Atmospheric and Oceanic General Circulation Models (AOGCMs)

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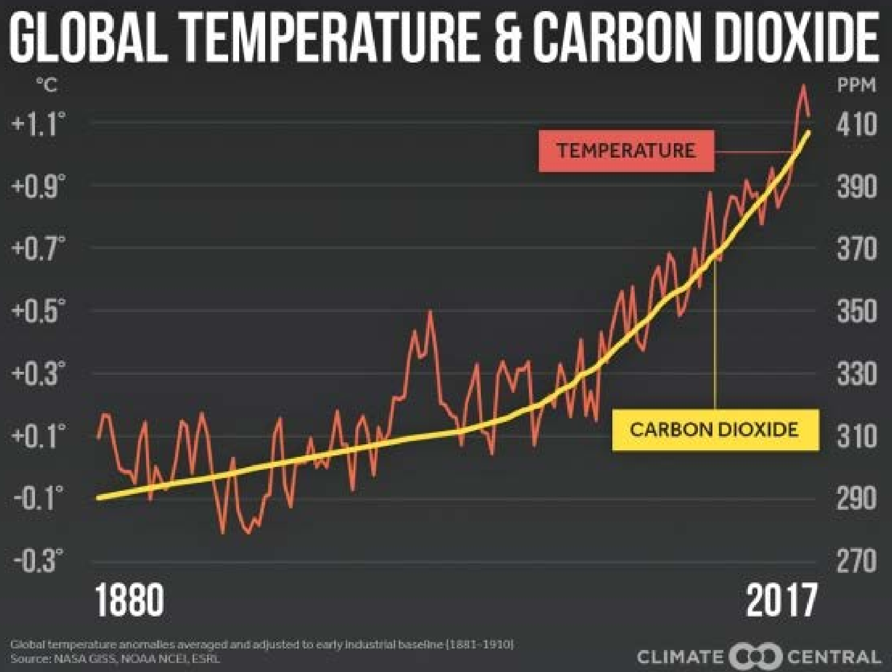
Quick introductions:

1. Name
2. What you study
3. UG/G
4. Why this class?
5. Any particular interest in atmospheric/ocean/climate circulation?

Structure of the lecture:

- Weather versus climate
- How are climate models used?
- Climate modelling under RCP scenarios (reading)
- Breaking down a climate model
    - Governing equations
    - Broad atmospheric/oceanic circulation patterns
    - Piecing components together
    - What does it cost to run a climate model?
- Sources of uncertainty in climate models
- Example: *Possible climate transitions from breakup of stratocumulus decks under greenhouse warming,* Nature, 2019.

Weather v.s. Climate



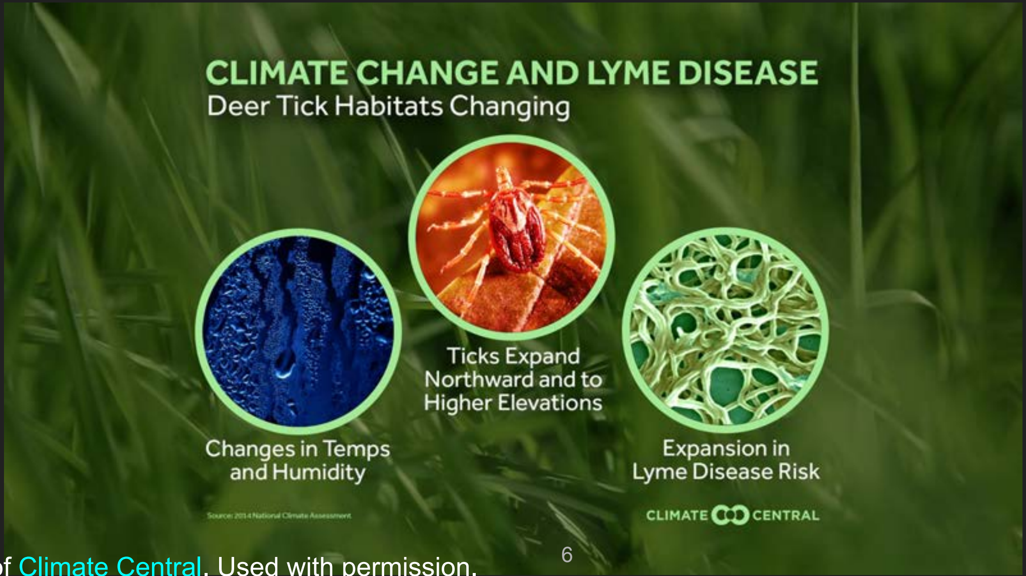
Courtesy of Climate Central. Used with permission.

How are climate models used?

- Decision-making:
    - **How high to build a sea-wall in Miami FL?**
        - Need to know: how high sea level is rising and how storm surge is change over the next 30 to 70 years.
    - **How large to make an irrigation dam in Egypt?**
        - Need to know: how precipitation frequency and intensity is changing and how evaporation is changing
    - **What global emissions target should be set to keep global temperature rise under 2°C**
        - Need to know climate sensitivity.
    - **How does changing climate affect food security in India?**
        - Hierarchy of models: Need to know how temperature and precipitation will change over next few decades, sensitivity of main crops to these parameters, whether growing regions of crops are in areas prone to changing climate and/or extreme weather
    - **How likely is it that a hurricane like Hurricane Harvey will occur again? Which will be the worst affected areas?**

How are climate models used?

