Introduction to the soil-plant-atmosphere continuum

Ray Leuning

CSIRO Marine and Atmospheric Research, Canberra, Australia

www.csiro.au
Outline

• Global climate change and the land surface
• Some basic plant physics & biology
  ▪ Mass and energy balances of leaves, plants and land surfaces
  ▪ Radiation absorption
  ▪ Leaf energy balances
  ▪ Water flow through soil & plant
  ▪ Photosynthesis
  ▪ Stomatal conductance

• Measurements
  ▪ Micrometeorology

• Modelling concepts
  ▪ Model states
  ▪ Model parameters
  ▪ Non-linearity
  ▪ Scaling up – classification/aggregation

• Putting it all together
  ▪ CABLE – Community Atmosphere-Biosphere-Land Exchange model
Atmospheric CO$_2$
Past and Future

Last 400,000 years: Vostok ice core record
Last 100 years: Contemporary record
Next 100 years: IPCC BAU scenario

Increases over last 100 years results from:
- Fossil fuel emissions
- Land use change

Why the interest in scaling from leaves to continents?
Global carbon budget

To predict response of land to climate change we need models & measurements.
Outline

• Global climate change and the land surface
• **Mass and energy balances of leaves, plants and land surfaces**
  - Radiation transmission & absorption
  - Leaf energy balances
  - Water flow through soil & plant
  - Photosynthesis
  - Stomatal conductance
• Measurements
  - Micrometeorology
• **Modelling concepts**
  - Model states
  - Model parameters
  - Non-linearity
  - Scaling up – classification/aggregation
• **Putting it all together**
  - CABLE – Community Atmosphere-Biosphere-Land Exchange model
Overview of a typical land-surface flux model

Key processes:

- Radiative transfer
- Leaf energy balance
- Stomatal conductance
- Water flow through soil & plant
- Photosynthesis

\[
\begin{array}{c}
\text{2-leaf canopy model} \\
\end{array}
\]

- Not discussed

  - Plant and soil respiration
  - heat, water transfer in soil and snow
Two-stream radiation approximation

Canopy

Two-stream approximation

Soil
Three radiation wavebands

• Solar radiation:
  - Visible (0.4 to 0.7 µm), 46-50%
  - Near infra red (0.7 to 1.5 µm) 44-46%

• Long-wave (thermal) radiation >10 (µm)
  - Emitted by anything with a temperature >0°K

• Sunlit & shaded leaves considered separately
  - Reflection, transmission & absorption
Canopy energy balance

\[ \Delta J_c = \underbrace{R_n}_{\text{solar}} - \underbrace{R_{S\downarrow} - R_{S\uparrow} + R_{L\downarrow} - R_{L\uparrow}}_{\text{longwave}} - H - \lambda E - G_0 - \Delta J_c = 0 \]

solar  longwave  heat  evap^n  soil  storage
Canopy fluxes – big leaves + soil

\[
R_n - G_0 - \Delta J_c = \lambda E + H
\]

Energy balance

\[
\lambda E = \sum_{i=1,2} \lambda E_{c,i} + \lambda E_s
\]

Evaporation

\[
H = \sum_{i=1,2} H_{c,i} + H_s
\]

Sensible heat

\[
F_c = \sum_{i=1,2} A_{n,i} - R_p - R_s
\]

CO₂ flux

\(i = 1\) sunlit 'big' leaf \(i = 2\) shaded 'big' leaf
Energy balance of ‘big’ leaf

\[ R_{nc} - \Delta J_c = \lambda E_c + H_c \]

\[ H_c = c_p \rho_a (T_c - T_a) / r_h \]

\[ \lambda E_c = \frac{\rho_a c_p}{\gamma} \frac{e^*_c - e_a}{r_w + r_{sw}} \]

Unknowns

\[ H_c, E_c, T_c \text{ & } r_{sw} \]

4 unknowns with only three equations?
Water flow through plant

Atmosphere

Epidermis

Soil

Root

J_w

L_R

LAI

RAI

Water flow through plant

\[ \psi_c \]

\[ g_s \]

\[ r_{sr} \]

\[ r_{re} \]
Soil water potential vs radial distance from root

Drying time

soil water potential (MPa)

$\psi_r$

$\psi_s$

$r$

$J_w$

$\psi_r$

$\psi_s$

$r$

$r$

$r$

$r$
Stomata – linking photosynthesis & transpiration

\[ C_a \]

\[ C_s \]

\[ C_i \]

\[ \psi_c \]

\[ \psi_{r} \]

\[ \psi_{g} \]

\[ \psi_{c} \]

\[ \psi_{e} \]

\[ F_c \]

\[ E \]

\[ J_W \]
Leaf photosynthesis: simple overview

Light reactions

\[ \text{Light} \rightarrow \text{H}_2\text{O} \rightarrow \text{O}_2 \]

\[ \text{CO}_2 \rightarrow \text{Calvin Cycle} \rightarrow \text{sugar} \]

\[ \text{ATP} \rightarrow \text{NADPH} \rightarrow \text{ADP + Pi} \]
Coupled leaf energy balance, photosynthesis & stomatal conductance

\[ R_{nc} = \lambda E_c + H_c \]
\[ H_c = c_p \rho_a (T_c - T_a) / r_h \]
\[ \lambda E_c = \frac{c_p \rho_a}{\gamma} \frac{e^*_c - e_a}{r_w + r_{sw}} \]

Unknwonns

\[ H_c, E_c, T_c, \psi_c, C_i, A_n, & g_{sc} \]

7 unknowns with 7 independent equations & many parameters for auxiliary equations

Ball-Berry-Leuning model
Links photosynthesis, stomatal conductance and transpiration
Demand - supply for CO$_2$

\[ A_n = -g_{CO_2}(c_i - c_s) \]

\[ A = \min(V_c, V_j) - R_d \]
Predictions for plant canopies during a soil drying cycle
Outline

