باسمه تعالی

Climate Change (Introduction)

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The problem with climate change

- Climate change is one of those unfortunate disciplines that cannot fit into the scientific method
- It is unethical, tedious and unfeasible for scientists to conduct experiments on our planet, examining what happens when certain amounts of greenhouse gases are emitted over centuries versus when they have not been emitted, for instance.
- It is unfeasible to construct many identical Earths so as to conduct the experiments on them.

The problem with climate change

- The situation is similar to the problem that was encountered in trying to link an increased incidence of certain diseases to cigarette smoking.
- It was considered unethical and rather challenging to force a random group of people to smoke for several decades and to force another random group to abstain, and then considered rather tedious to have to wait decades to see what happened.

The problem with climate change

- There is one way, though, in which the effects of anthropogenic greenhouse gas emissions and of smoking differ.
- There is one way, though, in which the effects of anthropogenic greenhouse gas emissions and of smoking differ:
  - The climate system is a physical system where the large-scale patterns are governed by a few well-understood laws governing the behavior of fluids and radiation, while the human body is a biochemical system of poorly understood processes.
  - This means that, in contrast to the human body, the climate system in theory can be modeled by constructing pseudo-Earths, consisting of a series of mathematical formulae in computer code. Thus, researchers can conduct true scientific experiments on multiple Earths after all.

The problem with climate change

- Of course, in practice things are a little messier.
- The physical laws behind the dynamics of the climate system may be simple enough, but the sheer size of the planet makes the collection of interactions enormously complex.
- Add to that the fact that poorly understood biochemical processes are involved in maintaining and changing chemical components of the atmosphere that are crucial to the operation of the climate system.
- Squeezing an essentially infinitely complex system into a finite computing structure means that shortcuts need to be taken. In the usual modeling framework, these shortcuts involve simulating what is happening at smaller spatial and temporal scales with rather crude approximations. With today's computing power, that means anything less than a few hundred kilometers.

The problem with climate change

- On the face of it, then, the prospect is not good for using climate models to elucidate the impacts of climate change on hydrology.
- Clouds and precipitation, two of the more obviously important aspects of weather from a hydrological perspective, are represented in climate models entirely by heuristic algorithms, not by direct simulation. Belief in any such experiment thus depends mainly on how much you trust the accuracy of these approximations. They may not be that bad in fact, but we simply do not know.

The problem with climate change

- Climate change is often known as ‘global warming’. There is a reason for that. The dominant cause of current climate change is our past and current emissions of greenhouse gases, in particular carbon dioxide (Intergovernmental Panel on Climate Change 2007a).
- These gases make it hard for the planet to radiate energy back into space, so in effect increasing their concentrations traps the energy that the planet receives from the Sun just a little bit longer, and consequently the planet gets warmer. Changes to clouds and precipitation are thus second-order aspects of climate change, because they occur in response to the warming, not to the increase in greenhouse gas concentrations themselves

The problem with climate change

- In particular, evaporation and evapotranspiration from the ground and plants will be forced to increase markedly, whilst the snowpack will be smaller and will melt earlier in the season
- Because variations in temperature tend to occur over large spatial and temporal scales, temperature is something we can argue that climate models are in fact simulating, rather than heuristically approximating. Further, because warming is the dominant response of the major factors potentially forcing our climate, we can argue that climate models are probably fairly accurate in their estimates of current and future warming

What are Climate and Climate Change?

- The traditional definition of climate is that it is the statistical properties of observed weather at some location and time of year, with these statistical properties determined from observations over some reference period of time.
- This definition runs into trouble though when we consider 'climate change', mainly because 'climate' here is ad hoc rather than describing some inherent property. If the observational period is, say, 30 years, then implicitly the climate cannot change on time scales shorter than 30 years. On the other hand, if we lengthen this period, then we can get rid of climate change altogether.