- Scientific enquiry:
  - How do volcanic eruptions affect the formation and destruction of stratospheric ozone?
  - How do changing climate conditions affect glacial mass balance and freshwater supply?
  - How do increasing temperatures affect the spread of ticks?



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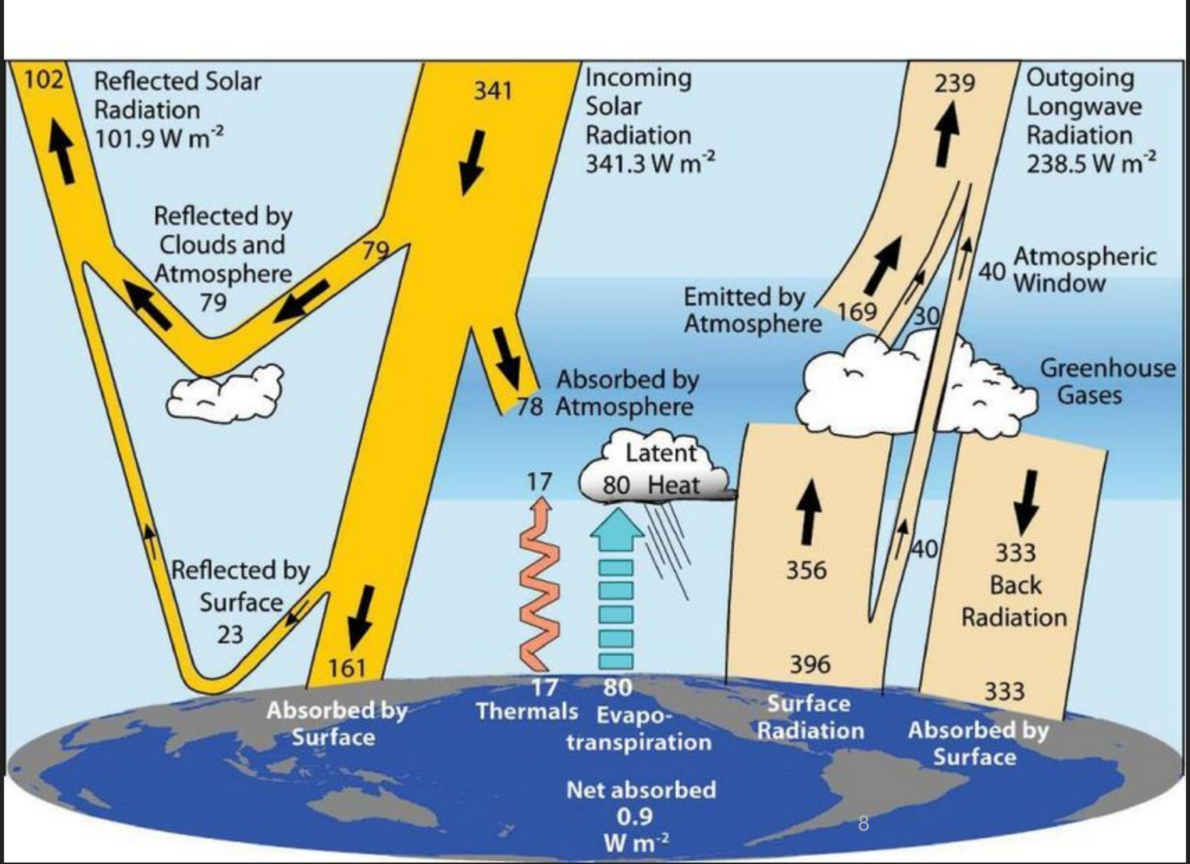
RCPs:
Representative **C**oncentration **P**athways

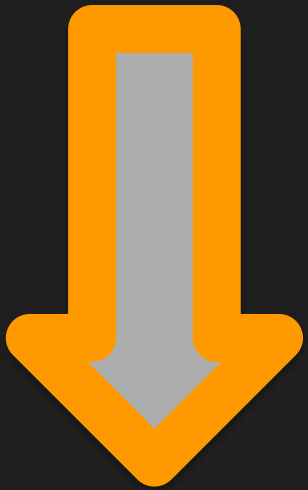
RCPs: Radiative Balance



Radiative forcing is the difference between the amount of energy from the sun entering the earth system vs the amount reflected back.

Trenberth et al., 2009

Representative Concentration Pathways (RCP)



2.6
4.5
6.0
8.5

Emissions
Temperatures
Extreme weather
End of civilisation

Shared Socioeconomic Pathways (SSPs)

Why new scenarios for climate change research?

