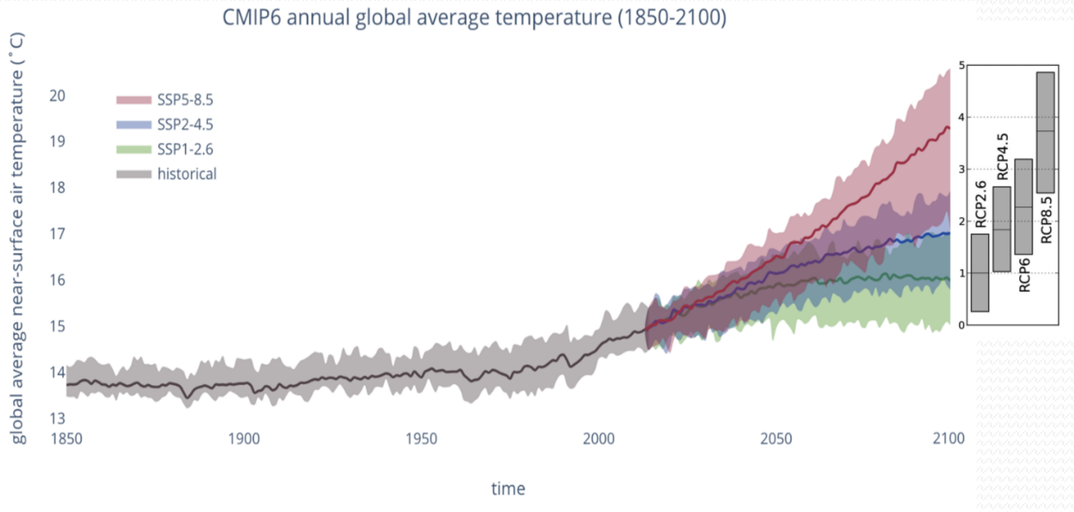
Modeled rainfall

(average of the results of many climate models)



[CMIP](#) – The Coupled Model Intercomparison Project

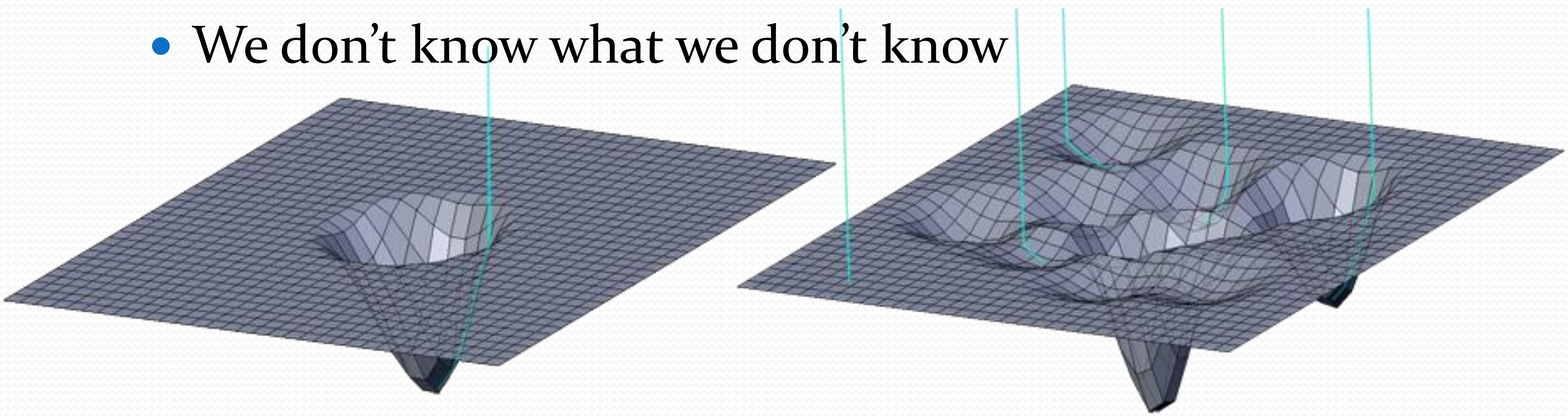
- A meeting where multiple global climate models are tested against each other using the **same forcings** so that only the climate models differ
  - Results of ~5-10 models are averaged to give projections for temperature change under the different SSPs/RCPs



Model Uncertainty

- Obviously lots of uncertainty because we are limited in spatial and temporal resolutions (some smearing & averaging of properties)

