Modeling terrestrial ecosystems: Biogeophysics & canopy processes

Gordon Bonan
National Center for Atmospheric Research
Boulder, Colorado, USA

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Role of land surface in Earth system models

- Provides the biogeophysical boundary conditions at the land-atmosphere interface
  - e.g. albedo, longwave radiation, turbulent fluxes (momentum, sensible heat, latent heat, water vapor)
- Partitions available energy (net radiation) at the surface into sensible and latent heat flux, soil heat storage, and snow melt
- Partitions rainfall into runoff, evapotranspiration, and soil moisture
  - Evapotranspiration provides surface-atmosphere moisture flux
  - River runoff provides freshwater input to the oceans
- Provides the carbon fluxes at the surface (photosynthesis, respiration, fire, land use)
- Updates state variables which affect surface fluxes
  - e.g. snow cover, soil moisture, soil temperature, vegetation cover, leaf area index, vegetation and soil carbon and nitrogen pools
- Other chemical fluxes (CH$_4$, Nr, BVOCs, dust, wildfire, dry deposition)
- Land surface model cost is actually not that high (~10% of fully coupled model)
Role of land surface in Earth system models

The land surface model solves (at each timestep)

**Surface energy balance** (and other energy balances, e.g. in canopy, snow, soil)

\[ S_U + L_U = S_D + L_D + \Delta E + H + G \]

- \( S_U, S_D \) are down(up)welling solar radiation
- \( L_U, L_D \) are down(up)welling longwave radiation
- \( \Delta \) is latent heat of vaporization, \( E \) is evapotranspiration
- \( H \) is sensible heat flux
- \( G \) is ground heat flux

**Surface water balance** (and other water balances such as snow and soil water)

\[ P = (E_S + E_T + E_C) + (R_{Surf} + R_{Sub-Surf}) + \Delta SM / \Delta t \]

- \( P \) is rainfall
- \( E_S \) is soil evaporation, \( E_T \) is transpiration, \( E_C \) is canopy evaporation
- \( R_{Surf} \) is surface runoff, \( R_{Sub-Surf} \) is sub-surface runoff
- \( \Delta SM / \Delta t \) is the change in soil moisture over a timestep

**Carbon balance** (and plant and soil carbon pools)

\[ \text{NPP} = \text{GPP} - R_a = (\Delta C_f + \Delta C_s + \Delta C_r) / \Delta t \]

\[ \text{NEP} = \text{NPP} - R_h \]

\[ \text{NBP} = \text{NEP} - \text{Fire} - \text{Land Use} \]

- \( \text{NPP} \) is net primary production, \( \text{GPP} \) is gross primary production
- \( R_a \) is autotrophic (plant) respiration, \( R_h \) is heterotrophic (soil) respiration
- \( \Delta C_f, \Delta C_s, \Delta C_r \) are foliage, stem, and root carbon pools
- \( \text{NEP} \) is net ecosystem production, \( \text{NBP} \) is net biome production
Coupling with the atmosphere every model timestep is a fundamental constraint (< 30 minute timestep)
So is the need to represent the global land surface, including Antarctica, the Tibetan Plateau along with forests, grassland, croplands, tundra, desert scrub vegetation, and cities
Conservation of energy and mass is required
We strive to develop a process-level understanding across multiple ecosystems and at multiple timescales (instantaneous, seasonal, annual, decadal, centuries)

**Top-down, empirical modeling**

Thornthwaite: Monthly potential evapotranspiration driven by air temperature

\[ E_p = 16 \left( \frac{L}{12} \right) \left( \frac{N}{30} \right) \left( \frac{10T}{I} \right)^a \]

Priestley–Taylor equation: Daily potential evapotranspiration driven by radiation

\[ E_p = \alpha \frac{s R_n}{s + \gamma} \]

Production efficiency model driven by radiation and empirical scalars

\[ GPP = \varepsilon S \downarrow f_1(T) f_2(\theta) f_3(VPD) \]

Annual NPP driven by temperature and precipitation

\[ NPP = \min \left\{ \frac{3000}{1 + \exp(1.315 - 0.119T)}, 3000 \left[ 1 - \exp(-0.000664 P) \right] \right\} \]

**Process modeling**

Penman-Monteith equation

FvCB photosynthesis model

Ball-Berry stomatal conductance model

Fick’s law of diffusion

Darcy’s law and Richards equation (soil water)

Fourier’s law (heat conduction)
Lack of a common language

Flux is proportional to the driving force:

\[
\text{Flux} = \text{proportionality constant} \times \text{gradient of driving potential}
\]