· Socio-economic scenarios used to derive emissions without (baseline scenarios) and with climate policies (mitigation scenarios)

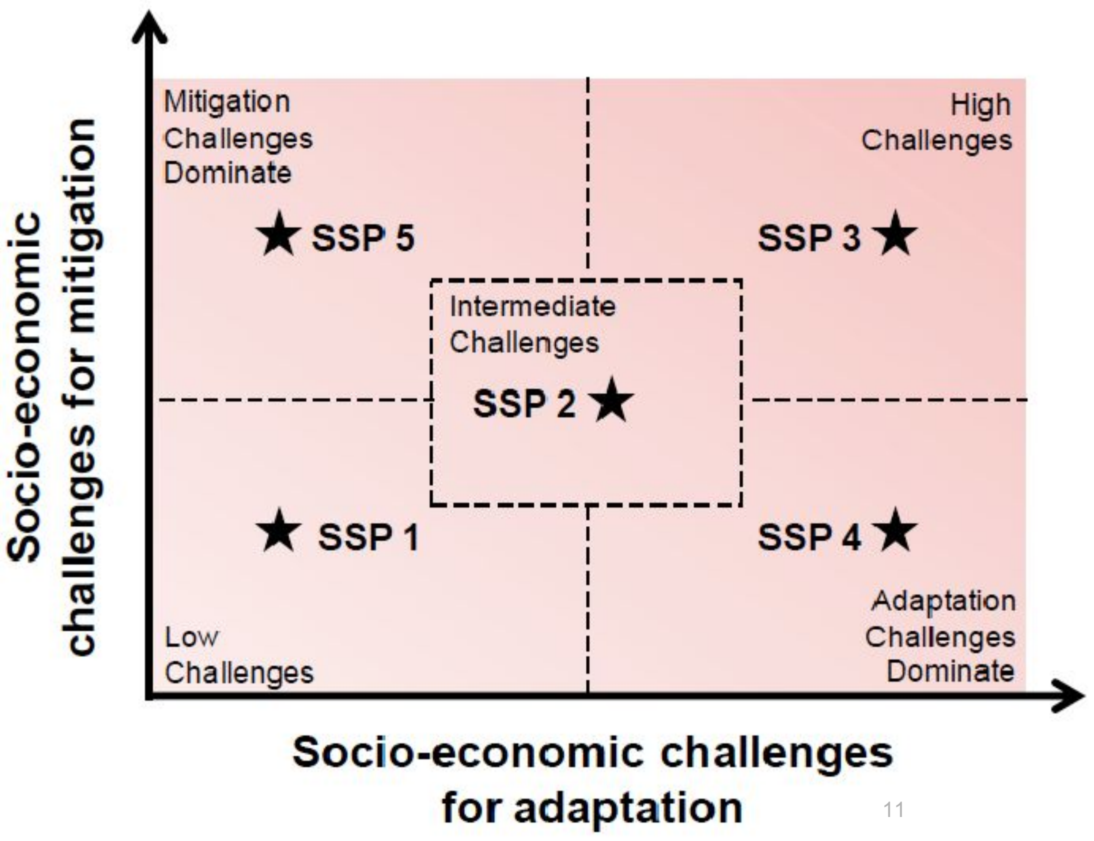
· Emissions scenarios used to derive climate chang eprojectsion

· Climate change projectsions and socio-economic scenarios used to evaluate climate impacts and adaptation measures

Previous set of socio-economic scenarious are 15 years old (SRES, 2000).

New socio-economic scenarios are needed (SSPs)

Shared Socioeconomic Pathways (SSPs)



SSP1: low challenges for mitigation (resource efficiency) and adaptation (rapid development)

SSP3: high challenges for mitigation (regionalized energy / land policies) and adaptation (slow development)

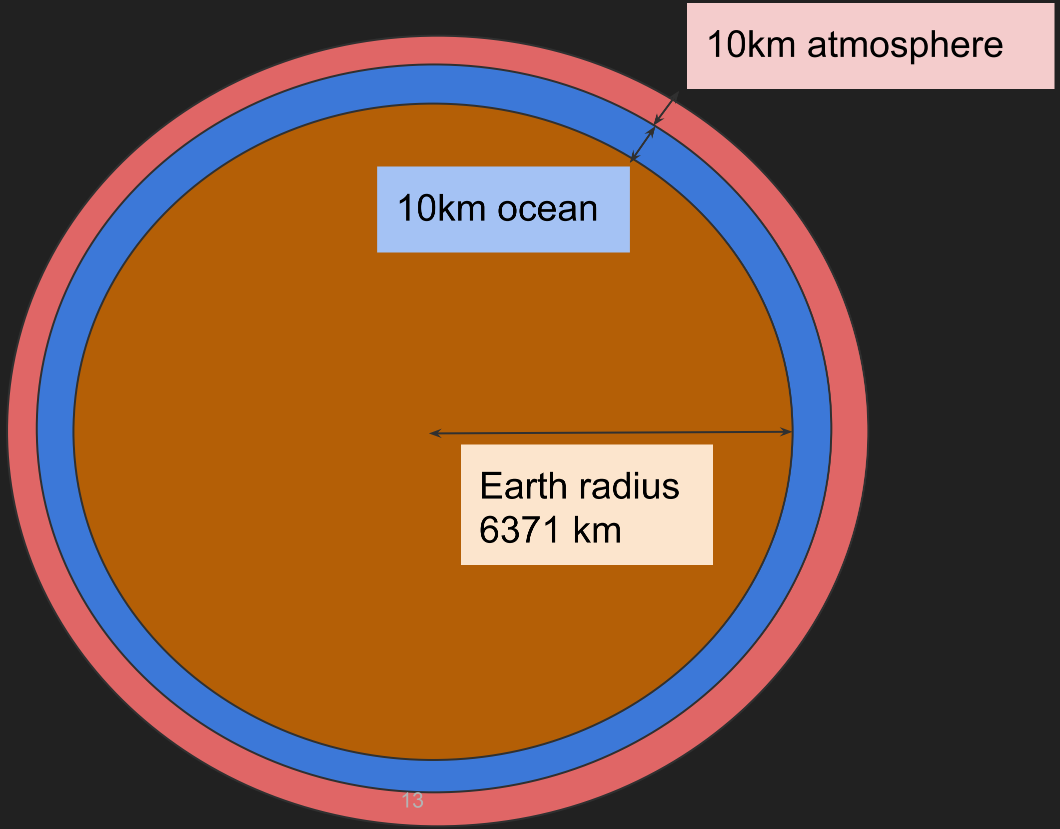
SSP4: low challenges for mitigation (global high tech economy), high for adapt. (regional low tech economies)