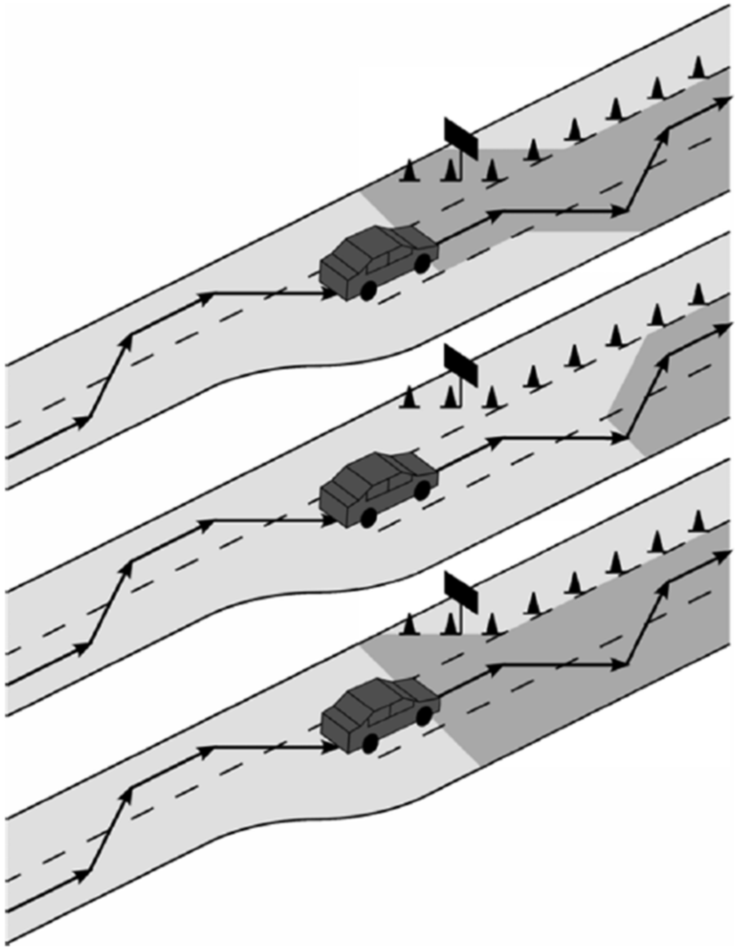
What are Climate and Climate Change?

- The second common definition uses a timescale threshold. Things that happen on a timescale of a few days, and are thus governed mainly by the 'memory' of the atmosphere, are termed 'weather', while things that happen on longer time scales are termed 'climate'.
- the division itself is vague: is a forecast for seven days in the future a weather forecast or climate forecast? What about eight days?

What are Climate and Climate Change?

- The third definition: the ensemble of all possible weather states, given conditions external to the climate (atmosphere ocean-land-snow-ice) system.
- given current solar brightness, time of day, time of year, orbital eccentricity, human emissions of carbon dioxide, human emissions of sulphates, etc., a certain set of weather states is possible.

What are Climate and Climate Change?



An analogy of the different definitions of climate using the example of a car's trajectory on a highway.

Top: the observational definition. The car has followed the route (weather) defined by the arrows to arrive at its current position (state), and will continue according to the arrows. The shaded area denotes the future climate successively defined by the current and two previous positions. Note that the climate can change even though nothing external has influenced it, and that it can be ignorant of the start of an additional lane and the closing of one of the original lanes.

Middle: the time scale definition. With the car at its current position, the next couple of positions of the car are considered weather, while later positions are considered climate.

Bottom: the external forcing definition. Anything in front of the car that is allowed by the road conditions (a new lane and the closing of a lane) is climate. Note that some of the climate, for instance the bit in the lane that is about to close, is actually inaccessible to the car because the car cannot change lanes fast enough.

Climate Models

- There are two main approaches to process based modeling: as simple as possible, and as complicated as possible.

	Simple models	**Complicated models**
Advantages	They are easy to implement and diagnose	they are as comprehensive as is possible given current resources.
Disadvantages	they are subject to many restrictive assumptions and they only model certain portions of the climate system	difficult to implement and diagnose

Climate Models: Simple Models

- The simplest model of time-dependent climate change due to external forcing is the simple linear relaxation model:

$$\frac{c \cdot d\Delta T(t)}{dt} = \Delta F(t) - \lambda \Delta T(t)$$

- This is usually referred to as an Energy Balance Model (EBM).

