"… and [they] struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it"

– *On Exactitude in Science*, Jorge Luis Borges

LECTURE 4:
Models of the earth’s climate

ML-4430: Machine learning approaches in climate science

12 May 2021

What is a climate model?

1

- Basic principles
- Different types
- Parametrization

Energy balance models

2

- Zero dimensional
- One dimensional
- Box models

Models of intermediate complexity

3

- Radiative convective models
- Statistical dynamical models
- ~~CLIMBER 2~~

General circulation models

4

- Methodological components
- Simulation components
- Challenges

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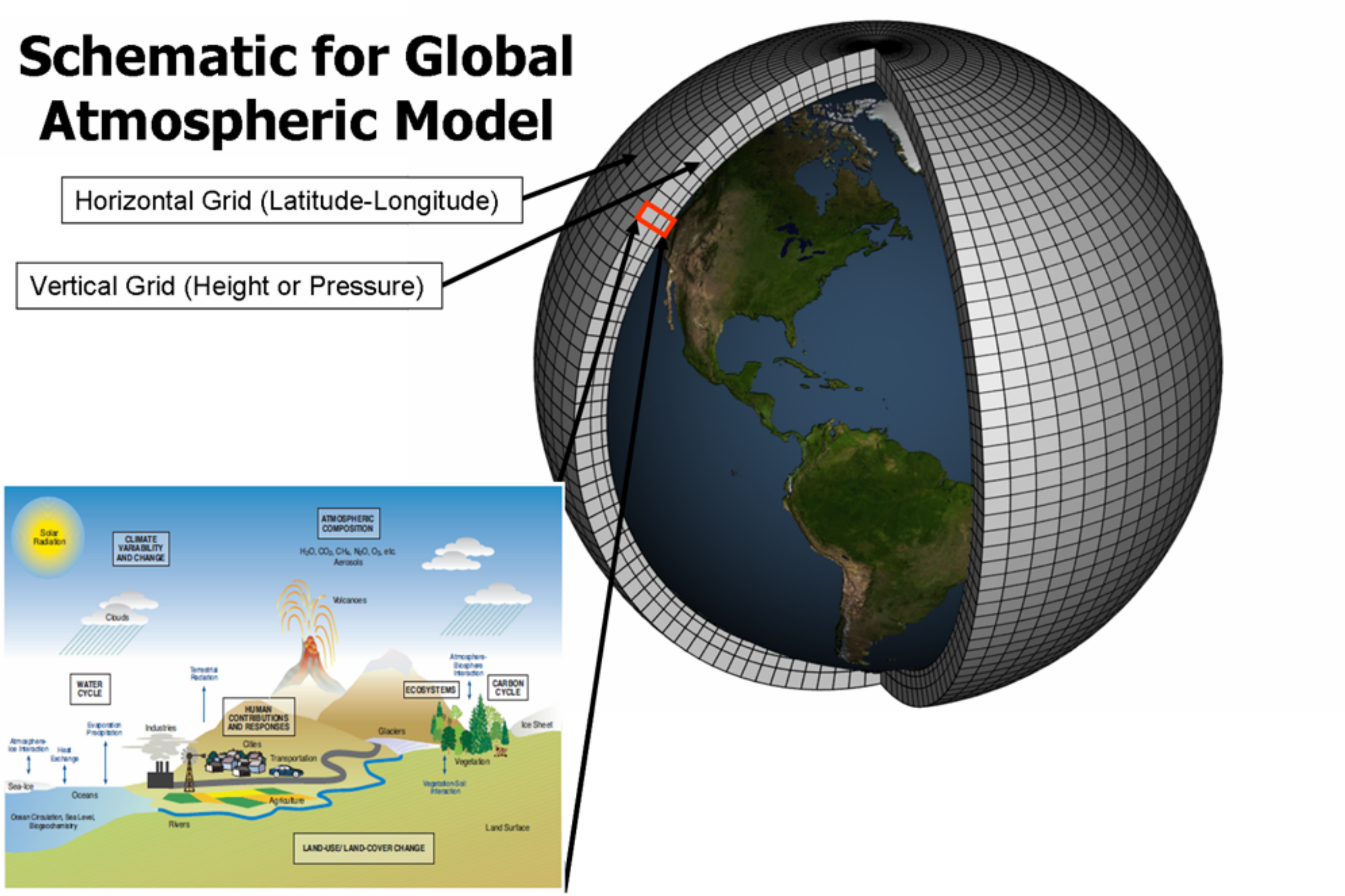
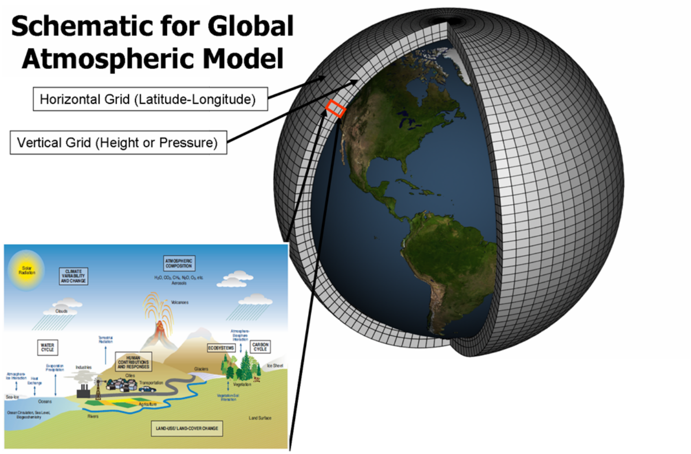