• Global climate change and the land surface
• Some basic plant biology & physics
  ▪ Mass and energy balances of leaves, plants and land surfaces
  ▪ Radiation absorption
  ▪ Leaf energy balances
  ▪ Water flow through soil & plant
  ▪ Photosynthesis
  ▪ Stomatal conductance
• Measurements
  ▪ Micrometeorology
• Modelling concepts
  ▪ Model states
  ▪ Model parameters
  ▪ Non-linearity
  ▪ Scaling up – classification/aggregation
• Putting it all together
  ▪ CABLE – Community Atmosphere-Biosphere-Land Exchange model
Measurements

Use to test model performance and to estimate model parameter values

e.g. Tumbarumba Ozflux site

70 m tower in 40 m temperate Eucalyptus forest
Continuous measurements at 70 m:
  • eddy fluxes (H, λE, CO\textsubscript{2})
  • $R_{\text{net}}$
  • upward and downward solar radiation fluxes
  • meteorological measurements
  • continuous temperature and water vapour profiles
Tumbarumba - micrometeorology
Micrometeorology – mass balance

\[ F_c = \frac{c_d w}{\chi_c} + \int_{c_d}^{h_r} \frac{\partial \chi_c}{\partial t} \, dz + \frac{1}{L^2} \int_{0}^{L} \int_{0}^{L} \left[ \frac{\partial \chi_c}{\partial x} u_{c_d} + \frac{\partial \chi_c}{\partial y} v_{c_d} + \frac{\partial \chi_c}{\partial z} w_{c_d} \right] \, dx \, dy \, dz \]
Tumbarumba - micrometeorology
Outline

• Global climate change and the land surface
• Some basic plant biology & physics
  ▪ Mass and energy balances of leaves, plants and land surfaces
  ▪ Radiation absorption
  ▪ Leaf energy balances
  ▪ Water flow through soil & plant
  ▪ Photosynthesis
  ▪ Stomatal conductance

• Measurements
  ▪ Micrometeorology

• Modelling concepts
  ▪ Model states
  ▪ Model parameters
  ▪ Non-linearity
  ▪ Scaling up – classification/aggregation

• Putting it all together
  ▪ CABLE – Community Atmosphere-Biosphere-Land Exchange model
Schematic diagram of model components from a systems perspective

1. system boundary, $B$
2. inputs, $u$
3. initial states, $x_0$
4. parameters, $\theta$
5. model structure, $M$
6. model states, $x$
7. outputs, $y$
8. Observations, $y'$

Errors in each component affects model performance

minimize $\sum_i \left( y_i - y'_i \right)^2$

Observation model – e.g.
- Eddy fluxes
- Remote sensing

Scaling up – non-linearity

How do we transfer knowledge at one scale to another?

Linear models are scale-independent

\[ y = ax + b \]

Variables \( x \) and \( y \), Parameters \( a \) and \( b \)

Double \( x \), double \( y \)

Not true for non-linear models

\[ R = R_0 \exp(\alpha T) \]

Soil respiration, Temperature

Double \( T \), do not double \( R \)
Parameter estimation
Multiple criteria possible, e.g. $\lambda E$, NEE

The dark line between the two criteria’s minima, $\alpha$ and $\beta$, represents the Pareto set
Scaling using land surface models and data layers

Model Output

Cell by Cell Application of Biogeochemistry Model

Net Primary Production

Model Drivers

Solar Radiation

Precipitation, Temperature, etc.

Leaf Area Index

Model Initialization

Landcover (25m grid)

Courtesy S. Running U. of Montana
Scaling up - spatial heterogeneity, topography, climate, landcover
Scaling up - classification and aggregation of landcover classes
Outline

• Global climate change and the land surface
• Some basic plant biology & physics
  ▪ Mass and energy balances of leaves, plants and land surfaces
  ▪ Radiation absorption
  ▪ Leaf energy balances
  ▪ Water flow through soil & plant
  ▪ Photosynthesis
  ▪ Stomatal conductance
• Measurements
  ▪ Micrometeorology
• Modelling concepts
  ▪ Model states
  ▪ Model parameters
  ▪ Non-linearity
  ▪ Scaling up – classification/aggregation
• Putting it all together
  ▪ CABLE – Community Atmosphere-Biosphere-Land Exchange model
CABLE simulates processes at multiple time scales

Rapid biophysical processes
- Canopy conductance
- Photosynthesis
- Leaf respiration
- Carbon transfer
- Soil temperature
- Moisture availability

Intermediate biogeochemical processes
- Phenology
- Turnover
- Nutrient cycle
- Solution of SEB; canopy and ground temperatures and fluxes
- Soil heat and moisture
- Surface water balance

Slow biogeographical processes
- Vegetation dynamics
- Land-use and land-cover change
- Vegetation change
- Allocation
- Autotrophic and heterotrophic respiration

Atmospheric forcing
- T, u, Pr, q, \( R_s, R_l, \text{CO}_2 \)

Wang
Ideal model-data integration cycle (bottom-up)

Model application

Model (re)formulation
(Definition of model structure)

Model characterization
(Forward runs, consistency check, sensitivity, uncert. analysis)

Model parameter estimation
(Multiple constraint)

Generalization
(‘up-scaling’)

Model validation
(against indep. data, by scale or quantity)

DATA

Parameter interpretation
(Thinking)
Summary

1. Knowledge of vegetation response to changing climate is needed at all scales from individual plants, ecosystems to regions

2. Land surface schemes in climate models include many processes and parameters

3. Assume that parameter information at one scale can be used at higher scales

4. Problems with non-linear models “the scaling problem”, need to measure at scale we want predictions