In which:

✓ ΔT(t): Change in temperature of the planet over time t

✓ ΔF(t): Anomalous energy flux entering the system. ΔF(t) is usually called the 'radiative forcing', or just simply the 'forcing'.

✓ c: The thermal inertia of the climate system (The response is delayed by c). This is dominated by the heat capacity of the mixed layer of the ocean, the surface layer that is in direct contact with the atmosphere but in little contact with the deep ocean.

✓ λ:The amplitude of the response, which in a single number represents how all of the various processes in the climate system respond to the anomalous energy flux.

Climate Models: Simple Models

- Energy Balance Models do reveal interesting aspects of climate change. Let's say that the external forcing $\Delta F(t)$ keeps increasing at a constant rate. This is in fact close to how the radiative forcing from anthropogenic greenhouse gas emissions is behaving.
- There are two possibilities. If both c and λ are small, then the climate system is always near equilibrium, so the behavior is dominated by λ. Otherwise, the heat capacity of the ocean mixed layer slows everything down so much that we are never close to equilibrium and c dictates the behavior. This is the reason that the observed historical warming puts a strong lower limit of about 1.5 ^{o}C on the equilibrium climate sensitivity to a doubling of CO2 concentrations over 1750 values, but cannot seem to impose a strong upper limit: the observed climate change is controlled by c, not λ, if the sensitivity is high (Knutti and Hegerl 2008).

Climate Models: Simple Models

- Simple models also exist for other aspects of the climate system related to water resources.
- For instance, because precipitation is essentially a way for the atmosphere to transfer energy upwards, average precipitation depends mainly on the vertical temperature gradient. This is a competition between how hot the surface gets against how quickly the top of the atmosphere can radiate energy into space and so cool down. Thus changes in average precipitation in a changing climate can be estimated by figuring out how the external forcings are altering the vertical temperature gradient of the atmosphere.
- Interestingly, changes in the incident visible light from the Sun, such as produced by natural explosive volcanic eruptions, have a much stronger effect than those that affect the atmosphere's opacity to the outgoing infrared radiation, relative to their respective effects on temperature.
- Extremely heavy precipitation events, however, are subject to different constraints than average precipitation. How much water can fall in a heavy event is limited by how much water the atmosphere can hold. Thus according to the Clausius–Clapeyron relation, relating the saturation vapor pressure to temperature, in a warmer world a warmer atmosphere will be able to hold more water and produce more intense precipitation events.