SSP5: high challenges for mitigation (resource / fossil fuel intensive) and low for adapt. (rapid development)

From "The Shared Socio‐Economic Pathways (SSPs): An Overview" *UNFCCC*

Breaking down a climate model: Governing equations

Atmosphere and ocean are thin fluids



Equation of motion for rotating fluid: Navier-Stokes

advection

Centrifugal force

diffusion

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla P - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times r) - 2\boldsymbol{\Omega} \times \mathbf{u} + \nu \nabla^2 \mathbf{u}.$$

time-derivative

pressure gradient

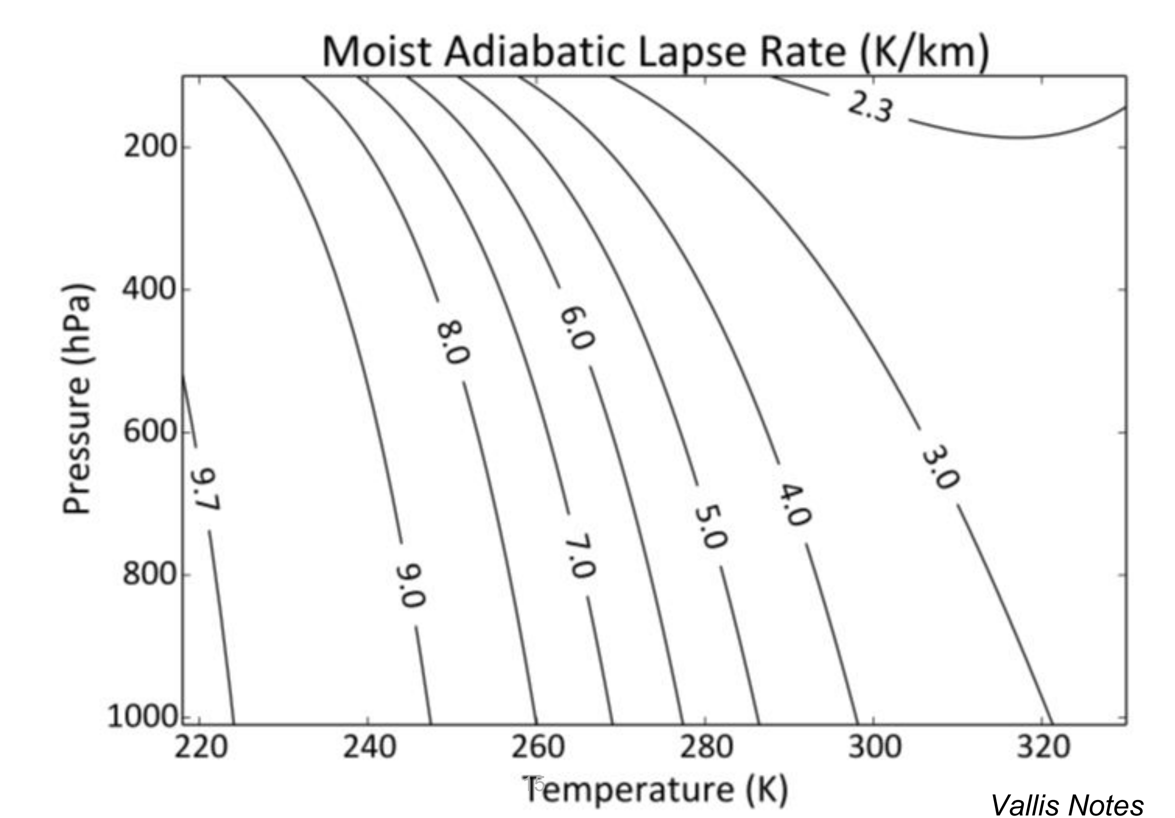
Coriolis force

Mass continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

For the atmosphere, thermodynamic considerations:

<u>3 main thermo variables:</u>
Temperature
Moisture
Entropy



Vallis Notes

One-dimensional radiative-convective model

The equilibrium state of an atmospheric column for which any net loss or gain of radiant energy is balanced by the vertical transport of latent or sensible heat.