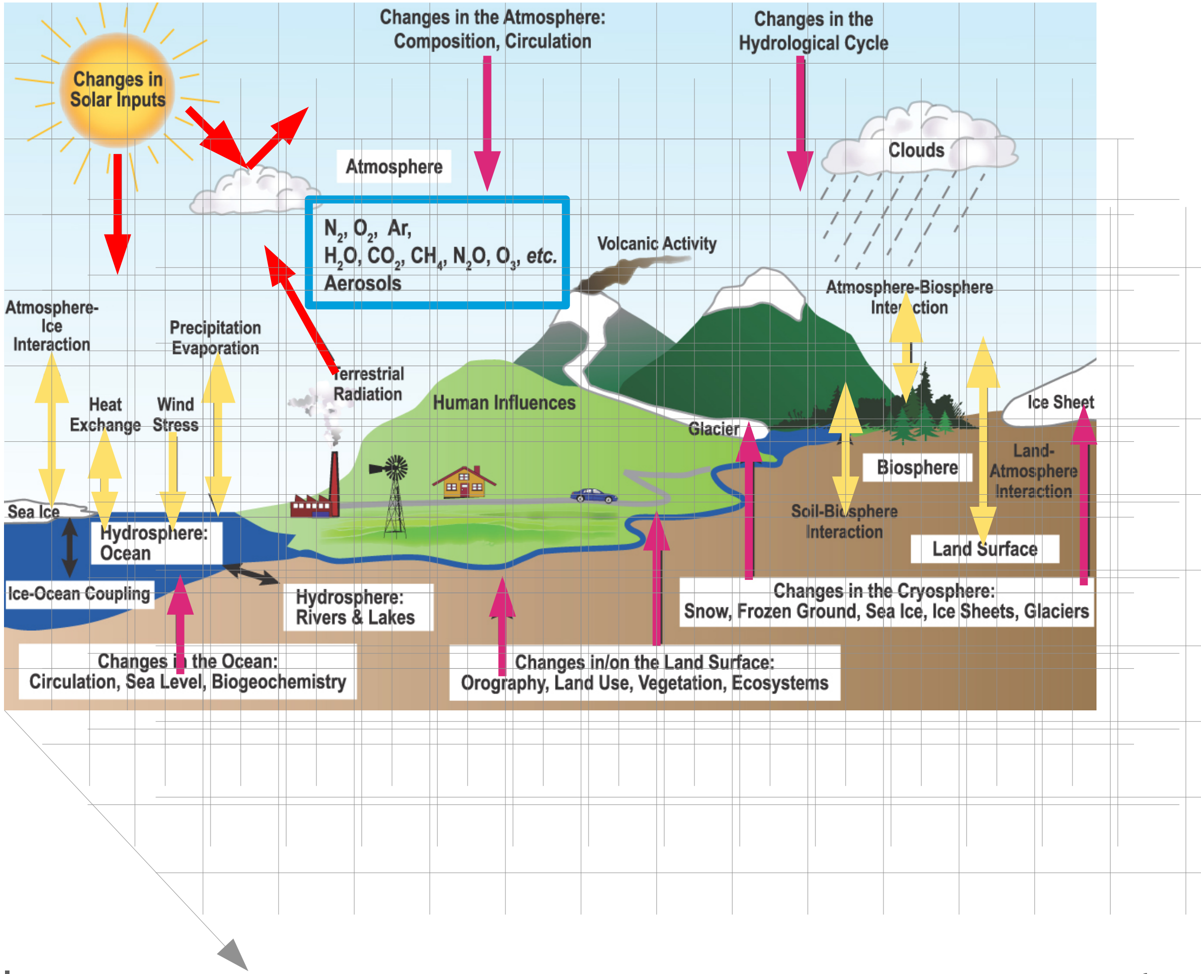
Climate models …

- Numerically simulate the evolution of weather / climatological states
- The evolution is based on fundamental principles of physics and chemistry
- Involves a conceptualisation of a part or all of the earth's atmosphere, ocean, land, and ice
- Adding vegetation and human activities to traditional climate models lead to an "earth system model"



Climate models involve …

- Radiation
- Dynamics
- Surface processes
- Chemistry
- Resolution in space
- Resolution in time



Climate models types include …

- Energy balance models
  - Predict earth's temperature as function of planetary energy balance

- Intermediate complexity models
  - A wide variety of 1-D and 2-D models which use simplified dynamics
  - Spectrum of models between simple conceptual models and full blown 3D models

- General circulation models
  - 3d models of "fully coupled" or "coupled" ocean and atmosphere models

Parametrization

- The neglect or simplification of parts of the climate system in favour of computational simplicity
- Necessary because the climate system in principle has infinite degrees of freedom
- Can be of different types:
  - Ignoring certain features (e.g. clouds)
  - Prescribing climatological averages
  - Observation based: sea ice extent, soil moisture, …
- They must be mutually consistent
  - E.g. Reflected longwave radiation and absorbed solar radiation in clouds

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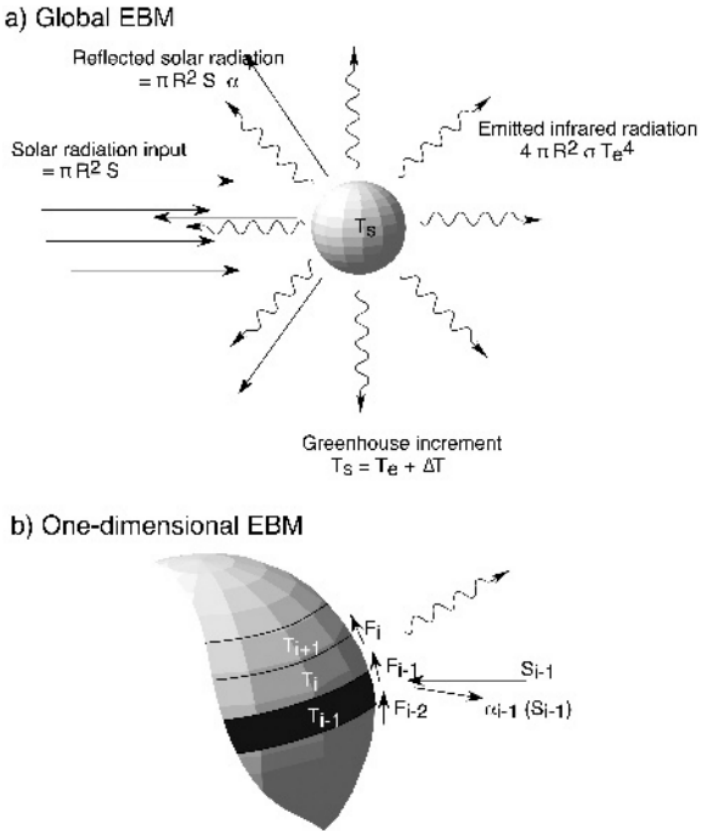
Energy balance models ...

- Estimate the earth's temperature using principles of balance of incoming and outgoing energy
- Blackbody radiation and Stefan-Boltzmann Law is fundamental to this approach
- Can be simple (0D or 1D) or increasingly complex (box models / coupled box models)
- Provides important first insights into planetary dynamics



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- We need:
  - S := solar constant, i.e. amount of incoming energy from the Sun per unit area, 1360 W m^{-2}
  - R := radius of the earth, 6371 x 10^{3} m
  - σ := Stefan-Boltzmann constant, 5.67 × 10^{-8} W m^{-2} K^{-4}
  - α := planetary albedo, 0.3
- The equality:
  - Incoming energy minus reflected energy equals the energy re-radiated back as a blackbody