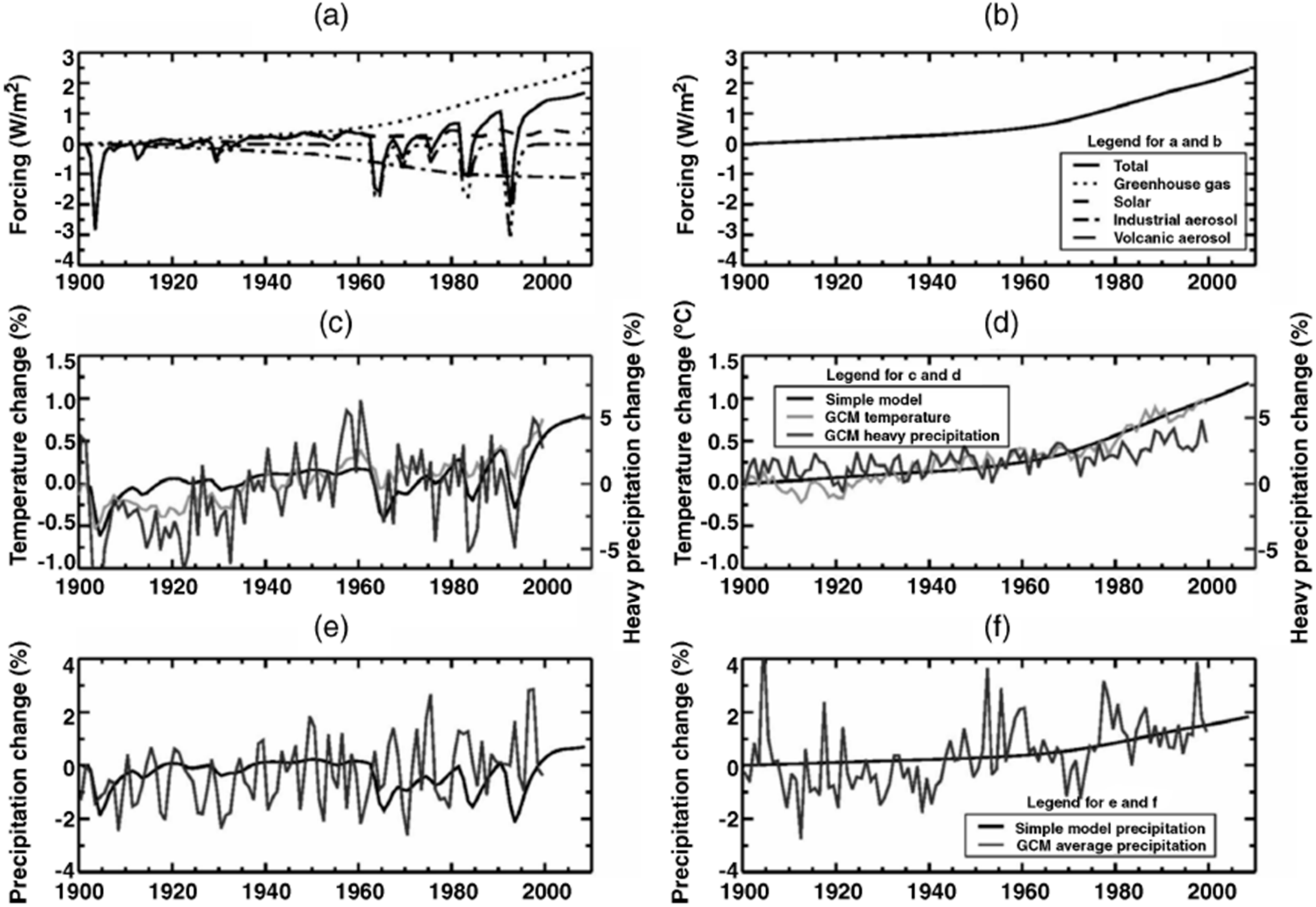
Climate Models: Simple vs. Complicated Models

Simple Model (EBM) | Complicated Model (GCM)

