Module 6: Global Climate Models and Downscaling

Outline

- Global climate models
- Applications of global climate models: Community Earth System Model (CESM)
- How to run a GCM: CESM
- Statistical downscaling
- Dynamical downscaling
- S2S databases

Global Climate Models General Circulation Models

- Global Climate Models (GCM), consist of a set of governing equations and physical parameterizations for the processes that can not be explicitly resolved, such as the parameterizations of cumulus convection, the boundary layer eddies and cloud microphysics.
- GCMs can be categorized according to how many and which subsystems of the full climate system are included. For example:
  - atmospheric GCM, or AGCM
  - ocean GCM, or OGCM
  - Land surface models (LSM)
  - Ice models
  - Ocean wave models
  - River runoff models

** GCMs also represent general circulation models in some context.*

Atmospheric GCM: Governing Equations

Box 12.1 Governing Equations of an Atmospheric GCM

$$\frac{\partial u}{\partial t} = -\vec{v}\cdot\nabla u + \frac{uv\tan\phi}{a} - \frac{uw}{a} - \frac{1}{\rho a\cos\phi}\frac{\partial p}{\partial\lambda} + fv - 2\Omega w\cos\phi + F_\lambda. \quad (12.5)$$

$$\frac{\partial v}{\partial t} = -\vec{v}\cdot\nabla v - \frac{u^2\tan\phi}{a} - \frac{vw}{a} - \frac{1}{\rho a}\frac{\partial p}{\partial\phi} - fu + F_\phi. \quad (12.6)$$

$$\frac{\partial w}{\partial t} = -\vec{v}\cdot\nabla w + \frac{u^2+v^2}{a} - \frac{1}{\rho}\frac{\partial p}{\partial z} - g + 2\Omega u\cos\phi + F_z. \quad (12.7)$$

$$\frac{\partial T}{\partial t} = -\vec{v}\cdot\nabla T + \frac{\omega}{\rho c_p} + \frac{Q}{c_p}. \quad (12.8)$$

$$\frac{1}{\rho}\frac{d\rho}{dt} + \nabla\cdot\vec{v} = 0. \quad (12.9)$$

$$p = \rho RT. \quad (12.10)$$

$$\frac{\partial(\rho q)}{\partial t} = -\vec{v}\cdot\nabla(\rho q) + E - P. \quad (12.11)$$

The specific form of the equations depends on the coordinate system of a model but the essential physics/dynamics of AGCMs are the same.

Momentum equations (conservation of momentum)

thermodynamic equation (conservation of energy)

continuity equation (conservation of mass)

the ideal gas law

Conversation of water vapor

- AGCMs use prescribed sea surface temperatures (SST) and sea ice to specify the lower boundary condition over the ocean.
- Green house gas and aerosol concentration can be specified to represent the radiative forcing.

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Ocean GCM

$$
\begin{aligned}
\frac{Du}{Dt} - \left(f + \frac{u\tan\phi}{a}\right)v &= -\frac{1}{a\cos\phi}\frac{\partial P}{\partial\lambda} + F_x \\
\frac{Dv}{Dt} + \left(f + \frac{u\tan\phi}{a}\right)u &= -\frac{1}{a}\frac{\partial P}{\partial\phi} + F_y \\
\frac{\partial P}{\partial z} + \frac{g\rho}{\rho_0} &= 0 \\
\frac{1}{a\cos\phi}\left(\frac{\partial u}{\partial\lambda} + \frac{\partial v\cos\phi}{\partial\phi}\right) + \frac{\partial w}{\partial z} &= 0 \\
\frac{D(T,S)}{Dt} &= SGS \\
\rho &= \rho[T,S,P]\,.
\end{aligned}
$$

horizontal momentum equations &hydrostatic equation

continuity equation (conservation of mass)