INPUT PARAMETERS:

Basic Parameters:

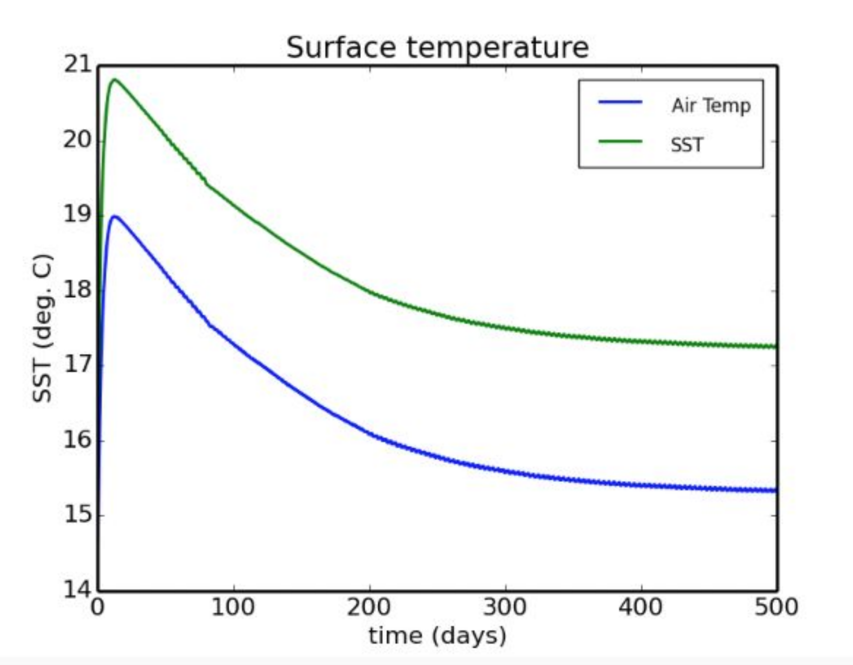
Length of simulation:	500	days
CO_2 concentration:	360	ppm
Solar Constant:	1360	W/m^2
Surface albedo:	0.2	
Initial SST:	15	deg C

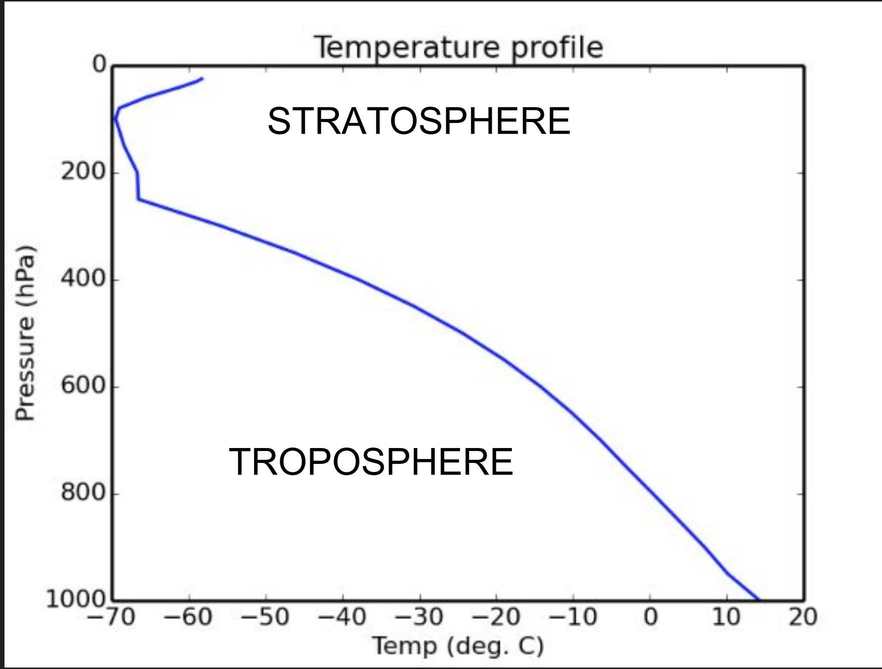
OUTPUT:

Avg. over last 25 days		
SST	17.3	deg C
F_{TOA}	0.4	W/m^2
LW_{TOA}	275.2	W/m^2
SW_{TOA}	-274.8	W/m^2
LW_{sfc}	107.7	W/m^2
SW_{sfc}	-217.2	W/m^2
LH_{sfc}	96.2	W/m^2
SH_{sfc}	15.0	W/m^2

Positive fluxes are directed upward.
Mouseover the variable names for their description.