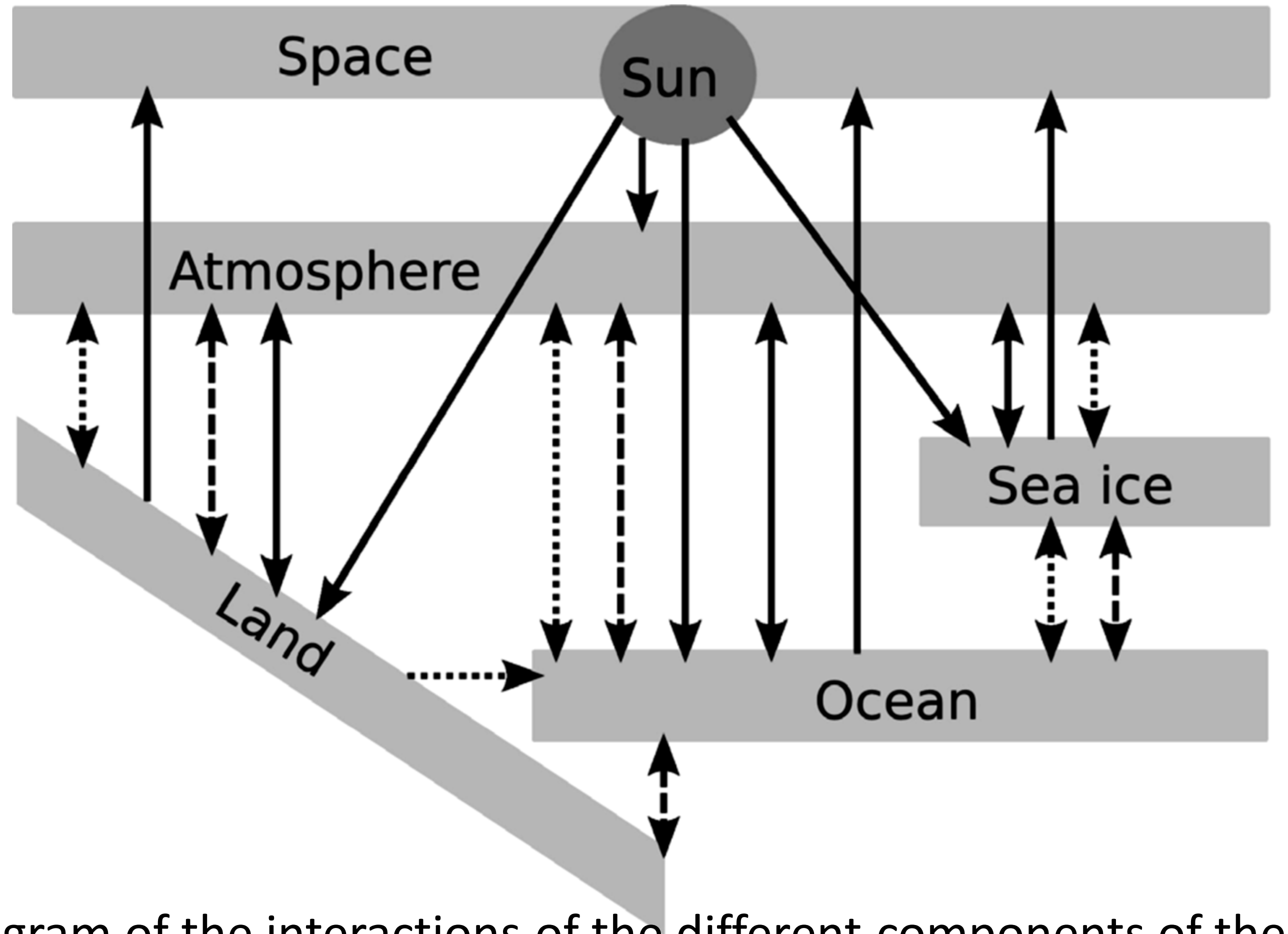
$\Delta F(t)$

$\Delta T(t)$

$\Delta P(t)$



Climate Models: Global Circulation Model (GCM)



