Why Complex pfts Will be Needed to Correctly Describe the Intensity of Incident Solar Radiation on Individual Leaves

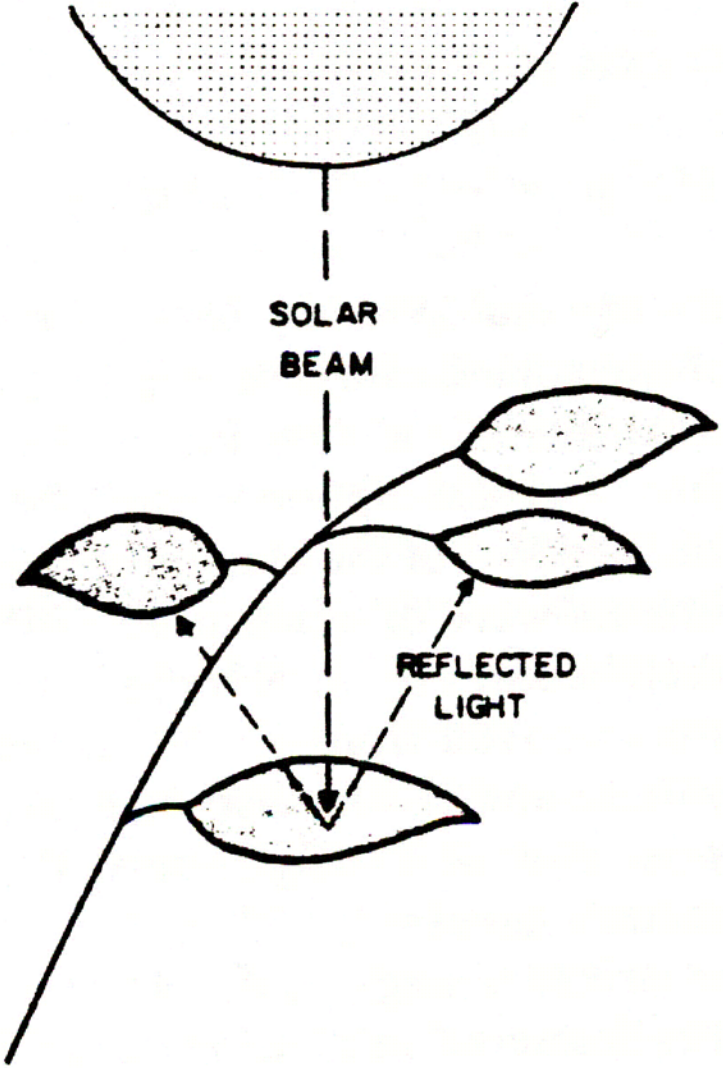
Robert E. Dickinson

University of Texas at Austin

CCSM Workshop, Breckinridge, June 2009

Review of Canopy Radiation

- Absorption of solar radiation drives climate system exchanges of energy, moisture, and carbon.
- Dickinson and Sellers advanced one dimensional analytic models of plant canopies for determining this absorption for a climate model.
- These early models have evolved into what is currently used in climate models.
- Issue of scaling from small scale to scale of climate model-substantial room for improvement in quantification