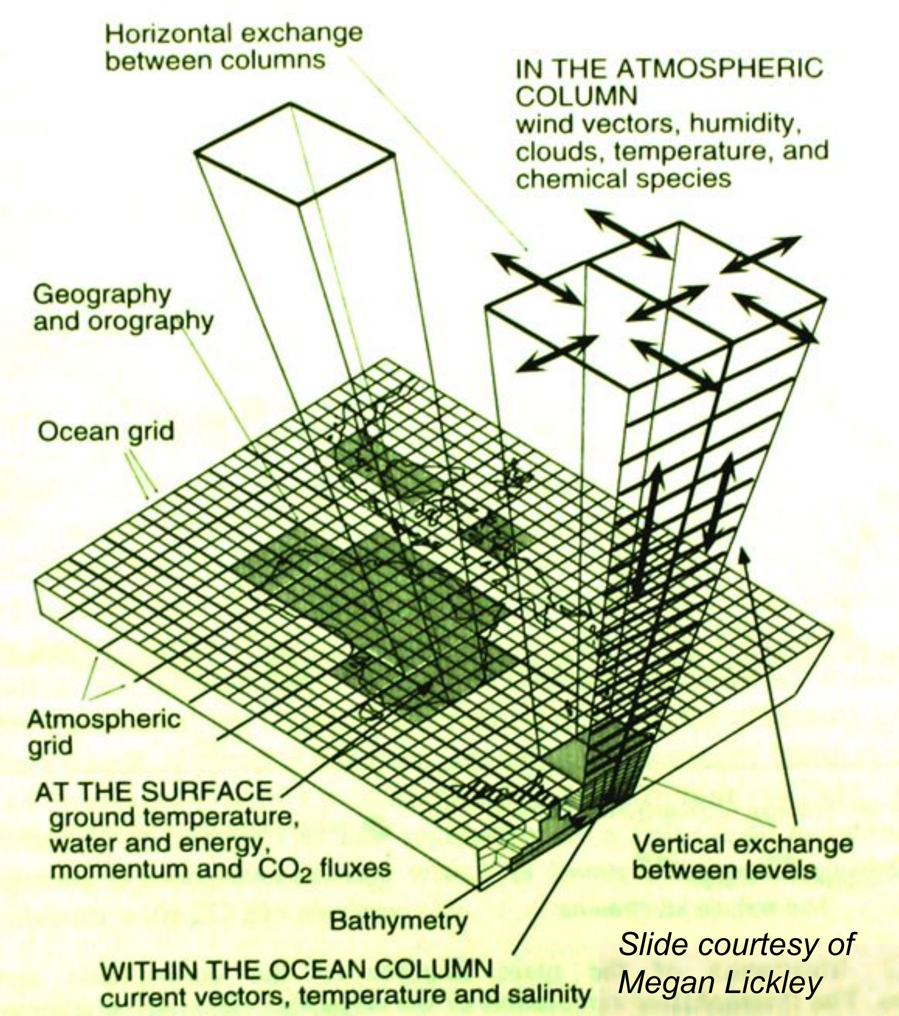
One-dimensional radiative-convective model





In each of the boxes we <u>solve</u> the following equations, applying **boundary conditions** and where appropriate making **approximations**:

- Momentum eqn
- Mass continuity eqn
- Thermodynamic eqn
- Chemical continuity eqns



Slide courtesy of Megan Lickley

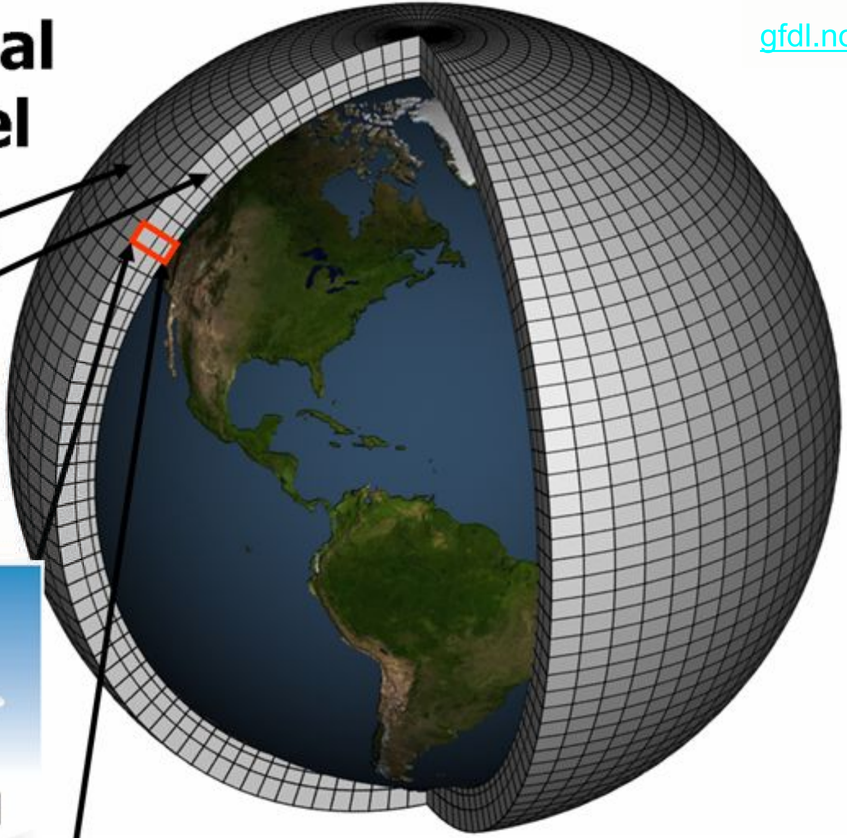
What goes into a general circulation model (GCM)?