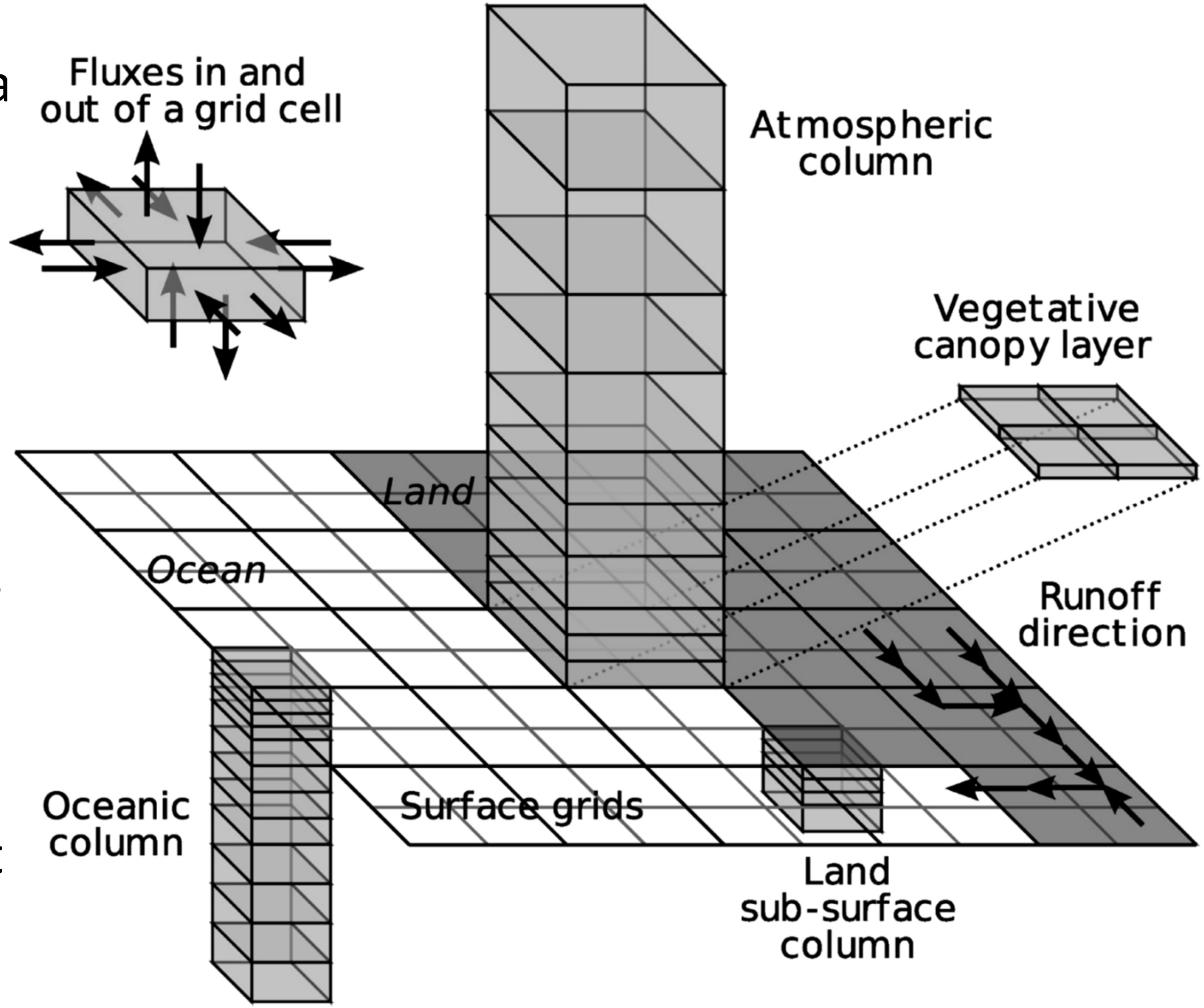
Schematic diagram of the interactions of the different components of the climate system that are simulated in a modern dynamical climate model. Solid arrows indicate the transfer of short-wave (visible and ultraviolet) and long-wave (infrared) radiation. Dotted lines indicate the direct transfer of heat and water, while dashed arrows indicate the transfer of momentum.

Climate Models: Global Circulation Model (GCM)

- GCM originally stood for ‘General Circulation Models’ but increasingly stands for ‘Global Climate Models’.
- The first GCMs were simply retired weather forecasting models, with computing power having reached a point at which it was feasible to run them over much longer simulation periods.
- They were models of the atmosphere, with ocean temperatures.
- By the early 1990s, a handful of modeling groups around the world had added dynamical models of the ocean to their atmospheric models, producing what was frequently referred to as a coupled atmosphere- ocean GCM (AOGCM).
- By the late 1990s, most of these climate models also had dynamic models of sea ice included, meaning that the ice now moved and cracked.
- Over the past ten years, the main addition has been chemistry models coupled to the atmospheric model.

Climate Models: Global Circulation Model (GCM)

Schematic diagram of how a dynamical climate model represents the climate system. The various components of the climate system are discretized into grid boxes. The model then calculates the fluxes of radiation, heat, moisture, momentum and sometimes other quantities between adjacent grid boxes. In the model represented here, the ocean and land surface components are resolved at twice the horizontal resolution of the atmosphere.



Climate Models: Global Circulation Model (GCM)

- The atmosphere model consists of a three-dimensional grid of cells, with each cell exchanging radiation, heat, moisture, momentum and mass with its neighbors.
- The ocean model also consists of a three-dimensional grid of cells, each cell exchanging radiation (the top levels), heat, salt, momentum and mass with its neighbors.
- In today's models, the horizontal size of the atmospheric grid boxes is about 100–300 km, while the ocean grid boxes are usually half that size.
- Movement of quantities between these grid boxes is calculated at regular time intervals on the order of 10 minutes long.
- Note that vertical resolution varies with height, with the highest resolution occurring near the interfaces with other components.