Total incoming energy per unit area → $\frac{\pi R^2 S}{4\pi R^2} = \frac{S}{4}$

Reflected energy per unit area → $\alpha \frac{S}{4}$

Re-radiated energy per unit area → σT_e^4

$$\frac{1}{4}(1-\alpha)S = \sigma T_e^4$$

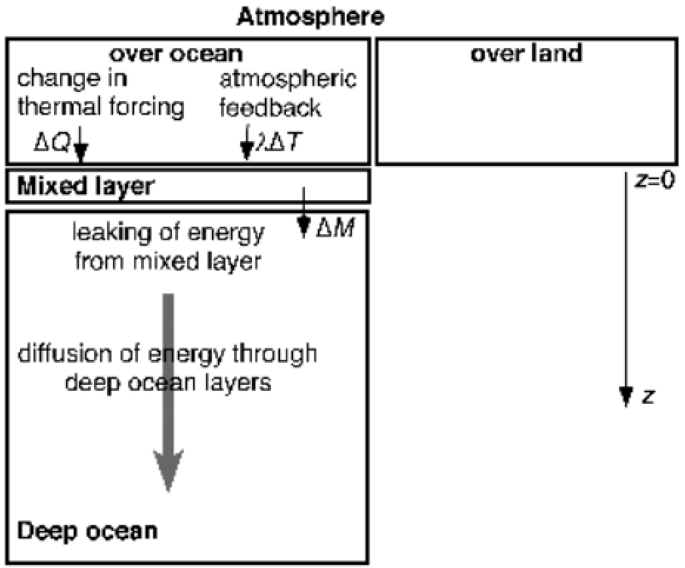
$$T_e = 254.54\,K = -18.61^o\,C$$

$$C\frac{dT}{dt}=\frac{1}{4}\left(1-\alpha\right)S-\tau_a\sigma T_e^4$$

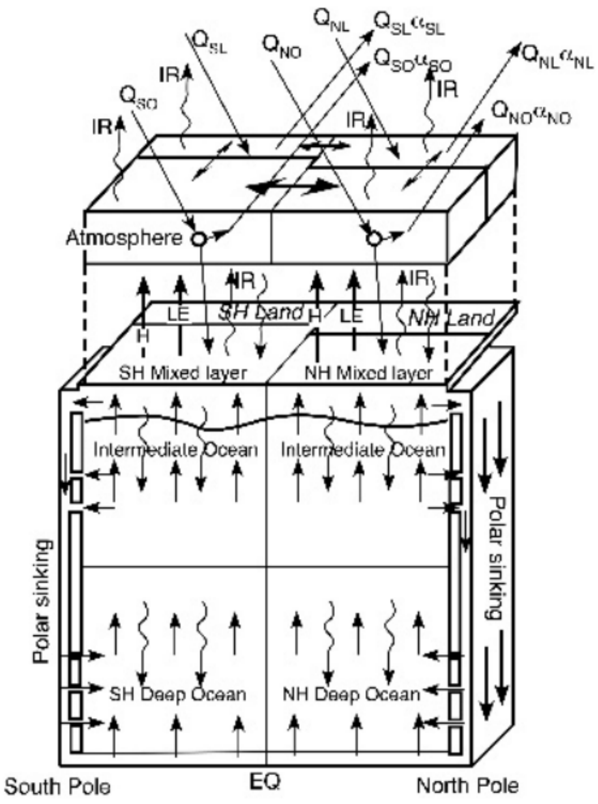
C := heat capacity of the Earth (primarily from oceans)
τ := infrared transmissivity of the atmosphere

- Sellers-Budyko model (1969)
- Energy balance per latitude
- Albedo is a step function of temperature (which in turn is a function of latitude)
- Transport term → loss of heat from warmer zones to bordering colder zones
- Emitted longwave radiation is a linear function of zonal temperature

$$S(\phi)\left(1-\alpha(\phi)\right)=k_i\left(T(\phi)-\overline{T}\right)+\left(A+B\,T(\phi)\right)$$



Wigley and Schlesinger (1985), Nature 315, 649–652



Harvey and Schneider (1985), J. Geophys. Res., 90, 2207–2222

2. Energy balance models → Box models

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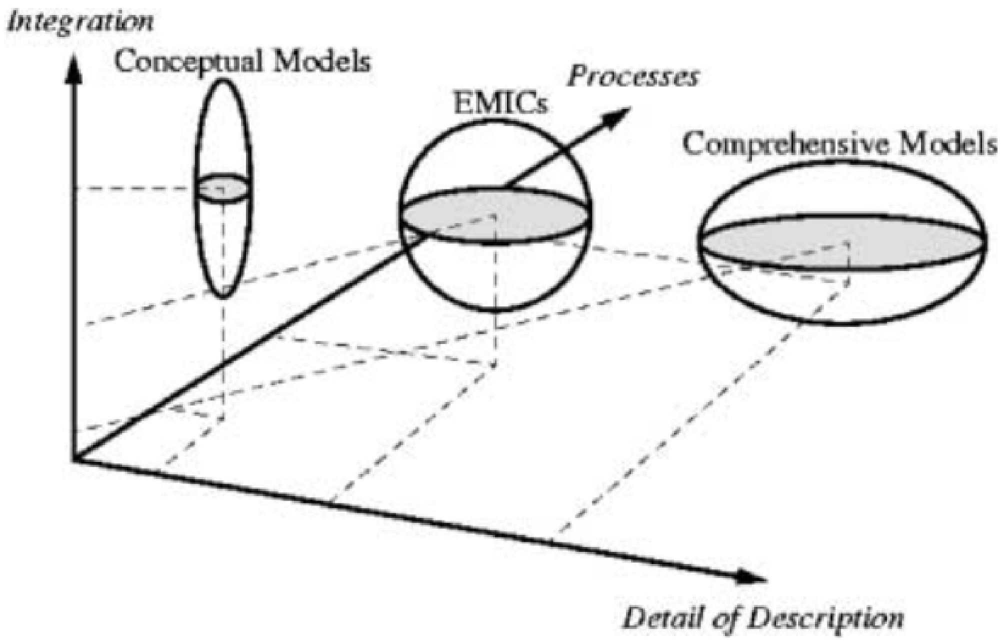
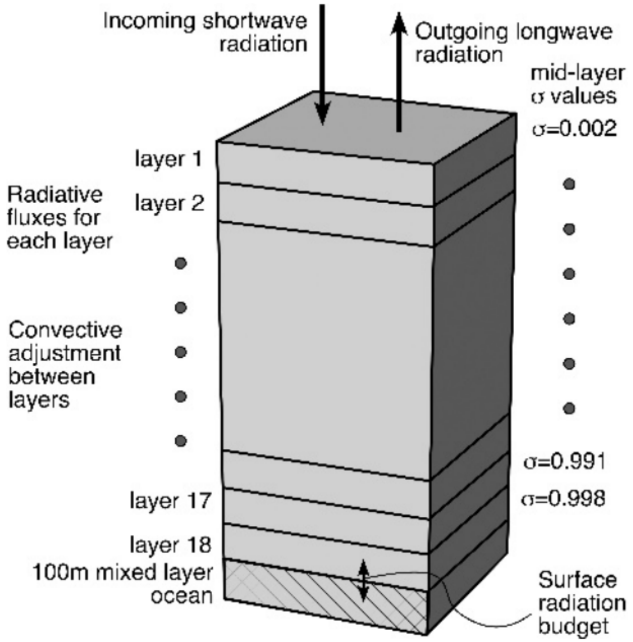