- Atmosphere general circulation model
- Ocean general circulation model
- Sea ice model
- Land model
- Chemistry

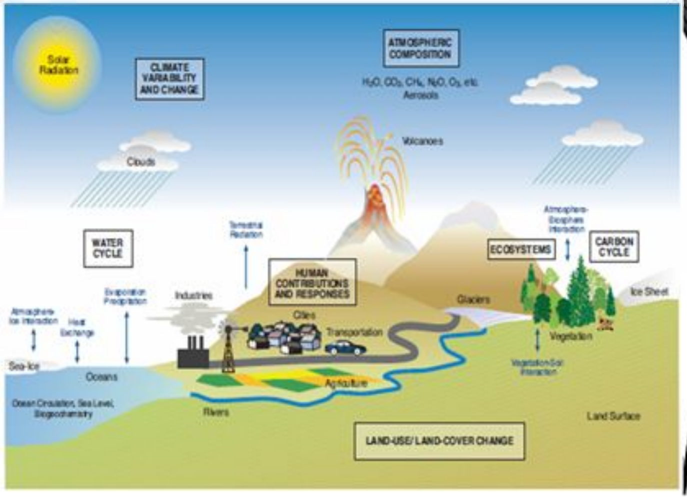
Adapted from Prof. Kerry Emanuel

gfdl.noaa.gov

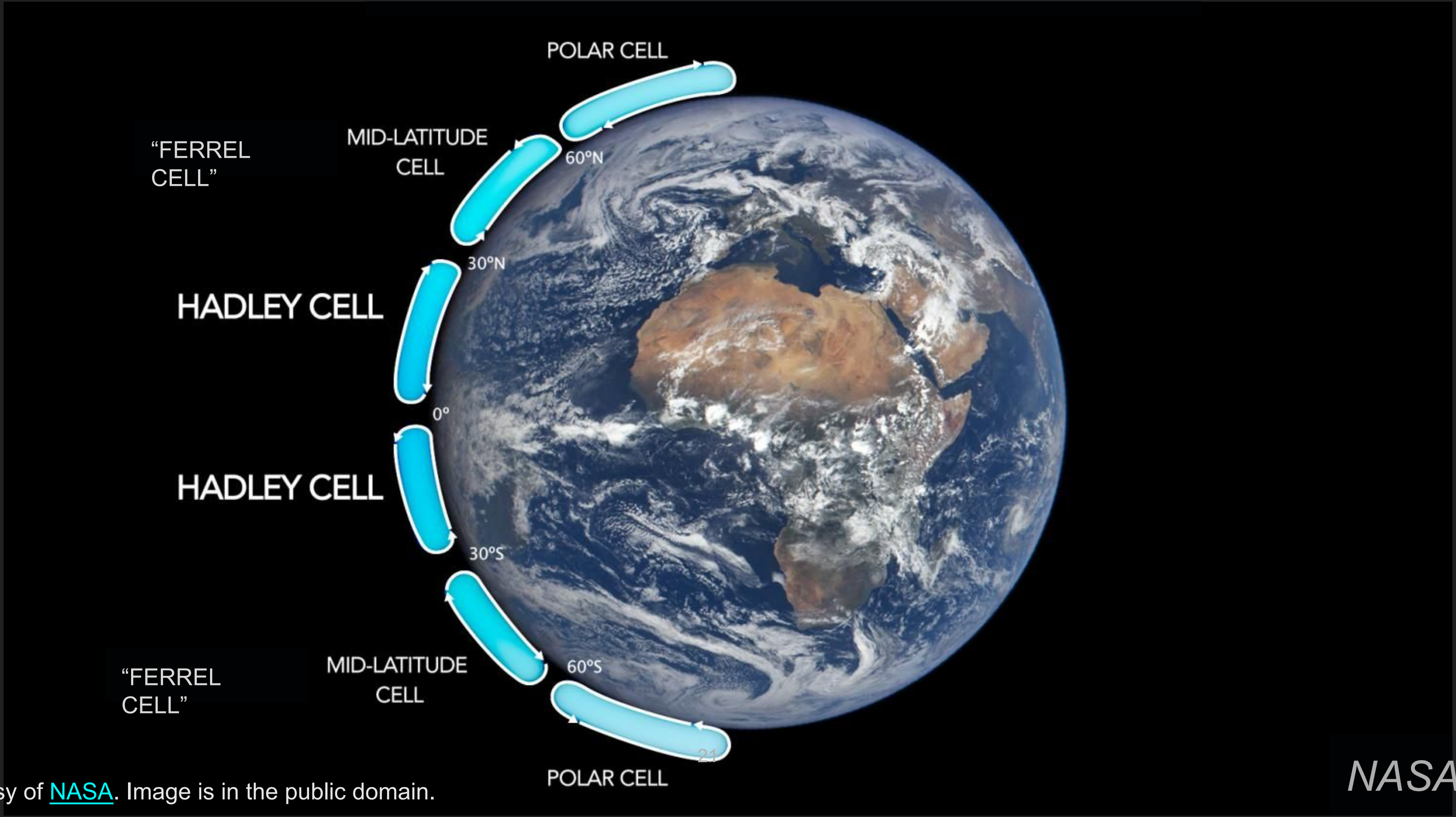
Schematic for Global Atmospheric Model



- 3D model
- Highly complex and computationally expensive
- Each model differs in resolution



Atmospheric Circulation



What exactly does a climate model compute?