Describes heat flow in soil (Fourier’s law), water flow in soil (Darcy’s law), turbulent fluxes (Fick’s law)

\[
E = \rho C_w u (q_s - q_a) \beta
\]

Atmospheric models:

\[
E = \frac{\rho (q_s - q_a)}{r_a + r_s} \quad \text{resistance (s m}^{-1}\text{)}
\]

Land surface models:

\[
\lambda E = \frac{c_p}{\gamma} (e_s - e_a) g_w
\]

Biometeorology:

\[
E = (q_s - q_a) g_w
\]

Plant physiology:

\[

\text{Dimensionless drag coefficient} \quad \text{Dimensionless soil moisture factor}
\]

\[
\begin{array}{c|c|c|c|c|c}
\text{kg m}^{-2} \text{s}^{-1} & \text{kg m}^{-3} & \text{m s}^{-1} & \text{kg kg}^{-1} \\
\hline
\text{Dimensionless drag coefficient} & \text{Dimensionless soil moisture factor}
\end{array}
\]
Model name depends on discipline:

**Atmospheric sciences**
land surface model
soil–vegetation–atmosphere–transfer model

**Hydrology**
hydrologic model (SVAT with lateral fluxes)

**Ecology**
biogeochemical model
dynamic global vegetation model
ecosystem demography model
Fluxes of energy, water, CO₂, CH₄, BVOCs, and Nr and the processes that control these fluxes in a changing environment

Oleson et al. (2013) NCAR/TN-503+STR (420 pp)
Lawrence et al. (2012) J Climate 25:2240-2260

Spatial scale
1.25° longitude 0.9375° latitude (288 192 grid), ~100 km 100 km

Temporal scale
- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century (disturbance, land use, succession)
- Paleoclimate (biogeography)

Landscape dynamics
Land surface heterogeneity

The model simulates a column extending from the soil through the plant canopy to the atmosphere. CLM represents a model grid cell as a mosaic of up to 5 primary land units. Each land unit can have multiple columns. Vegetated land is further represented as patches of individual plant functional types.

Sub-grid land cover and plant functional types

- Glacier 16.7%
- Lake 16.7%
- Urban 8.3%
- Crop 8.3%
- Vegetated 50%

1.25° in longitude (~100 km)
0.9375° in latitude (~100 km)
Surface energy balance and surface temperature

Surface energy balance:

\[(S - S) + L - \sigma T^4 - H[H_s] - E[T_s] = \text{soil heat storage}\]

Flux = \(\Delta\) concentration * conductance

\[H = c_p(T_s - T_a)g_{ab}\]

\[\lambda E = \lambda(q_s[T_s] - q_a)\]

Atmospheric forcing

- \(S\) - Solar radiation (vis, nir; direct, diffuse)
- \(L\) - Longwave radiation
- \(T_a\) - air temperature
- \(q_a\) - atmospheric water vapor
- \(u\) - wind speed
- \(P\) - surface pressure

Surface properties

- \(S\) - reflected solar radiation (albedo)
- \(\lambda\) - emissivity
- \(g_{ah}\) - aerodynamic conductance (roughness length)
- \(g_c\) - surface conductance
- \(k\) - thermal conductivity
- \(c_v\) - soil heat capacity

With atmospheric forcing and surface properties specified, solve for temperature \(T_s\) that balances the energy budget
Logarithmic wind profile in atmosphere near surface

\[ \bar{u}(z) = \frac{u_s}{k} \left[ \ln \left( \frac{z - d}{z_0} \right) - \psi_m(\zeta) \right] \]

\[ \bar{\theta}(z) - \bar{\theta}_s = \frac{\theta_s}{k} \left[ \ln \left( \frac{z - d}{z_{0h}} \right) - \psi_h(\zeta) \right] \]

\[ \bar{q}(z) - \bar{q}_s = \frac{q_s}{k} \left[ \ln \left( \frac{z - d}{z_{0h}} \right) - \psi_w(\zeta) \right] \]

with \( z_0 \) roughness length, \( d \) displacement height, and \( \psi(\zeta) \) corrects for atmospheric stability

Turbulent fluxes – logarithmic profiles

\[ \bar{u}(z) = \frac{u_*}{k} \left[ \ln \left( \frac{z-d}{z_0} \right) - \psi_m(\zeta) \right] \]

\[ \bar{\theta}(z) - \bar{\theta}_s = \frac{\theta_*}{k} \left[ \ln \left( \frac{z-d}{z_{0h}} \right) - \psi_h(\zeta) \right] \]

\[ \bar{q}(z) - \bar{q}_s = \frac{q_*}{k} \left[ \ln \left( \frac{z-d}{z_{0h}} \right) - \psi_w(\zeta) \right] \]

with \( z_0 \) roughness length, \( d \) displacement height, and \( \psi(\zeta) \) corrects for atmospheric stability.