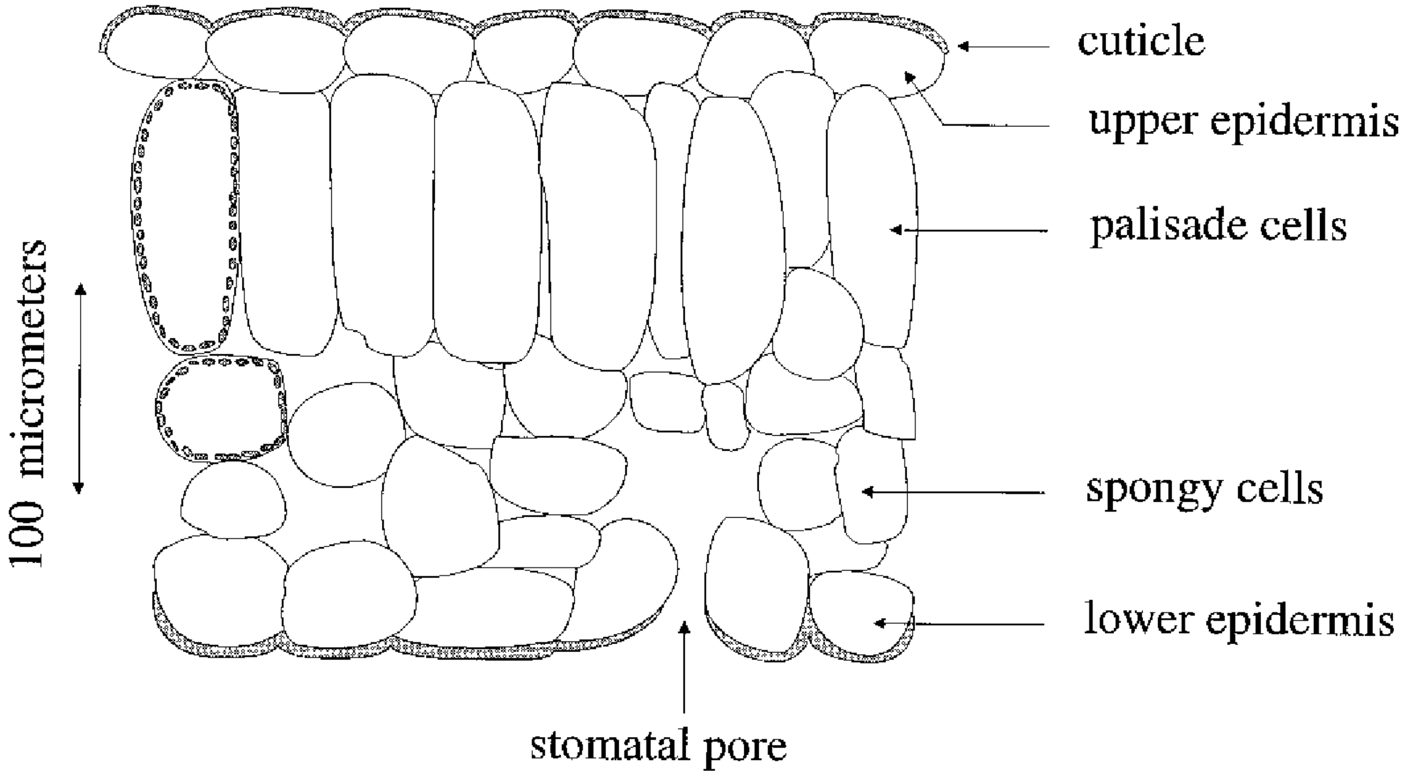
Sketch of the partial trapping of light reflected from a canopy leaf by overlying leaves.