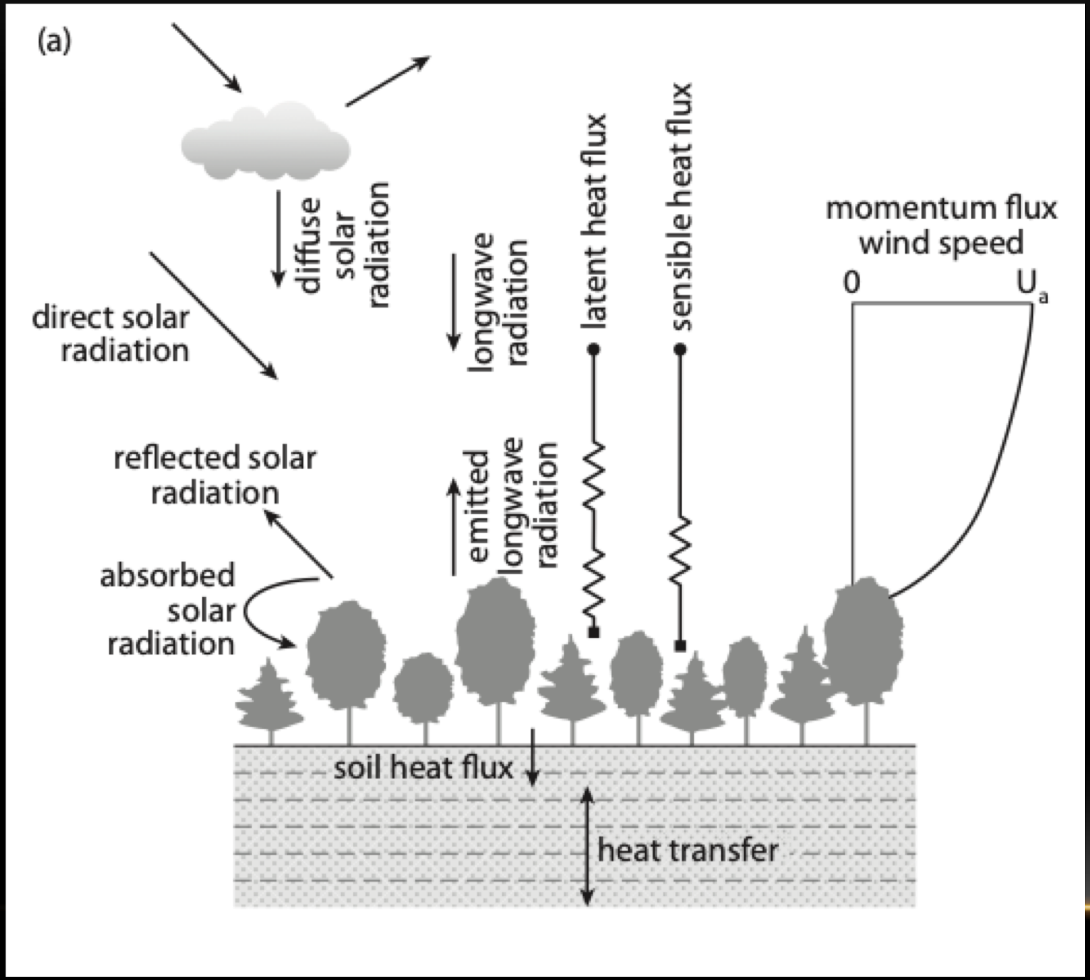
Equation of state

Here (λ, ϕ, z) are longitude, latitude, and height; (u, v, w) are the associated velocities; T is the potential temperature (*i.e.*, invariant under adiabatic compression); S is the salinity; and D/Dt is the substantial time derivative,

$$
\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{u}{a\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{a}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial z}\,. \tag{2}
$$

- OCGMs are governed by a set of equations that are similar to those used in AGCMs but with some important differences.
  - The equation of state for the ocean includes the dependence of water density on salinity, temperature and pressure.
  - The conservation of water vapor is replaced by an equation for the conservation of salt.
- An OGCM can be coupled with an AGCM, or be driven by the atmospheric forcing (including the surface wind and precipitation).

Land Surface Models (LSM)



- Contemporary LSMs govern the exchanges of water (precipitation, evapotranspiration, and sublimation), energy (latent and sensible heat fluxes, longwave and shortwave radiation) and momentum exchanges (through the treatment of surface friction) between the atmosphere and the land surface.
- The land surface may be covered with natural vegetation, managed vegetation, or buildings and cement as in an urban environment.