Plant canopies

Sensible heat flux

Latent heat flux

(a) Bulk surface without canopy  (b) Bulk surface with canopy  (c) Two-source canopy  (d) Multi-layer canopy

Flux to atmosphere uses MOST

“Surface” is an imaginary height (where wind speed extrapolates to zero)

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Deardorff (1978) JGR 83C:1889-1903
Dickinson et al. (1986) NCAR/TN-275+STR
Dickinson et al. (1993) NCAR/TN-387+STR
Radiative transfer

(a) Direct beam

Fractional canopy absorption

Visible

Near-infrared

Leaf area index

(b) Snow

Albedo

Visible

Near-infrared

Leaf area index

CLM uses the two-stream approximation (Dickinson, Sellers)

\[
\frac{dI^\uparrow}{dx} = \left[1 - (1 - \beta) \omega_1\right] K_d I^\uparrow - \beta \omega_1 K_d I^\downarrow - \beta_0 \omega_1 K_b I_{\text{sky},b} e^{-K_{bx}}
\]

\[
\frac{dI^\downarrow}{dx} = -\left[1 - (1 - \beta) \omega_1\right] K_d I^\downarrow + \beta \omega_1 K_d I^\uparrow + (1 - \beta_0) \omega_1 K_b I_{\text{sky},b} e^{-K_{bx}}
\]
How do we scale from leaf to canopy?
Leaf energy balance:

\[ c_L \frac{\partial T_1}{\partial t} = Q_a - 2\varepsilon_1 \sigma T_1^4 + 2c_p(T_1 - T_a)g_{bh} + \lambda \left[ q_*(T_1) - q_a \right] g_1 \]

**Atmospheric forcing**
- \( Q_a \) - radiative forcing (solar and longwave)
- \( T_a \) - air temperature
- \( q_a \) - water vapor (mole fraction)
- \( u \) - wind speed
- \( P \) - surface pressure

**Leaf properties**
- \( \varepsilon_1 \) - emissivity
- \( g_{bh} \) - leaf boundary layer resistance
- \( g_e \) - leaf resistance to water vapor
- \( c_L \) - heat capacity

With atmospheric forcing and leaf properties specified, solve for temperature \( T_1 \) that balances the energy budget.
Leaf boundary layer

\[
\text{CO}_2 + 2 \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2 + \text{H}_2\text{O}
\]
Stomatal gas exchange

\[
\text{CO}_2 + 2 \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2 + \text{H}_2\text{O}
\]

- Photosynthetically Active Radiation
- Moist Leaf
- Warm Temperature
- Moist Air
- Moderate CO\(_2\)
- High Leaf Nitrogen

Stomatal conductance

Ball-Berry stomatal conductance model

\[ g_s = g_0 + g_1 \frac{A_n h_s}{c_s} \]

Empirical relationship between stomatal conductance and photosynthesis and is applied separately to sunlit canopy and shaded canopy

Optimization theory

Stomata optimize photosynthetic carbon gain per unit transpiration water loss while preventing leaf desiccation

\[ \Delta A_n \leq t D_s \Delta g_s \quad \text{and} \quad \psi_{l} > \psi_{l,\text{min}} \]

Bonan et al. (2014) Geosci. Model Dev. 7:2193-2222
Leaf photosynthesis

Farquhar, von Caemmerer, Berry photosynthesis model

\[ A_n = \min(A_c, A_j) - R_d \]

\( w_c \) is the rubisco-limited rate of photosynthesis, \( w_j \) is light-limited rate allowed by RuBP regeneration

rubisco-limited rate is

\[ A_c = \frac{V_{c_{\text{max}}}(c_i - \Gamma_*)}{c_i + K_c(1 + o/K_o)} \]

RuBP regeneration-limited rate is

\[ A_j = \frac{J(c_i - \Gamma_*)}{4(c_i + 2\Gamma_*)} \]

Leaf physiological parameters

- $K_C$
- $K_O$
- $\Gamma^*$
- $V_{cmax}$
- $J_{max}$
- $T_p$
- $R_d$
Canopy conductance – gradients of PAR

(a) Graph showing height (m) vs. leaf area index in an oak forest.