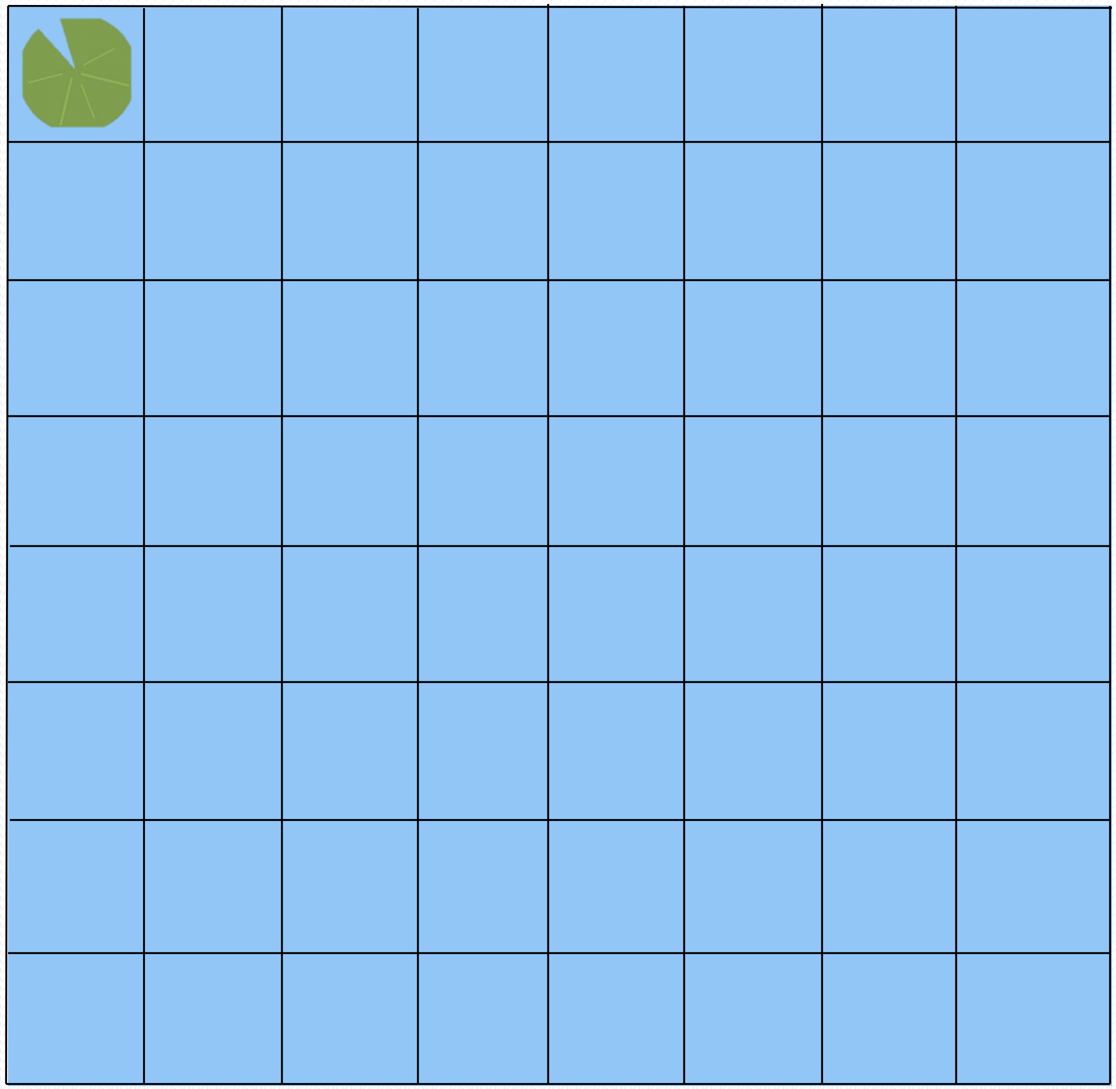
- CMIP only compares among a small number of the near-infinite possible climate models that could exists
  - We don't know what we don't know



