Revamping the land in ESMs: Where remote observation and conservation of energy and mass meet ecology

Nancy Y. Kiang
NASA Goddard Institute for Space Studies, New York, NY

CalTech/JPL Earth System Modeling Futures Workshop: Land and Biosphere Modeling
CalTech, Pasadena, CA, March 26-28, 2018
To use the general circulation model the following parameters must be prescribed for each grid point:

- surface characteristics (open ocean, ice-covered ocean, bare land, and land covered by glacial ice);
- elevation of the land;
- surface roughness;
- thickness of the sea ice;
- and ocean surface temperature.

(and surface albedo)
GCM land physics vs. Ecological gap models

- **1D Fluxes** of water & energy
- **2D Area** coupling with atmosphere

**Top down**

**Bottom up**

- **Quanta**: individual plants
- **Stochastic rules, carbon allometry**

---

**Figure 2**: General functioning of a gap model. As one moves to the right to left, spatial scale increases from an individual tree to a small plot to a landscape. The tree-level response shown here is the elementary growth (or tree ring) equation from the FORET (Shugart and West 1977) model. The magnitude of the tree-mortality probability of each tree is also determined at the tree-level depending on tree growth as an index of vigor, species longevity, and other conditions. The form of the growth equation with no constraints is shown at the top and the decrement to this optimal growth equation is found below according to the particular controlling environmental factors (available light, soil moisture, etc.). At the plot level, the vertical profile of light, available soil moisture, and other environmental and biogeochemical factors are calculated and tree to tree interactions are computed. Conditions for potential new seedlings for each year are determined factors such as the environmental conditions and seed sources. At the landscape model, a basic gap model can be used to represent the landscape as: (a) the summation of a Monte Carlo collection of independent random points; (b) gridded points at some spacing; (c) a tessellation of adjacent plots; (d) a spatially explicit landscape simulation with a spatial map of trees that is windowed or updated for tree birth, growth and death by dropping a gap-model computational window onto the two-end map to solve for a subset of a new map. This is repeated to produce the new map. The size of this subset determines the resolution of the spatial map.

**Figure 3**: Schematic illustration of model structure at a single gridbox. Hansen et al. 1983
Adding vegetation, coupling energy, \( H_2O, CO_2 \) - SiB2


with Two-stream canopy radiative transfer (Dickinson, 1983; Sellers et al. 1985)

\[
-\mu \frac{dI}{dL} + \left[ 1 - (1 - \beta)\omega \right] I^\uparrow - \omega \beta I^\downarrow = \omega \mu K_{\beta_0} \exp(-KL)
\]

(1)

\[
\mu \frac{dI}{dL} + \left[ 1 - (1 - \beta)\omega \right] I^\downarrow - \omega \beta I^\uparrow = \omega \mu K (1 - \beta_0) \exp(-KL)
\]

(2)

\( L = \) cumulative leaf area index (LAI)
\( \mu = \cos(\theta), \theta = \) solar zenith angle
\( K = G(\mu)/\mu = \) direct beam optical depth per leaf area

\( G(\mu) = \) relative projected leaf area

\[ \text{How to get } K? \]

\[ \text{How does } L(z) \text{ vary?} \]
Problem: No gaps! Or formulated for 30 m scale, fixed solar zenith. Rule-based rather than physics-based canopy radiative transfer.
Physics: What does remote sensing see?
Boundary conditions: vegetation structure & quality

**Horizontal**
- Area (cover, LAI)
- Spectra

**Spectral**
- Albedo
- Physiological status (NDVI, PRI, etc.)
- Activity (SIF, NDVI)
- Diversity (PFTs, species)

**Vertical**
- Height
- Shape profiles of foliage/stem density

LiDAR
NASA/ICESat-GLAS

Gap-probability Geometric-Optical radiative transfer (GORT) for demographic DGVMs - consistent with LiDAR

**Ent TBM:**
Analytical Clumped Two-Stream (ACTS)
(Ni-Meister et al., 2010; Yang et al. 2010)
- Ellipsoidal crowns
- Analytical clumping factor for effective two-stream parameters
- LAI layering
- Trunks

**POP-DGVM** (after LPJ-GUESS):
Canopy Semi-analytic Pgap And Radiative Transfer (CanSPART)
(Haverd et al., 2012, 2014)
- Poisson-distributed crowns

- Non-intersecting crowns
- Optional branch effect
Canopy radiative transfer modeling

RAdition transfer Model Intercomparison (RAMI)

(shortwave/VIS/NIR/hyperspectral, energy balance,

(a) - Homogeneous scenes

(b) - Heterogeneous scenes
**Figure 6.** Histogram of relative model-to-reference deviations, \( \delta_{m-ref} \) (in percent) for simulation of (left) canopy absorption, (middle) canopy reflectance, and (right) canopy transmission within (top) 1-D and (bottom) 3-D plant environments. The zero deviation line is indicated by a gray vertical line, and all deviations larger than \( \delta_{m-ref} = 100\% \) are grouped into a single gray-colored bin.
Reference model: 

*raytran* (Monte Carlo ray-tracing)

Effective scattering parameters clumping:

Poisson = CanSPART > Actual canopy clumping? > ACTS > Uniform
Gap-probability based canopy radiative transfer for demographic DGVMs