(b) Graph showing solar radiation (%) and cumulative leaf area index.

Oak forest

Solar radiation (%)

Height (m)

Cumulative leaf area index

Radiation

LAI
Sunlit and shaded canopy

(a) Direct beam

(b) Diffuse

Fraction absorbed vs. Leaf area index for Sunlit and Shaded Canopy
Decline in foliage N (per unit area) with depth in canopy yields decline in photosynthetic capacity ($V_{c_{\text{max}}}, J_{\text{max}}$)

$$V_{c_{\text{max}}}25 (x) = V_{c_{\text{max}}}25 (0) e^{-K_n x}$$

$$f_{\text{sun}} (x) = e^{-K_{s,x}}$$

$$V_{c_{\text{max}}25} (\text{sun}) = \int_{0}^{L} V_{c_{\text{max}}25} (x) f_{\text{sun}} (x) dx$$

$$V_{c_{\text{max}}25} (\text{sha}) = \int_{0}^{L} V_{c_{\text{max}}25} (x) [1 - f_{\text{sun}} (x)] dx$$

Note: CLM5 has a more complex canopy optimization

Plant canopy as a “big leaf”

Most models use two-leaves (sunlit and shaded)
Flux towers & model validation

1990s: single site comparison, short intensive observing period

Boreal Ecosystem Atmosphere Study (BOREAS)

Bonan et al. (1997) JGR 102D:29065-75
Flux towers & model validation

2000s: annual cycle, multi-site comparison (boreal to tropical)

Morgan Monroe State Forest, Indiana

CLM3.0 – dry soil, low latent heat flux, high sensible heat flux
CLM3.5 – wetter soil and higher latent heat flux

Flux towers & model validation

CLM4 overestimates GPP. Model revisions improve GPP. Similar improvements are seen in evapotranspiration.
Improved annual latent heat flux

Model improvements reduce ET biases, especially in tropics, and improve monthly fluxes

Modeling across scales

Tower ➔ Large basin ➔ Global

Morgan Monroe State Forest

Mississippi basin

Water storage (mm)

0 10 20 30 40 50 60 70 80 90 100

Annual latent heat flux

0 10 20 30 40 50 60 70 80 90 100 110 120

CLM3.5

CLM3

dry soil, low latent heat flux

CLM3

GRACE

CLM3

CLM4

D. Lawrence et al. (2012)

J Climate 25:2240-2260


Stöckli et al. (2008) JGR, 113, doi:
10.1029/2007JG000562
Research areas

**Surface fluxes**
Roughness sublayer, multilayer canopies

**Radiative transfer**
3D structure, canopy gaps

**Photosynthesis**
Temperature acclimation, $CO_2$ response, product-limited rate, C4 plants

**Stomatal conductance**
Soil moisture stress, WUE optimization, $CO_2$ response

**Canopy scaling**
Optimal distribution of nitrogen
Canopy turbulence and the roughness sublayer

CLM (and most other models) use MOST, which fails above and within plant canopies.

Profiles from the CSIRO flux station near Tumbarumba

Two ways to model plant canopies

Photographs of Morgan Monroe State Forest tower site illustrate two different representations of a plant canopy: as a “big leaf” (below) or with vertical structure (right).

**Big-leaf canopy**
- Two “big-leaves” (sunlit, shaded)
- Radiative transfer integrated over LAI (two-stream approximation)
- Photosynthesis calculated for sunlit and shaded big-leaves

**Multilayer canopy**
- Explicitly resolves sunlit and shaded leaves at each layer in the canopy
- Light, temperature, humidity, wind speed, $H$, $E$, $A_n$, $g_s$, $\psi_L$
- New opportunities to model stomatal conductance from plant hydraulics ($g_s$, $\psi_L$)
Friction velocity (momentum flux)

US-Ha1, July 2001

CLM4.5

Obs

Mid-day

Model

n = 427
r = 0.74
slope = 0.63
bias = -0.17
rmse = 0.23

US-Var, March 2006

CLMml

Obs

Mid-day

n = 1290
r = 0.84
slope = 0.94
bias = 0.04
rmse = 0.08

n = 427
r = 0.85
slope = 0.73
bias = -0.05
rmse = 0.13

n = 1290
r = 0.89
slope = 0.81
bias = 0.02
rmse = 0.06
US-Ha1, July 2001 (DBF)

CLM4.5

CLMml