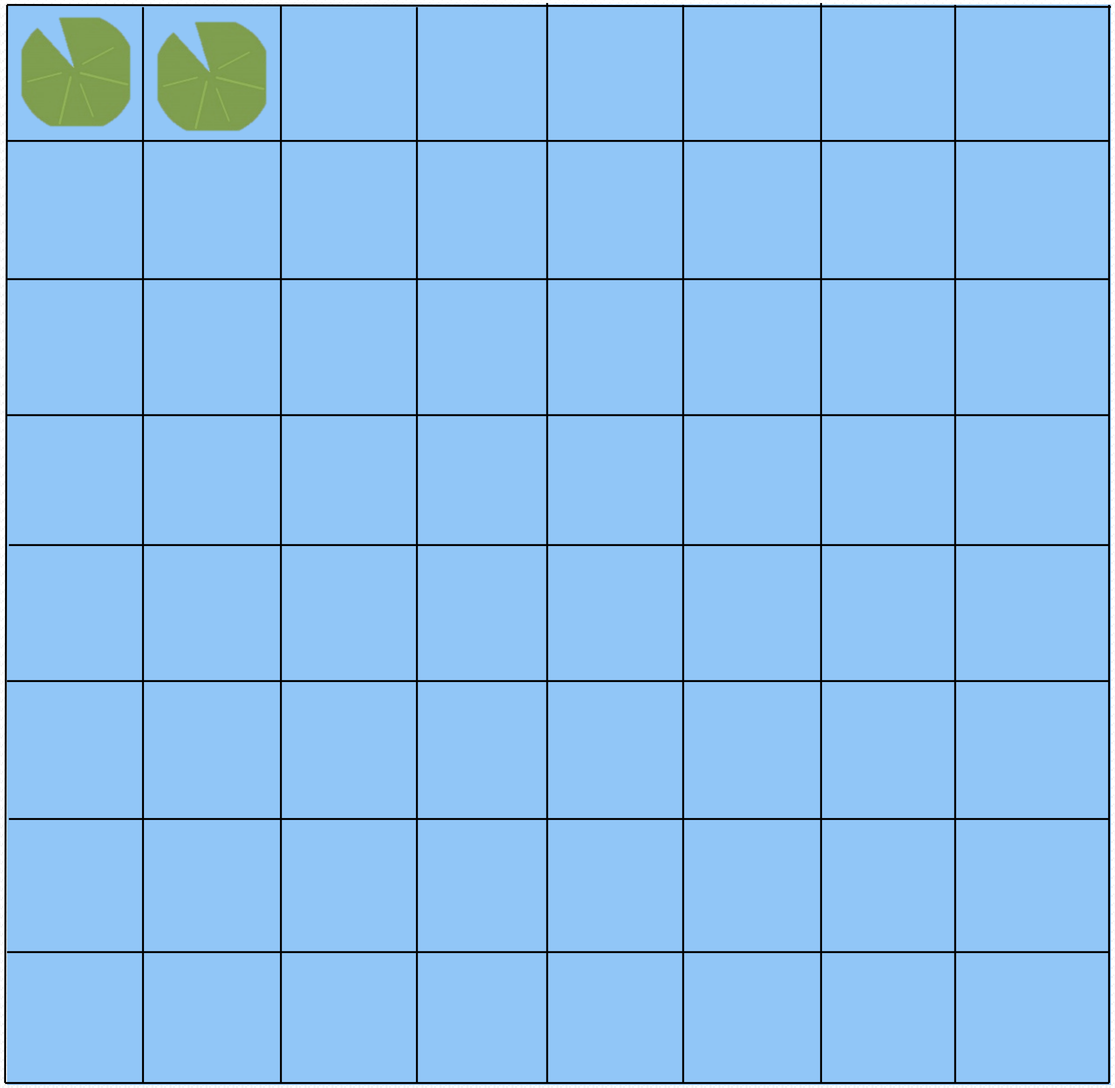
Model Uncertainty

- Biases in training/validation techniques
  - Amazon hiring AI was trained using previous ten years of resumes, mostly men, and so was biased against women applicants for certain jobs
  - LLM image generation is fed by and reinforces racial/gender stereotypes
- Models of climate systems can be inaccurate or biased and so can the models of linkage between the systems
  - Simplified system (ex. treating biosphere as a single system)
  - Mistaking an exponential process for a linear one