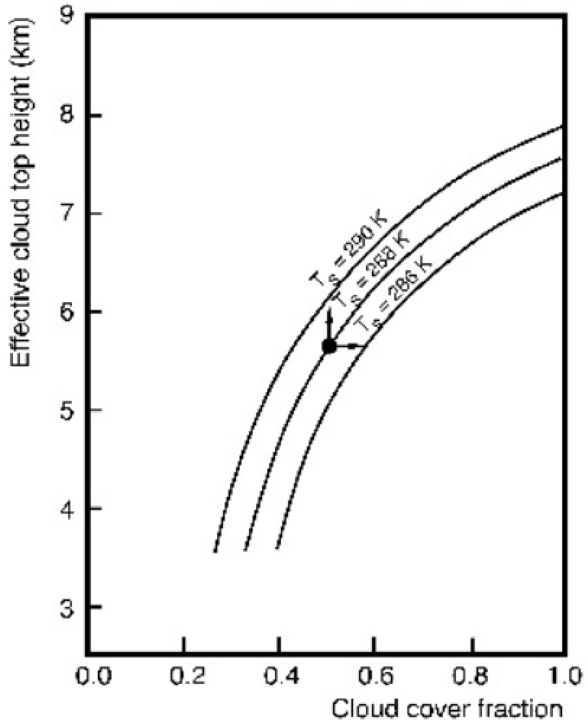
3. Models of intermediate complexity

- Similar to EBMs, but has vertical stratification of atmosphere
  - Single column, layered stratified atmosphere
  - Each layer is approximated as a blackbody

- Convective adjustment
  - Rise of warm air → convection
  - Mixes the air across layers → influences temperature
  - Not modeled -> needs to be "adjusted"

- Radiative-convective equilibrium
  - Net loss/gain of radiative energy is balanced by vertical transport





Schneider (1972), J. Atmos. Sci., 29, 1413–1422

- 2-D models
  - Latitude (i.e., zones)
  - Height
- Variables of interest
  - Zonal averages of wind velocities, temperature, and pressure
- Conserves momentum and energy
- Maintains continuity
- First step to model meridional transport (Hadley cell, Polar cell, …)

- u, v, w := velocities in eastward (x), northward (y), and vertical (z) directions
- < . > := zonally average quantities
- T := temperature
- p := pressure
- Q := zonal diabatic heating, i.e. heating involving absorption of energy
- R := ideal gas constant
- C_p := specific heat at constant pressure
- Φ := friction term
- f := Corioli's pretty parameter
- u' = u - <u>; <ρ> = <p> / (R <T>)

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Zonal momentum

$$\frac{\delta \langle u \rangle}{\delta t} - f \langle v \rangle + \frac{\delta \langle u' v' \rangle}{dy} = \Phi$$

Meridional momentum (geostrophic balance)

$$f \langle u \rangle + R \langle T \rangle + \frac{\delta}{\delta y} \left(\ln \left(\langle p \rangle \right) \right) = 0$$

Hydrostatic balance

$$\frac{\delta}{\delta z} \left(\ln \langle p \rangle \right) = \frac{-g}{R \langle T \rangle}$$

Thermodynamic balance

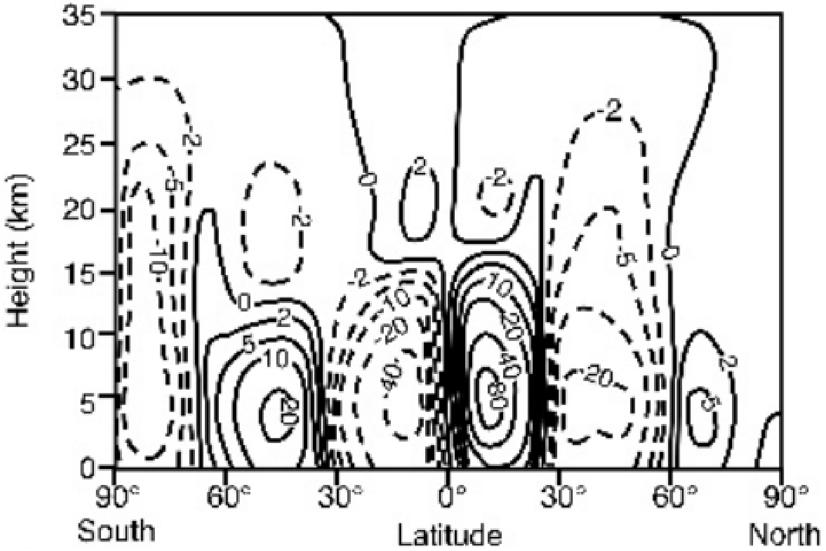
$$\frac{\delta \langle T \rangle}{\delta t} + \frac{\delta \langle v' T' \rangle}{\delta y} + \frac{\delta \langle w' T' \rangle}{\delta z} + \langle w \rangle \left(\frac{g}{\langle \rho \rangle c_p} + \frac{\delta \langle T \rangle}{\delta z} \right) = \frac{Q}{\langle \rho \rangle c_p}$$

Continuity

$$\frac{\delta}{\delta y} \left(\langle \rho \rangle \langle v \rangle \right) + \frac{\delta}{\delta y} \left(\langle \rho \rangle \langle w \rangle \right) = 0$$