Climate Models: Global Circulation Model (GCM)

- Unfortunately, in the ocean most of the interesting and significant vertical exchange of water occurs in small eddies about 100km across, so the method of parameterization of these eddies is extremely important for the large-scale behavior of the model’s climate.
- In the atmosphere, all cloud and precipitation processes are represented by these parameterizations. Because clouds are very good at both reflecting visible light and at absorbing infrared radiation emitted from the ground, tiny changes in the behavior of clouds in a changing climate can be an extremely influential feedback.
- In fact, most of the differences between estimates of both current and future surface temperatures made by different GCMs come down to differences in their parameterized representation of clouds.

Climate Models: Global Circulation Model (GCM)

- In some ways, the most dramatic improvement in dynamical climate models over the years has been in their representation of sea ice.
- Originally, it was just imposed according to observed coverage, even when dynamical oceans were included.
- Eventually, thermodynamic sea ice modeling was implemented, meaning that the ice could grow or melt but could not move. This was at least physically consistent with the other components of the model, but it still missed some major aspects of sea ice.
- Because evaporation is so much faster than sublimation, the opening of a lead (crack) one meter across for just several minutes can have profound effects on the amount of moisture in the Arctic air, and thus on cloud formation.
- Puddles on the ice surface are hugely influential in speeding up the melting of ice in direct sunlight. These are all processes occurring on much smaller scales than are resolved by the models though.

Climate Models: Global Circulation Model (GCM)

- From a hydrological modeling perspective, the representation of the land surface in climate models is still very primitive. As indicated in Figure 2.4, the ground is generally represented as a grid-cell bucket of several layers, sometimes with some slow underground flow between buckets.
- Overflow is routed along a prescribed route to the ocean (this used to be instantaneous, but now is generally delayed). Different soil and vegetation types are prescribed for each grid cell, with variations in bucket depth, surface albedo, and what happens when snow falls. Most current models use a tiling scheme that allows a grid cell to be divided into multiple surface types, with more complex behavior as a result.