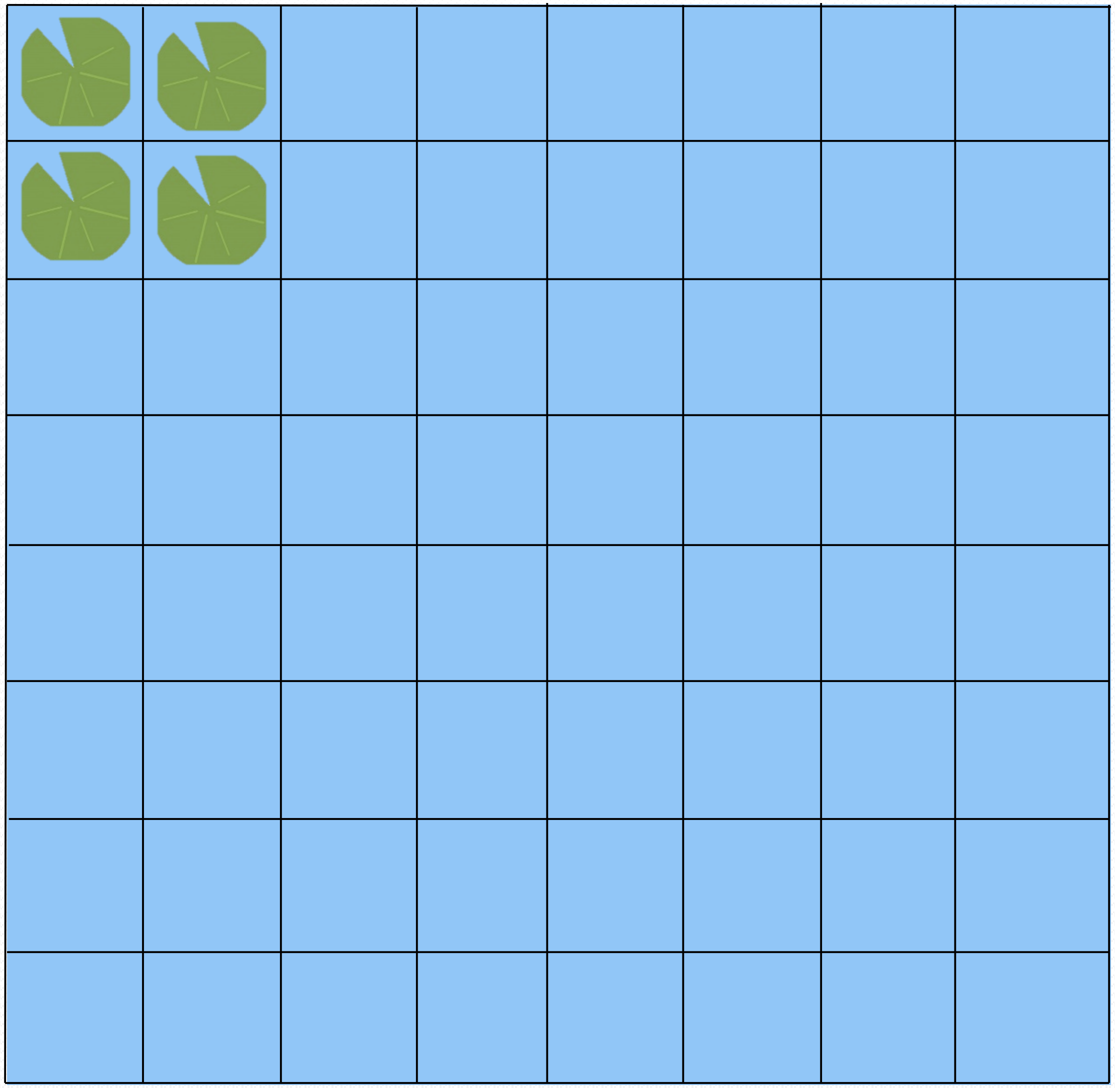
Year 1
1.6% Cover



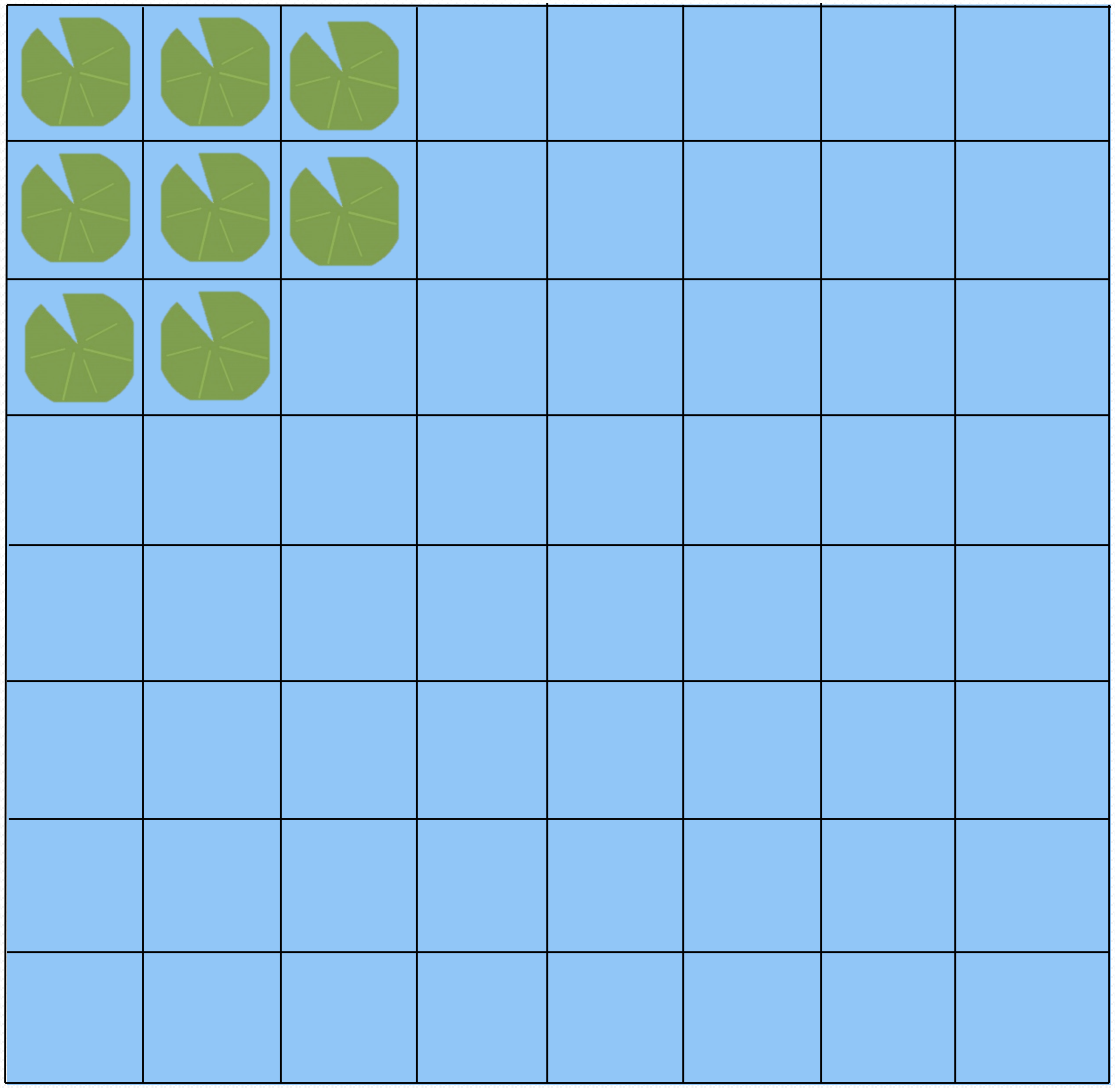
Year 2
3.1% Cover



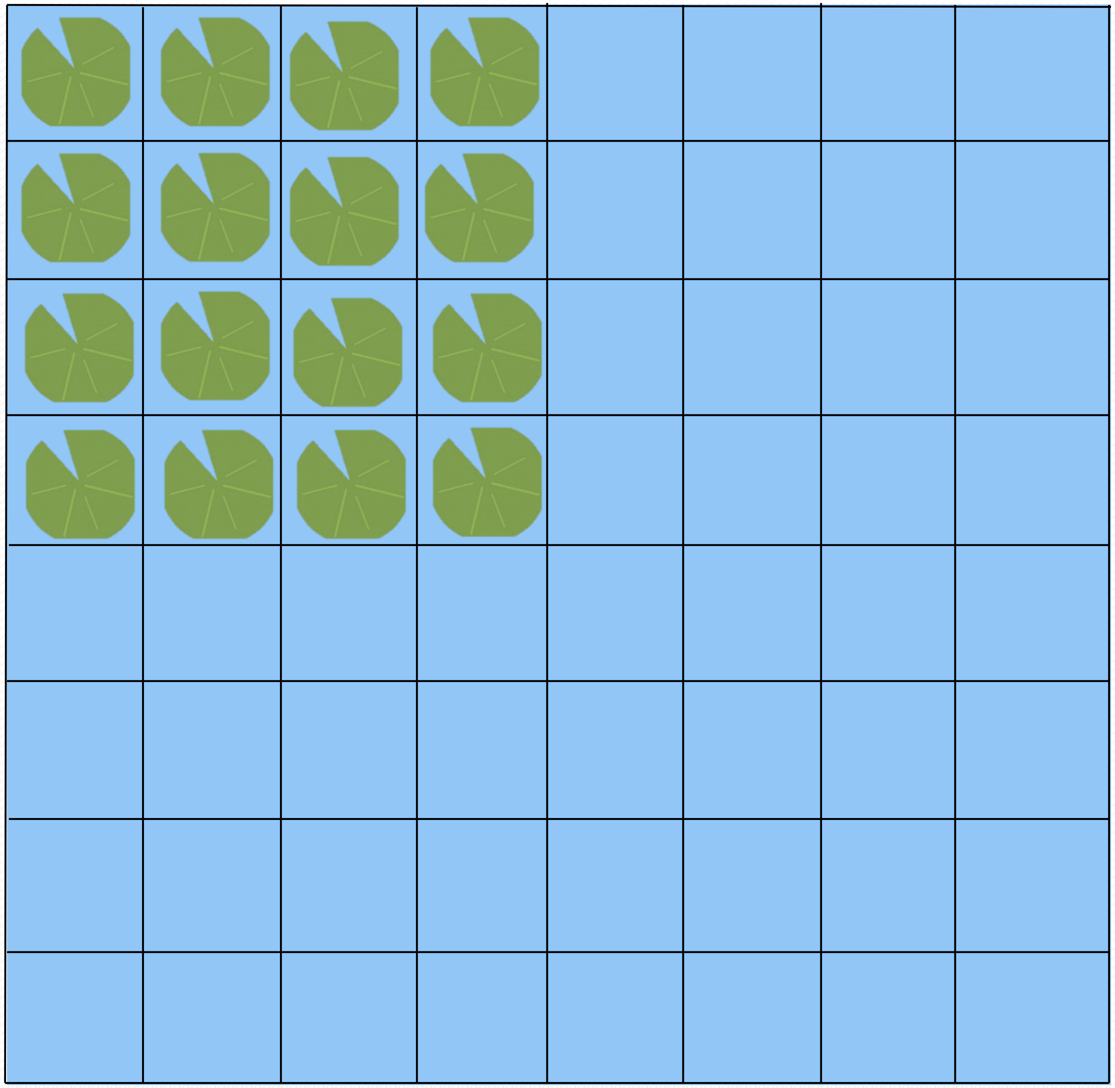
Year 3
6.3% Cover



Year 4
12.5% Cover

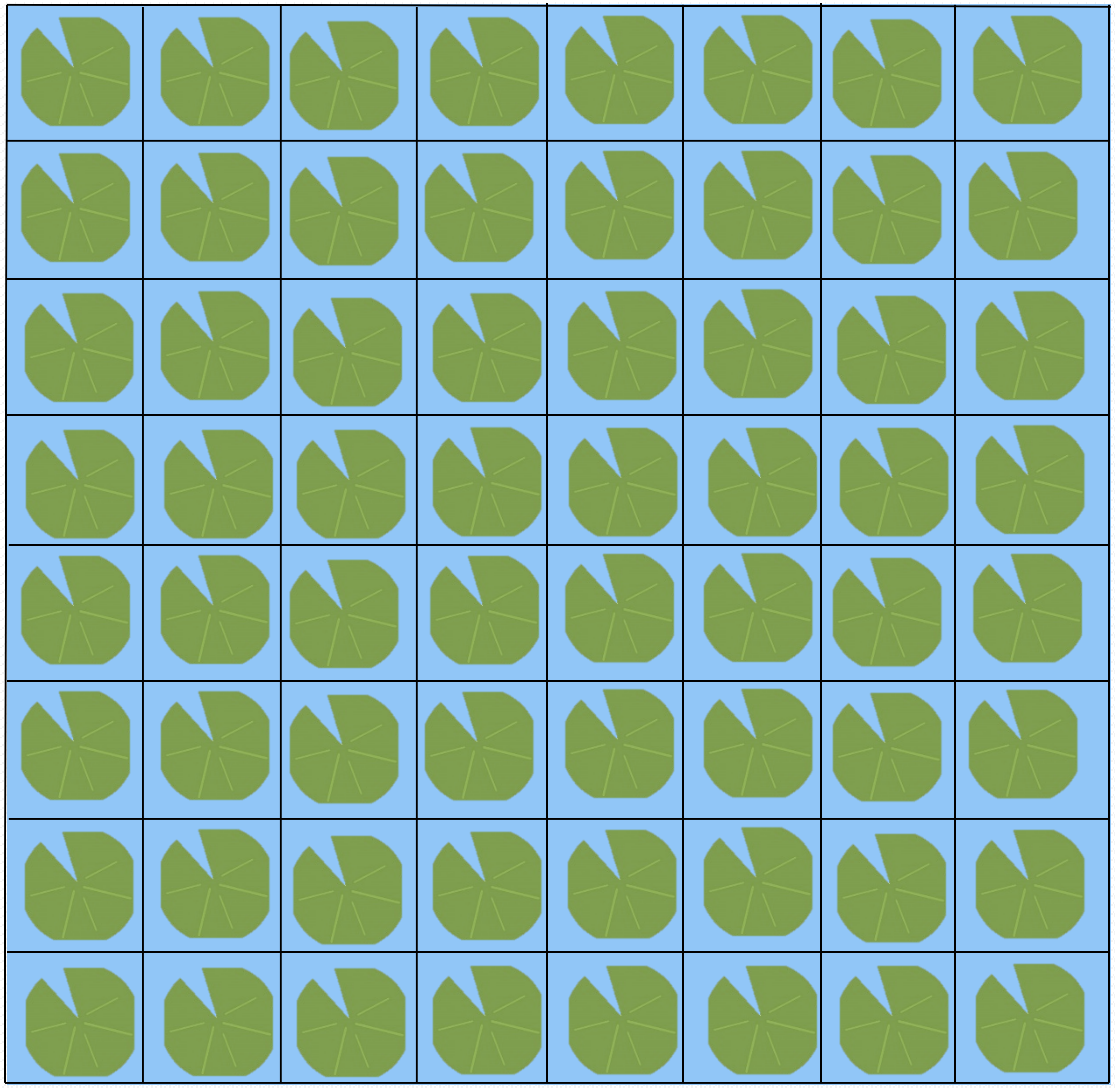


Year 5
25% Cover



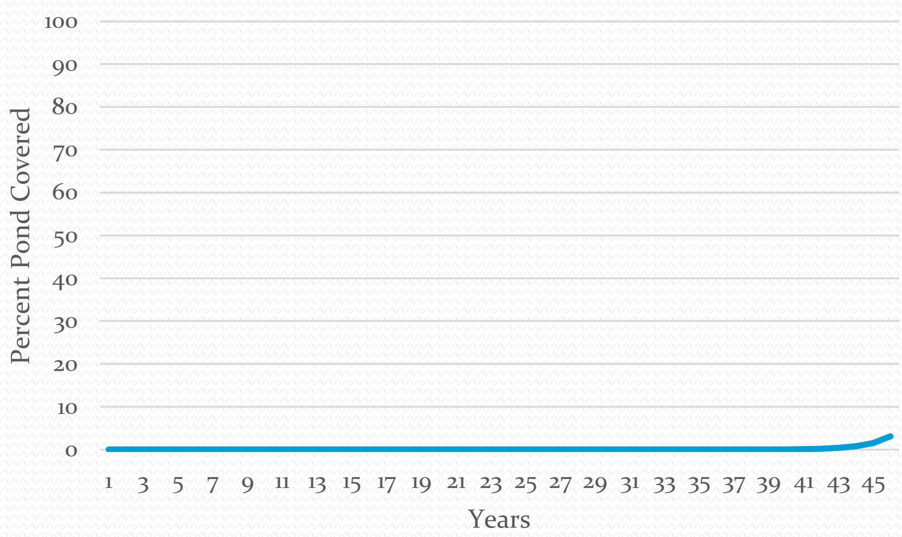
Year 6
50% Cover