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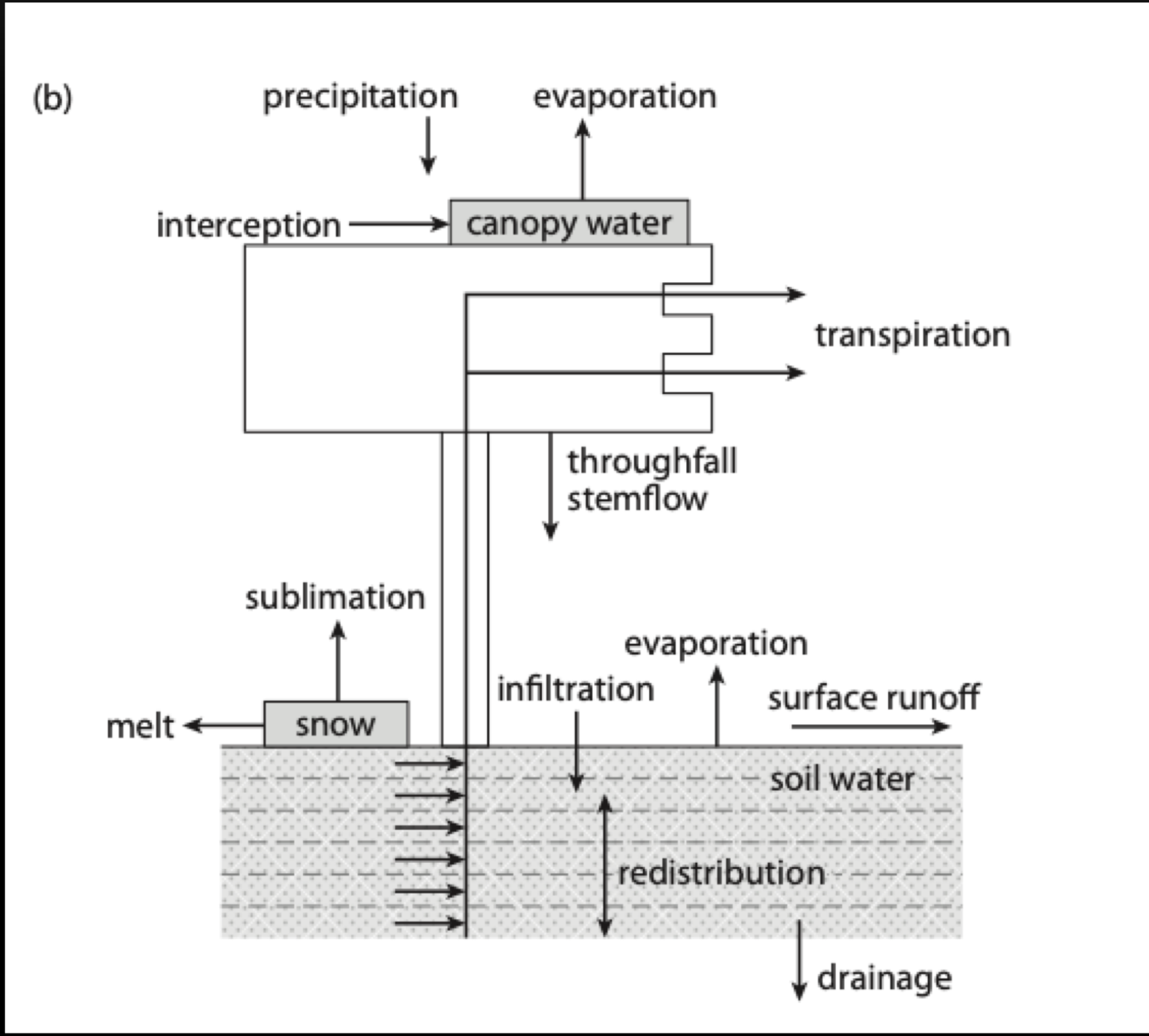
Land Surface Models (cont'd)



- The more complex LSMs represent the land surface with multiple soil layers through which heat diffuses and water infiltrates.
- Surface runoff is accounted for and may be organized into streams and rivers to allow for reabsorption of the water before it reaches the ocean, and flooding is simulated.
- The vegetation type can be calculated as a function of the modeled climate state in dynamic vegetation models (DVMs).

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Earth System Models

- Earth System: the integrated system of physical, chemical, and biological processes in the atmosphere, ocean, land, biosphere, and cryosphere.
- Earth system models (ESMs) combine fully coupled GCMs (including AGCMs, OGCMs, LSMs, and ice models) with biogeochemistry models that track the cycling of chemical elements in the climate system, such as the carbon cycle and the methane cycle.