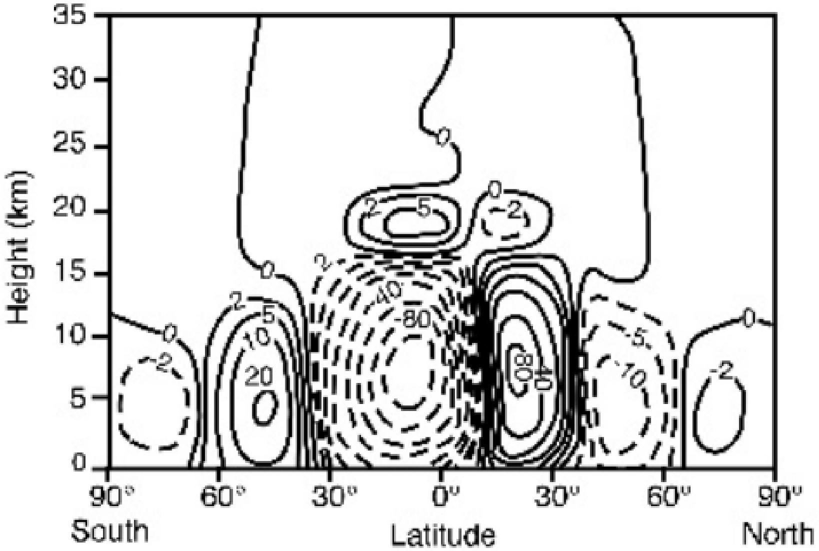
Mass flux stream function

Observed



Oort and Peixóto, 1983

Modelled



Lawrence Livermore 2-D SD model, MacCracken and Ghan, 1987

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- Simulation components
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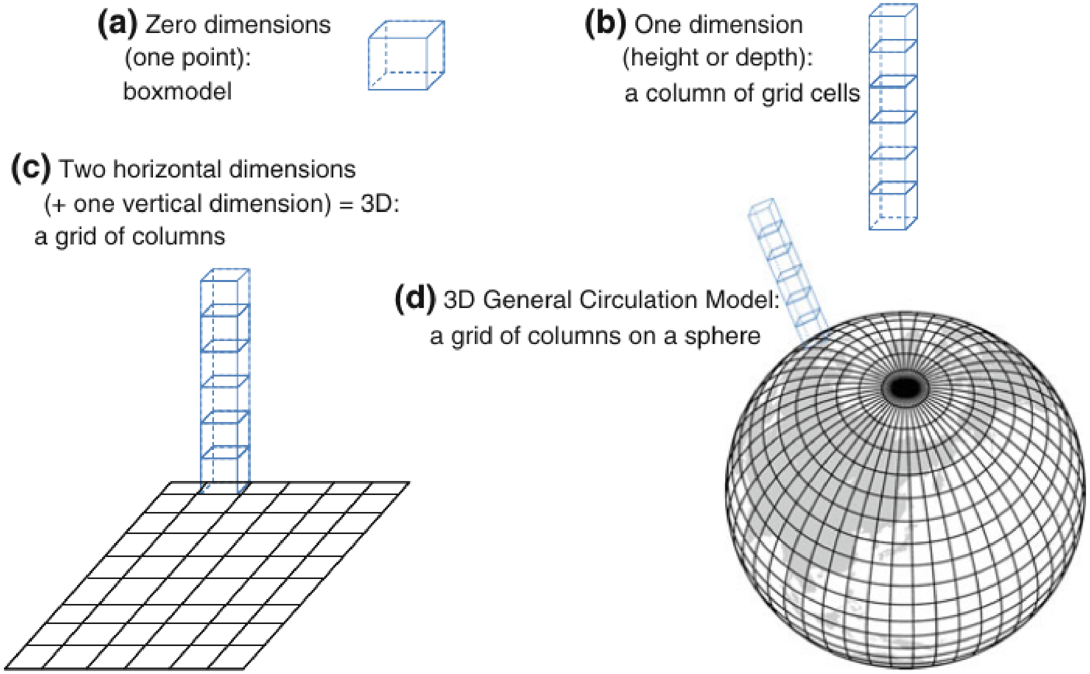


Fig. 4.1 Dimensions of models and grids. **a** Point or box model (no dimensions). **b** Single column (one dimension in the *vertical*). **c** Three dimensional (3D) model with *two horizontal* dimensions and *one vertical* dimension. **d** 3D grid on a sphere

4. General circulation models → Methodological components: Finite elements

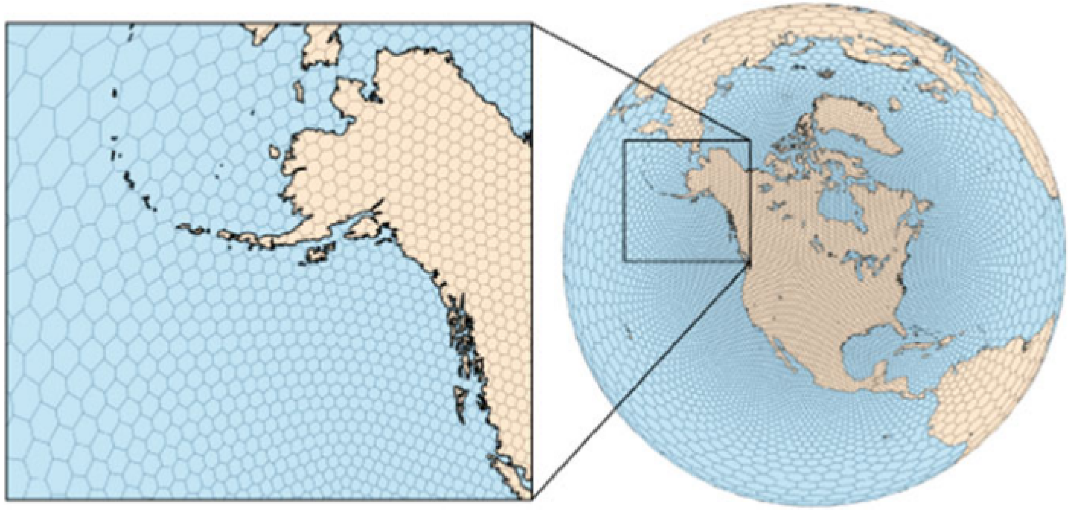
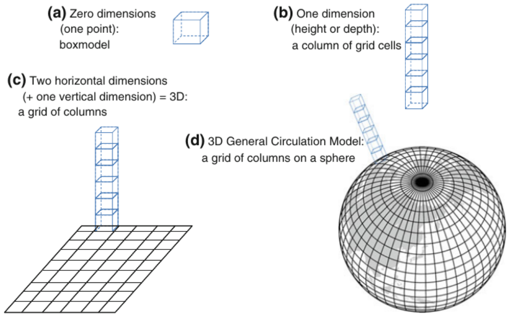


Fig. 4.2 An example of a variable resolution grid from the model for prediction across scales (*MPAS*). The grid gets finer over the continental United States using a grid made up of hexagons. *Source* http://earthsystemcog.org/projects/dcmip-2012/mpas



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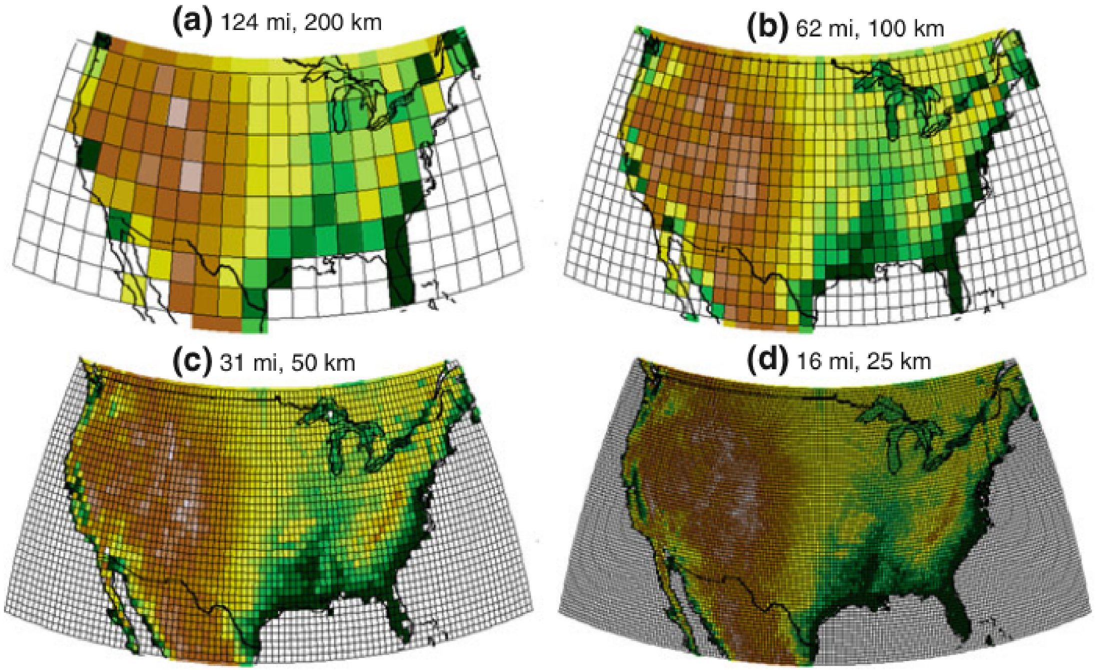
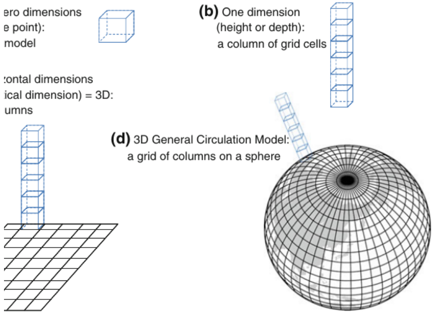