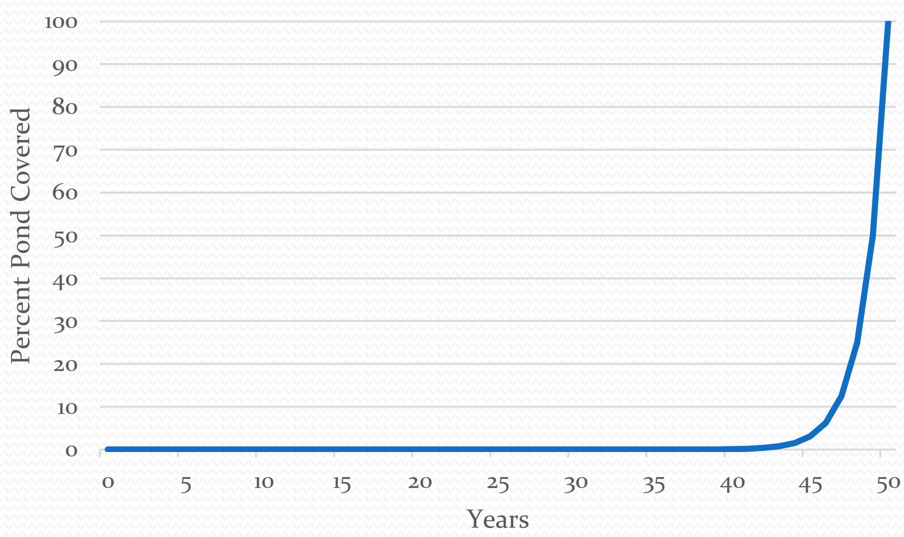
Year 7
100% Cover



Exponential Growth

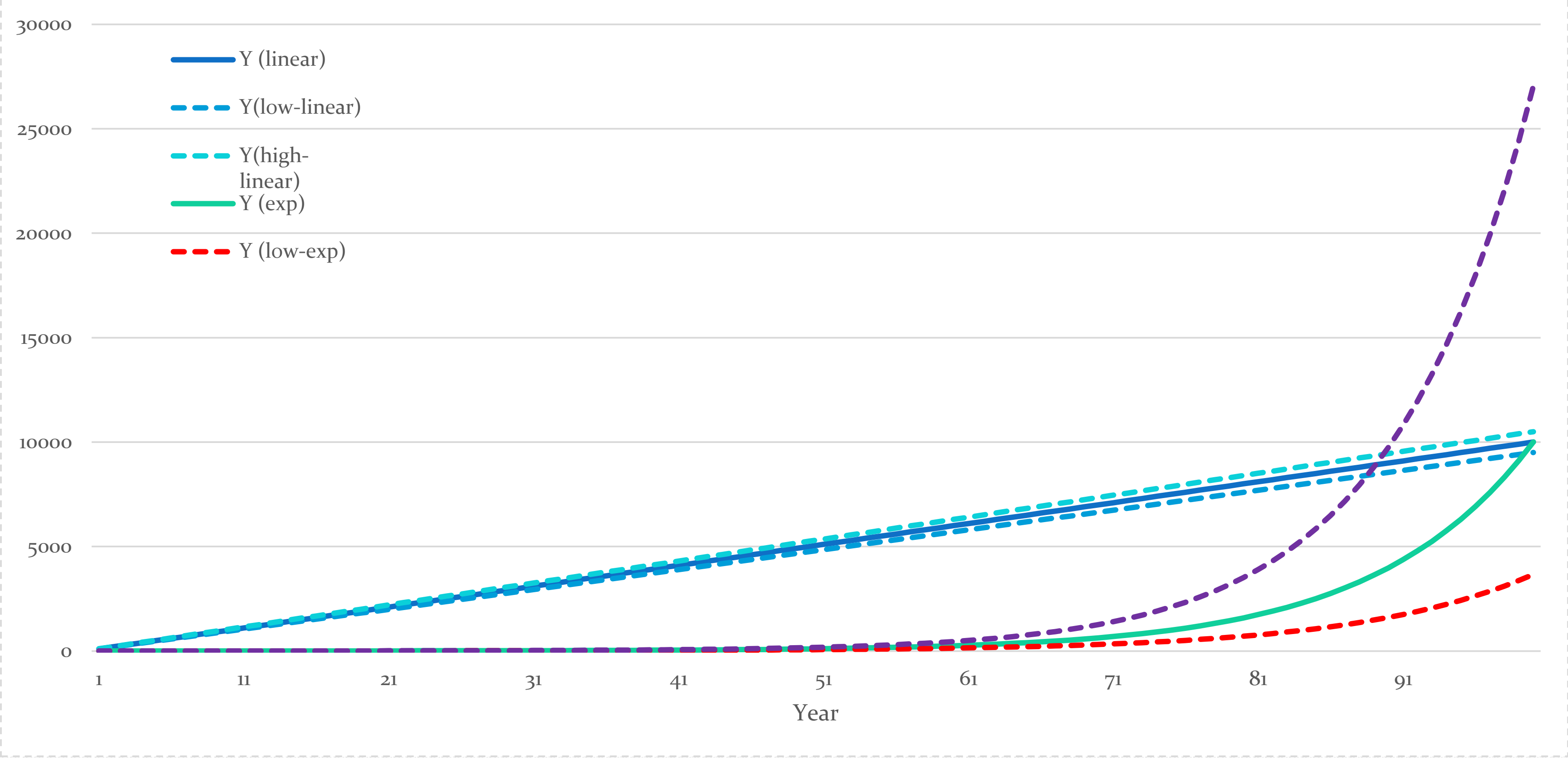
- Consider a much larger pond and again starting with 1 lily pad
  - After 45 years only 3% of the lake is covered…no action seems to be needed…but 5 years later the pond is completely choked by lily pads





Exponential Versus Linear Error

- Uncertainty scales exponentially too if your model is off (drastic mistake if a process turns out to be exponential rather than linear)
  - Possible risk in our understanding of the effects of permafrost thaw



Uncertainty Summary

- We know there is room for improvement in climate models
  - Steady improvements to spatial and temporal resolution and computing power have all been critical to constraining possible futures
  - Also seen climate models with increasingly connected systems more reflective of reality and more likely to capture emergent properties

- Biggest risks are those place for which we have little idea of the uncertainty involved (potential permafrost tipping point, small number of different models being compared)

Today's Learning Outcomes

1. Know what spatial and temporal resolution refer to in climate models

2. Be able to briefly explain sources of error in climate models and projections

3. Be able to explain exponential growth and its relevance to climate change modeling