Ref. Dickinson 1983

Controls on Canopy Radiation

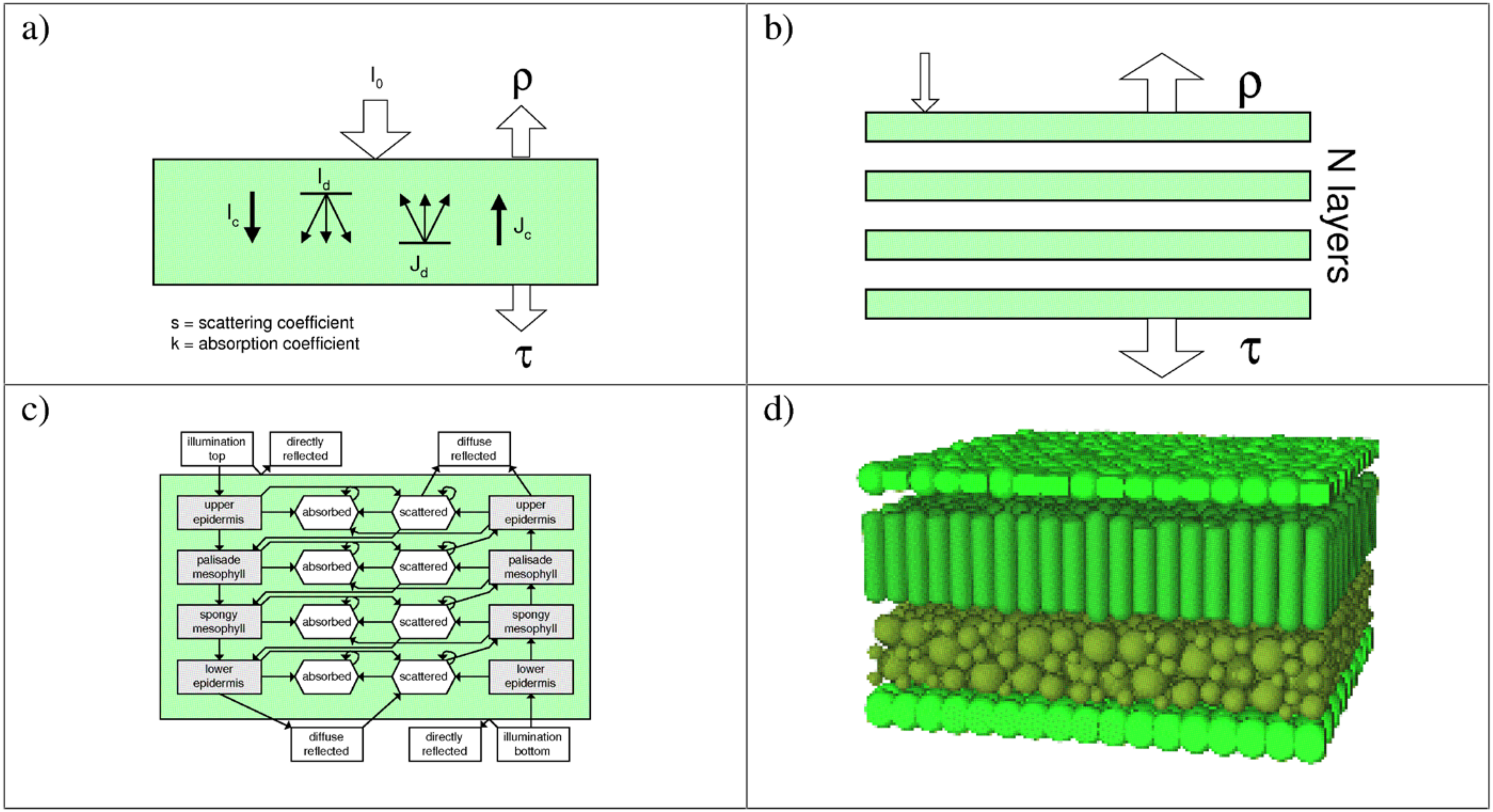
- Leaf orientation
- Leaf optical properties
- LAI
  - Stems also commonly included but yet not constrained by any observations – leave out here
- Canopy geometry
- Interaction with underlying soil or under-story vegetation

Schematic Yves Govaerts et al.



Schematic transverse section through a dicotyledon leaf indicating the arrangement of tissues. Chloroplasts are drawn in one cell only of both palisade and spongy tissues.

Mechanistic Leaf Models (Jacquemoud & Ustin



Different leaf optical properties models:
(a) Plate models, (b) N-flux models, (c) Stochastic models, (d) Ray tracing models

Simple Parameterization for Leaf Scattering (Lewis/Disney)

- $W_{leaf} = \exp[-a(n)\,A(\lambda)]$
- a is O(1), depends on refractive index n
- A(λ) is the bulk absorption averaged over leaf materials at wavelength λ (i.e,, water and dry matter at all wavelengths, chlorophyll and cartinoids in visible).

Leaf Area (LAI)

- From remote sensing, get pixel average.
- Because of non-linearities, need details about spatial distribution
- How are these currently estimated?
  - Ignore – view LAI /canopies as applied to model grid square
  - Use concept of fractional cover of a pft – LAI a constant for a given pft –covers some fraction of model grid-square.

Canopy Geometric Structure.