Fig. 4.3 Example of a model with different horizontal resolutions on a latitude and longitude grid over the continental United States. Resolutions are **a** 2° latitude, **b** 1° latitude, **c** 0.5° latitude, and **d** 0.25° latitude. Elevation shown as a color



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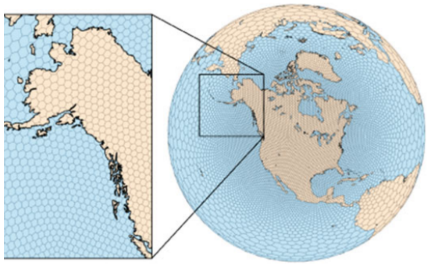

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emcog.org/projects/dcmip-2012/mpas

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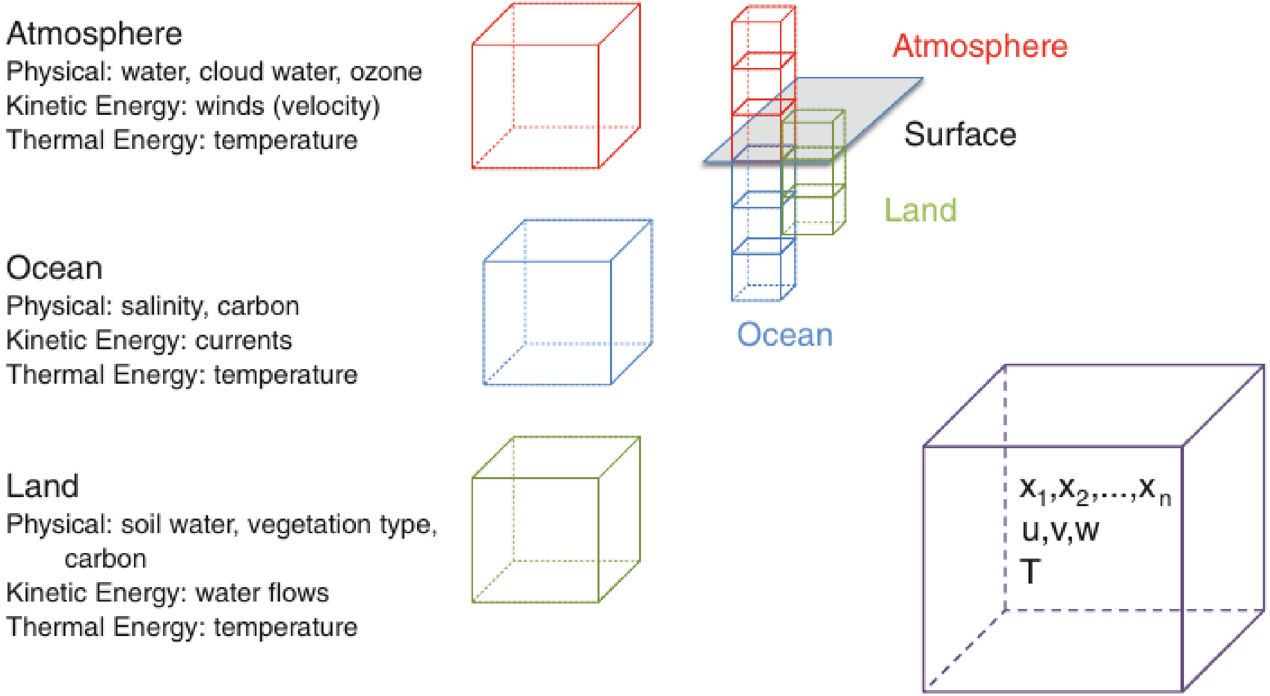
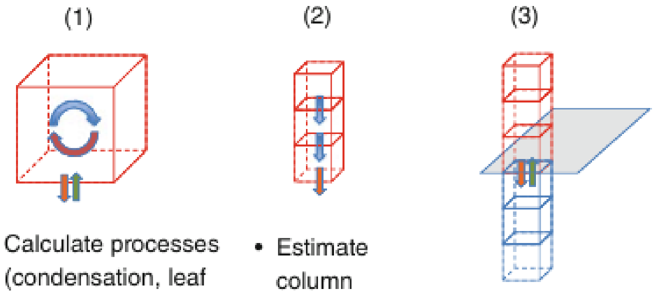


Fig. 4.4 State of the system. Different grid columns for the atmosphere (*red*), ocean (*blue*) and land (*green*) with description of contents. Also a grid box (*purple*) with a 'state' vector of temperature (T), wind in 3 dimensions (U, V for *horizontal* wind and W for *vertical* wind) and the mass fraction of compounds like water (X_n)



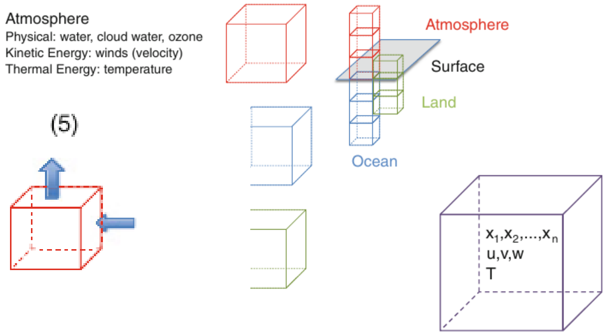
(1)
- Calculate processes (condensation, leaf growth, chemical reactions)
- Heat input
- Source/loss terms

(2)
- Estimate column interactions (precipitation, runoff)
- Couple processes

(3)
- Couple with other columns/ components (fluxes)
- Add to forcing

(4)
- Calculate physical laws
- Thermal energy (radiation)
- Include source/loss

(5)
- Calculate motion (dynamics)