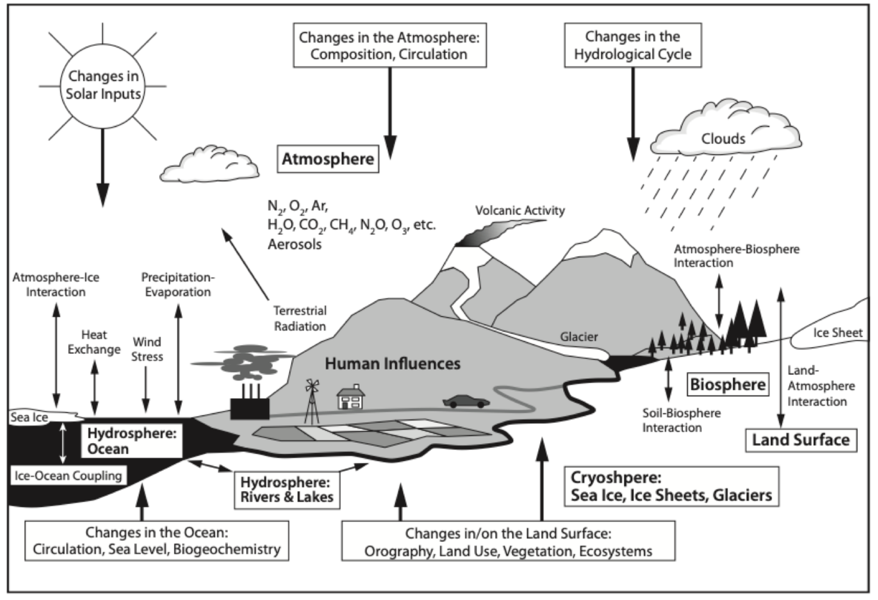

Figure 1.1 Schematic of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows). From IPCC, 2001.

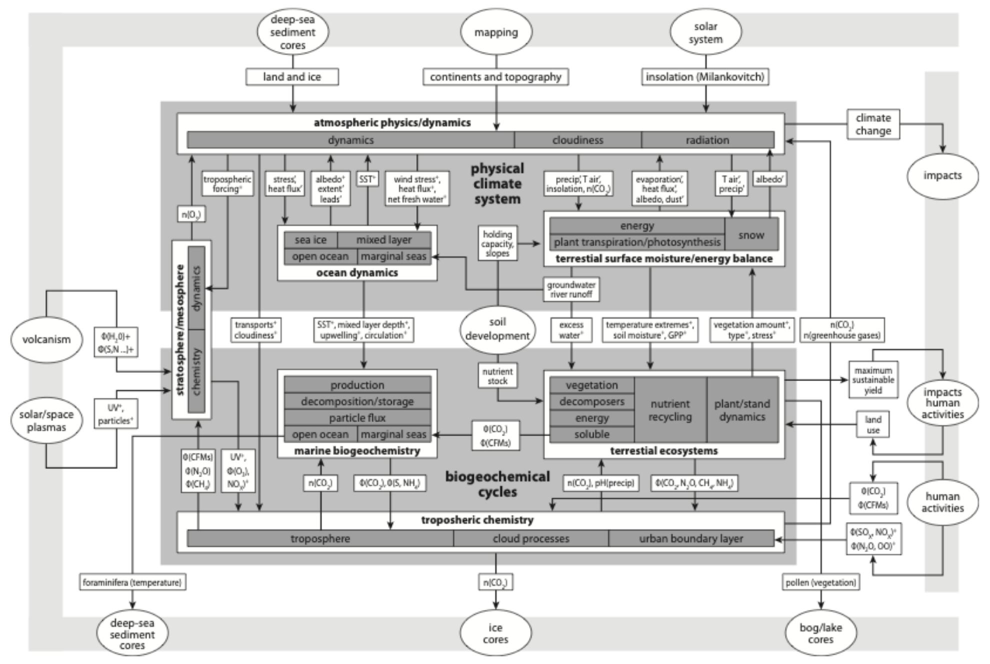

Figure 1.2 The Bretherton diagram, illustrating the components of the climate system and the interactions among them. (′ = on timescale of hours to days; * = on timescale of months to seasons; ϕ = flux; n = concentration; SST is sea surface temperature)

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References

- Cook, K. H., 2013: Climate Dynamics. Chapters 1, 12
- AMS Glossary