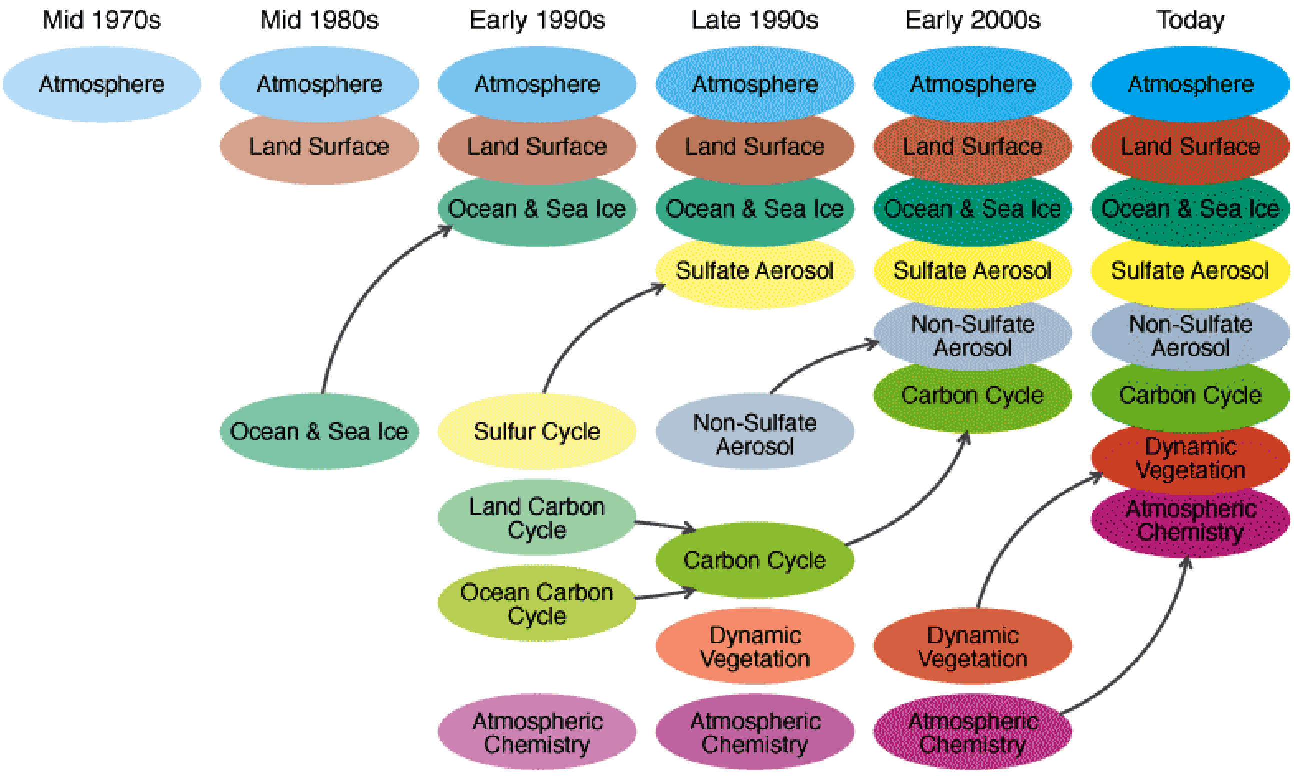
- At each grid point:
    - 10-15 variables
    - 20 levels
    - Grid points spaced ~ 120 km apart
- → 1,000,000 - 5,000,000 variables over the globe
- Typical time step: 20 minutes
- → 70,000,000 - 350,000,000 variables simulated per day

Estimates by Prof Kerry Emanuel, Fall 2017

What exactly does a climate model compute?

Earth simulator at JAMSTEC Yokohama Institute for Earth Sciences

Development of Climate Models



Sources of Uncertainty in Climate Models

Sources of Uncertainty in Climate Models

- Cloud microphysics
- Thin/broken clouds
- Convection
- Boundary layer (e.g. atmosphere/ocean)
- Aerosols and chemistry
- Turbulence
- Sea ice
- Land ice

Propagating uncertainty in climate models

- Too coarse of a time step
- Too coarse of spatial resolution
- Incomplete/inaccurate representation of feedbacks
- Natural variability
- Known unknowns
- Unknown unknowns

Slide courtesy of Megan Lickley

See video of LES simulation at https://doi.org/10.1038/s41561-019-0310-1

Any questions?

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