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J, V for *horizontal* wind and W for *vertical* wind) and the
(X_n)

Fig. 4.5 Changing the state: one time step. Climate model calculations in a time step that change the state of a model. *1* calculate processes, *2* estimate column interactions like precipitation, *3* couple with other columns and components, *4* calculate physical laws like radiation, *5* estimate motions

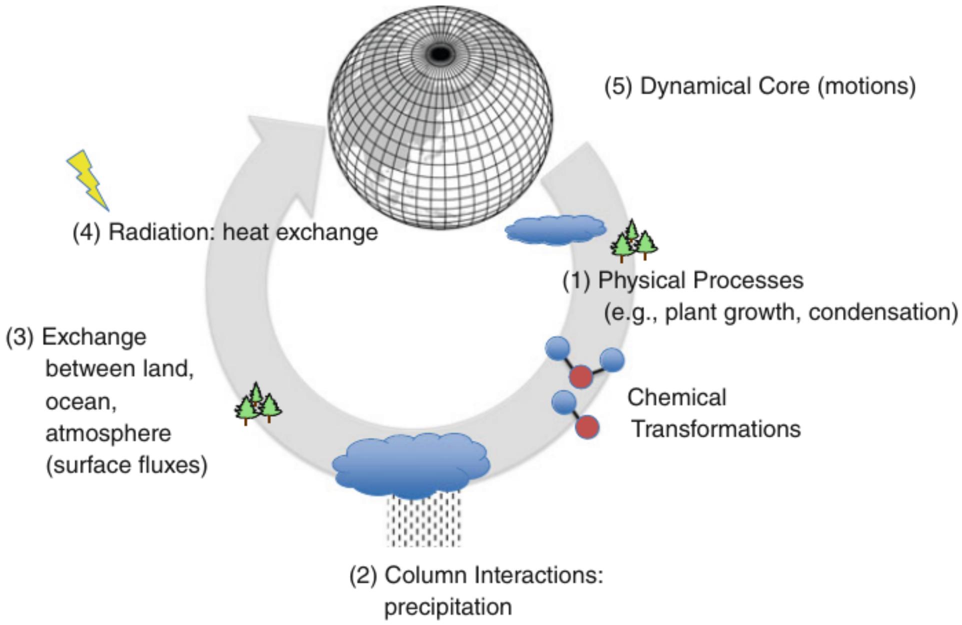


Fig. 4.6 Marching forward in time within a climate model. Time step loop typical of a climate model. Processes are calculated in a sequence at each time. *1* Physical processes and chemical transformations, *2* column interactions, *3* exchange between different components, *4* radiation and heat exchange, *5* dynamics and motion

4. General circulation models → Methodological components: Time steps

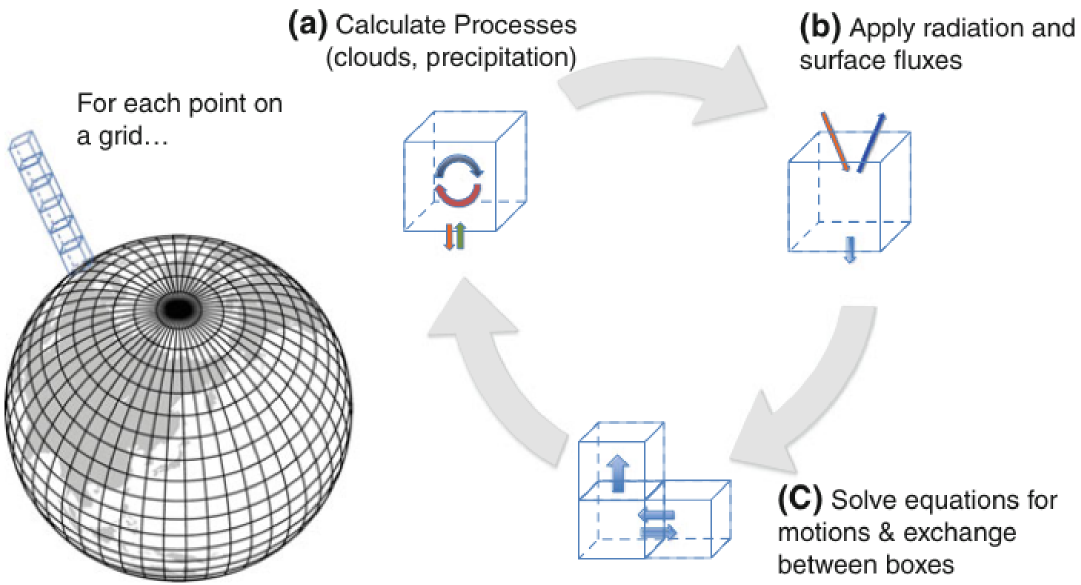
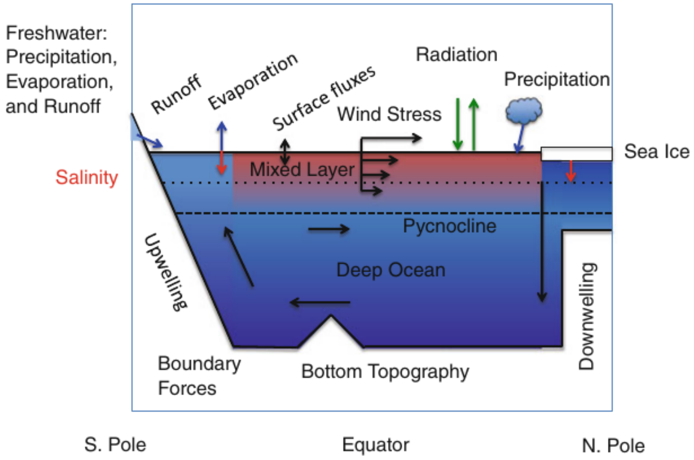
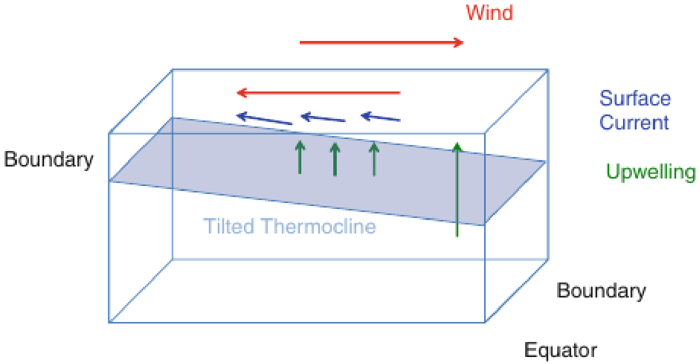
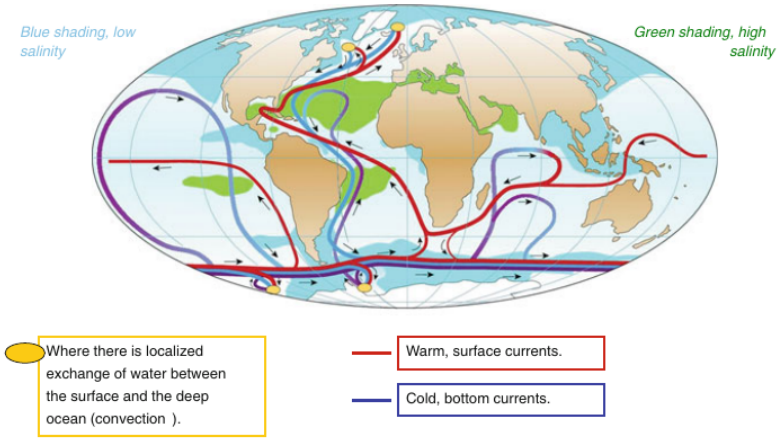