Understanding Climate Model Output

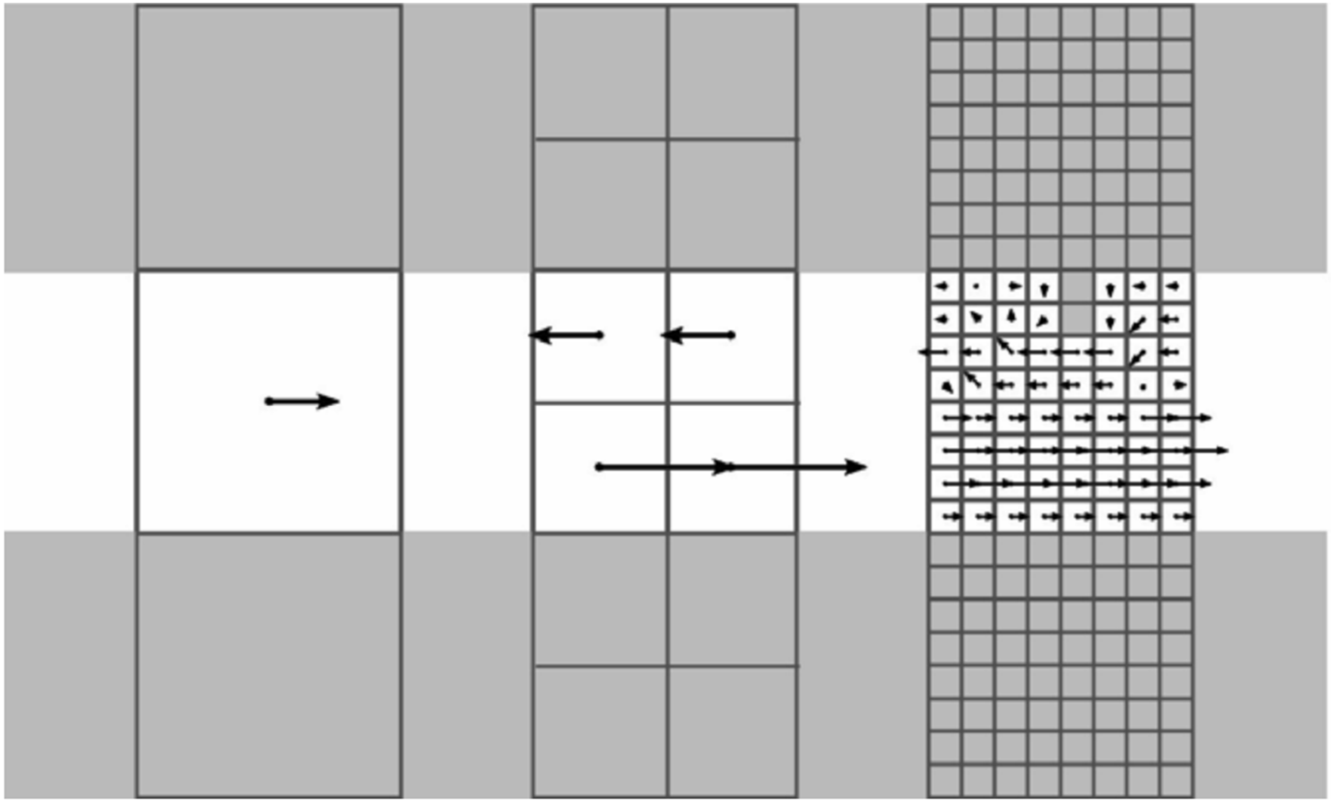
Spatial and temporal resolution

- As we covered earlier, GCMs calculate the transfer of momentum, energy, mass, moisture and composition between grid boxes. This means that nothing smaller than the size of that grid box is resolved by the model.
- Similarly, the model runs in discrete time steps, so nothing happening on a shorter time scale is explicitly resolved.
- More fundamentally, however, a phenomenon is not truly resolved by one grid box and one time step.

Understanding Climate Model Output

Spatial and temporal resolution

An illustration of the importance of resolution in the context of flow through a channel.



Left: the channel is resolved by the grid in that the grid box width equals and aligns with the channel width.

Middle: doubling the resolution reveals that the coarser grid was missing a small reverse flow, which could be important for the moisture (atmosphere) or salt (ocean) that it carries.

Right: increasing the resolution further resolves processes important for the flow through the channel, such as frictional drag along the edges and the existence of a small blockage. This idealized example is mirrored in the climate system, for instance in flow through ocean straits and in flow between atmospheric high- and low-pressure systems

Understanding Climate Model Output
Spatial and temporal resolution

- The main point to take from here is that GCM (and RCM) output should not be taken literally at the grid resolution provided. Note that GCM output products generally provide daily or monthly average data, not data for every 10-minute time step of the model. One of the reasons for this is that the output is not considered to contain enough potentially accurate information at the time step resolution to add anything useful over the daily resolution.
- Technically, the same should apply in the spatial dimension: GCM output should be provided at a lower resolution than it is.

- At some point, we want to be able to say whether a particular climate model is useful for us. How do we go about evaluating it? Unfortunately, there is no clear way of doing this. There are a few different schools of thought, which we will review here.
- Possibly the most basic approach could be thought of as the ‘first principles’ approach.

Understanding Climate Model Output Evaluation, 'first principles' appr.

- In theory, climate models are designed purely from first principles, mathematically solving the various basic physical equations. These equations are considered fundamental, so the philosophy behind the big dynamical climate models is that, in essence, the real world is in fact doing the same thing, i.e. solving those same equations but with an infinite precision and resolution of which we are incapable.
- This holds even for parameterizations in the models, which in some cases are based on rigorous high-resolution physical modeling themselves, but at the least are usually based on physical arguments following the structure of the basic governing laws. Following this reasoning further, then, we could argue that the more complicated a model the better it is.

Understanding Climate Model Output Evaluation, 'first principles' appr.

- So we want to evaluate the output of the climate model. The idea is to take output from the climate model and compare it against something else.
- We could compare it against the output from other models. One could argue that climate models that produce similar results to other models are more likely to be useful than models that are outliers.
- This would hold if models where constructed purely upon first principles and if the development of shortcuts was independent across models and unbiased. Unfortunately, there are reasons for doubting that these conditions are satisfied.

Understanding Climate Model Output Evaluation, ‘the Black Box’ appr.

- another school of thought holds that the climate model should in fact be treated completely as a black box, judged only by the output in which we are interested.