Ent: Analytical Clumped Two-Stream (ACTS) (Ni-Meister et al., 2010; Yang et al. 2010)

- Cohorts of identical individuals
- Non-intersecting crowns
Gap-probability based canopy radiative transfer for demographic DGVMs

Current challenges:

- Cohort structure:
  - Vertical: variable height instead of identical?
  - Horizontal: early->mature : random->uniform
  - Allometry, geometry: ellipticity by age, light status?
  - Branch effect: data
- Optical properties of end members:
  - Data
  - Seasonal variation - prognostic modeling
- RT theory:
  - Vertically heterogeneous optical properties (e.g. tree above grass)
- Spatial scale:
  - Ecology (carbon) vs. Remote Sensing (light)
LiDAR
GLAS
waveform
Gap-probability based canopy radiative transfer for demographic DGVMs

Ent TBM Global Vegetation Structure Data Set (Ent GVSD)

Single-cohort from RH100 ± std. dev.
Gap-probability based canopy radiative transfer for demographic DGVMs

Ent: Analytical Clumped Two-Stream (ACTS) (Ni-Meister et al., 2010; Yang et al. 2010)

- Cohorts of identical individuals
- Non-intersecting crowns

LiDAR
Vegetation Height + Foliage Density Profiles

Three Representative Return Pulse Waveforms

Received Waveform Return Energy

Credit: NASA / ICESat-GLAS
Scaling up Ecology & LiDAR waveforms

- 0.5 degree GCM grid Subgrid patches
- 1/12 degree = 5' ~ 10 km In-fill heights by Ent PFT cover Assign max LAI3g Partition LAI max by Landsat. Continuous.
- 500 m subgrid Ent 17 PFTs assigned Waveforms. Gaps.
- Extrapolate height stats to 500 m. Gaps.
- 30 m Gappy GLAS waveforms and Gaussians Continuous Landsat max LAI
- Collated waveform stats by Ent PFT
- LAI
- In-fill to 1/12" by PFT cover
- Assign subgrid PFTs same waveform stats within 500 m
- Extrapolate waveform stats to 500 m
Scaling up Ecology & LiDAR waveforms

Even if continuous coverage...

0.5 degree GCM grid
Subgrid patches

1/12 degree.

1 km

500 m

30 m

rms
Vertical foliage profiles (VFP) from LiDAR

Fig. 1: Location of ICESat ground tracks over California, USA. ICESat did not provide a wall-to-wall coverage but rather data along transects separated by relatively long distances across track at mid-latitudes.

Fig. 6: Left: VFP (vertical resolution of 2 m) averaged for all GLAS shots over California for different land cover types. Each profile represents a single land cover type. Mean values are central lines within the color-filled 95% envelope. Note that the low height of peak LAD is because of the averaging process over the land cover type. Individual profiles have much more variable shapes (see right). Right: individual VIP examples with foliage density peak occurring at understory (<5 m), middle-story (~10 m) and up-story (~20 m).
Conclusions

- Accurate vegetation structure boundary conditions
  - Accurate fluxes
  - Better community light competition
- Rethink cohort description in demographic DGVMs
- Global data sets of vegetation community structure possible with LiDAR data -- HOW-TO translate VFP to cohorts bins:
  - Vertical partitioning
  - Horizontal spatial scale
- Data needs: seasonal variation in leaf albedo ~ C, N
- Theory needs:
  - Two-stream RT with systematic heterogeneity in leaf spectra
  - Allometry ~ climate ~ PFT
Acknowldgments

Ent Terrestrial Biosphere Model: A demographic Dynamic Global Vegetation model

Igor Aleinov – Columbia University
Software infrastructure, land hydrology, carbon coupling & tracers

Carlo Montes -- formerly NASA Postdoctoral Program

Ensheng Weng – Columbia University
Carbon allocation, ecological dynamics

COLLABORATORS:

Wenge Ni-Meister – CUNY Hunter College
Wenze Yang – Univ. of Maryland
canopy radiative transfer

Yeonjoo Kim – Yonsei University, Seoul
Phenology

Crystal Schaaf – Univ. of Massachusetts-Boston
Satellite global vegetation structure data sets

Support: David Considine - NASA Modeling, Analysis, and Prediction (MAP) Program
Ent Canopy Radiative Transfer: Analytical Clumped Two-Stream (ACTS)
(Ni-Meister et al., 2010; Yang et al. 2010)

LiDAR Vegetation Structure

PHOTOSYNTHESIS/CONDUCTANCE

ALBEDO

BORERAS diurnal
measured
GORT model
ACTS model

CO2
GPP
R_auto

CO2
GPP
R_auto

COHORT-COMMUNITY
COMPETITION/ECOLOGICAL DYNAMICS
Ent Biophysics: All models can simulate NEE (GIVEN correct LAI and biophysics tuning)

Broadleaf deciduous temperate
Morgan-Monroe State Forest, IN

Needleleaf evergreen boreal
Hyytiala, Finland

Annual grassland
Vaira Ranch, CA

Broadleaf evergreen tropical
Tapajo, Brazil

Except in the tropics...

To do:
Photosynthesis and respiration parameter sets for global diversity