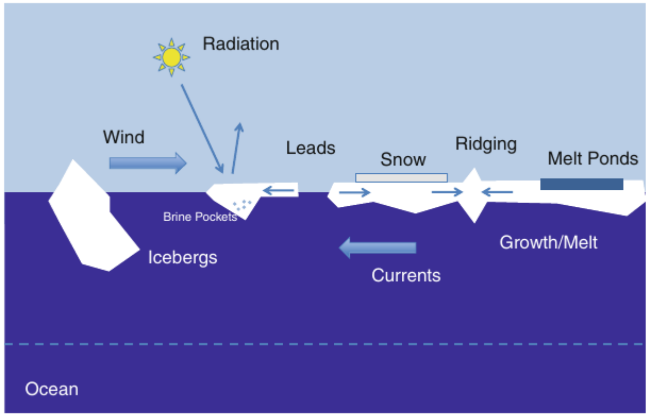
Fig. 5.7 General Circulation Model. Schematic of calculations in a time step in each grid box of a General Circulation model, including. **a** Calculate processes, **b** Apply radiation and surface fluxes and **c** Calculate motions and exchanges between boxes

4. General circulation models → Simulation components: Atmosphere



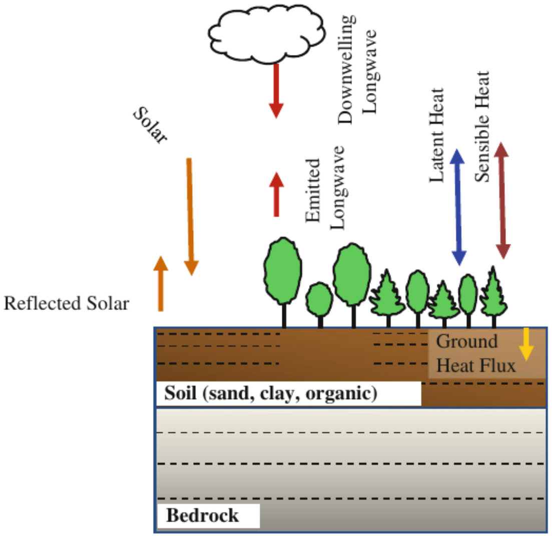


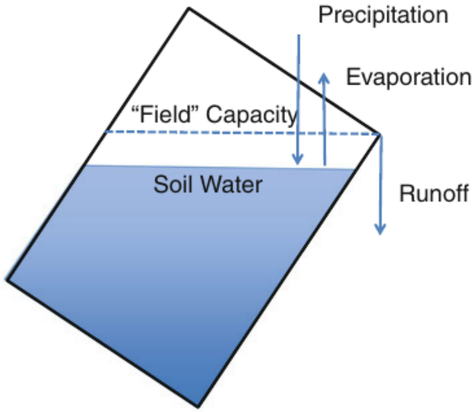


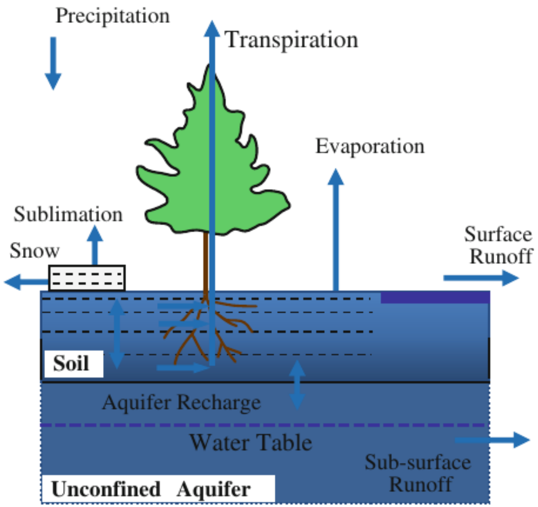


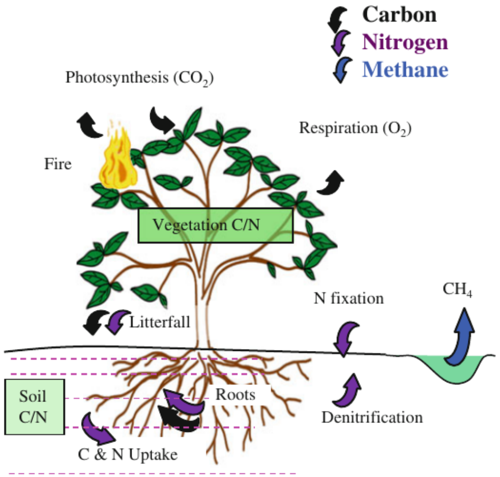
4. General circulation models → Simulation components: Ocean

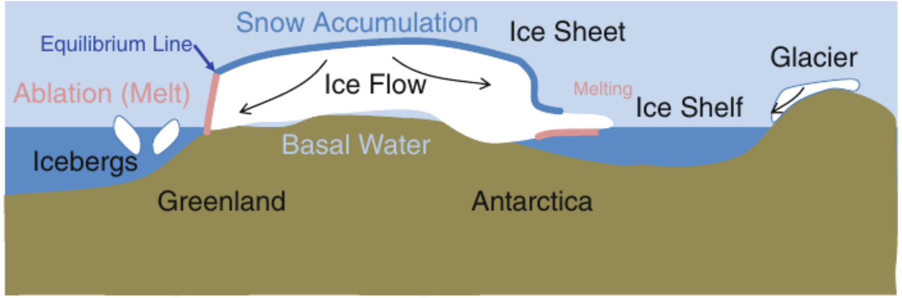
Gettelman & Rood, 2016











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4. General circulation models → Simulation components: Land

Challenges in global circulation models

- Atmosphere
  - Unknown processes
  - Feedbacks
- Ocean
  - Less observations
  - Small scale eddies
  - Long time scales; deep overturning
- Sea Ice
  - Less data on ice thickness
  - Sensitivity to atmospheric forcing
- Land
  - Albedo feedback
  - Carbon feedback

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Q
A