- Climate models have only used plane parallel RT models
- Uniform versus fractional cover f_c of pft.
- Transmission of sunlight T = fraction of area covered by sun or sun-flecks.
- Compare: $(1.- f_c) + f_c \exp (- \frac{1}{2} LAI/ f_c)$ versus $\exp(- \frac{1}{2} LAI)$
  - Both 1 – ½ LAI for small LAI, but (1.-fc) versus 0 for large LAI – non-vegetated fraction a canopy “gap”

Where canopy, LAI, hence optical path lengths, depend on location in space.

- Radiation decay as : exp (- ½ LAI(x,y))
- Average transmission, an area average-can simplify by use of distribution, e.g. x a scaling parameter, $0 \leq x \leq 1.0$, $LAI = x \, LAI_{max}$ and D(x) the fractional area where LAI/LAI_{max} between x and x+ dx , then $T = \int^1_0 dx \, D(x) \exp (- \frac{1}{2} x \, LAX_{max})$. Integrates analytically if D(x) simple enough.
- Can fit T to exponentials and infer effective leaf parameters (approach of Pinty et al.)

Use of distributions depends on canopy geometry

- Suppose canopy symmetric about some vertical axis, i.e LAI = LAI(r) depends on radial distance from this axis. Then

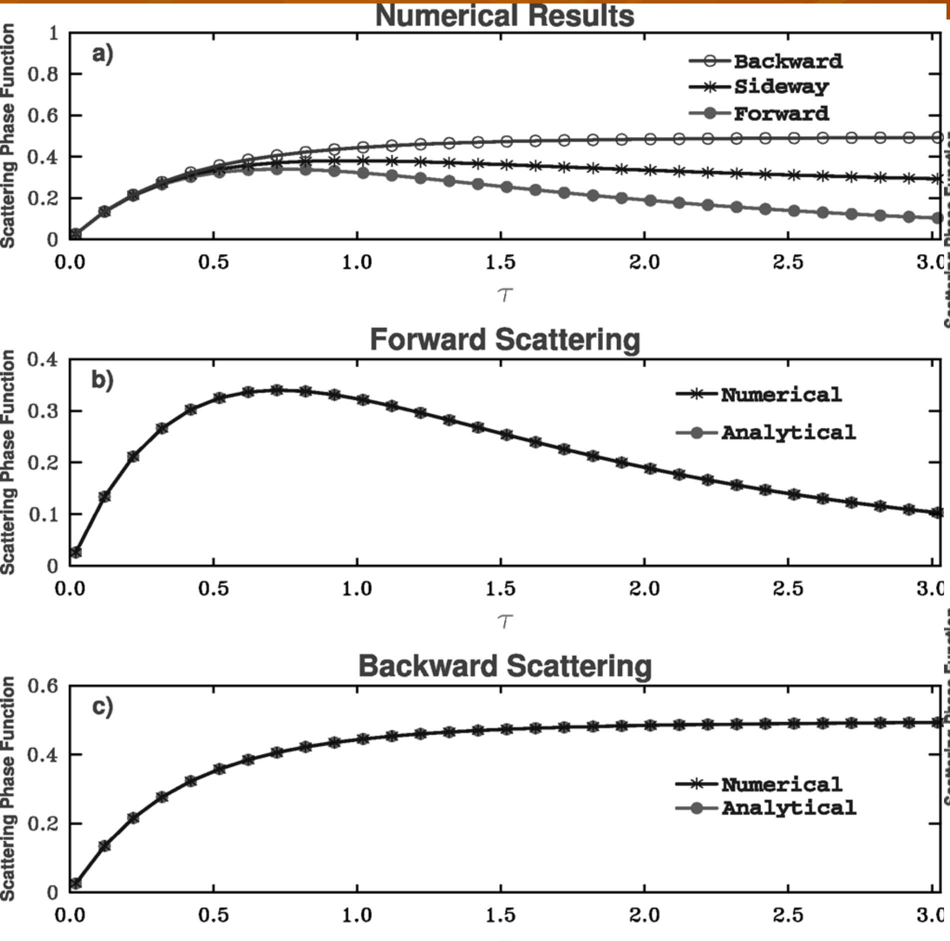
$$T = 2\int r\,dr \exp\left(- \tfrac{1}{2} \mathrm{LAI}(r) \right).$$

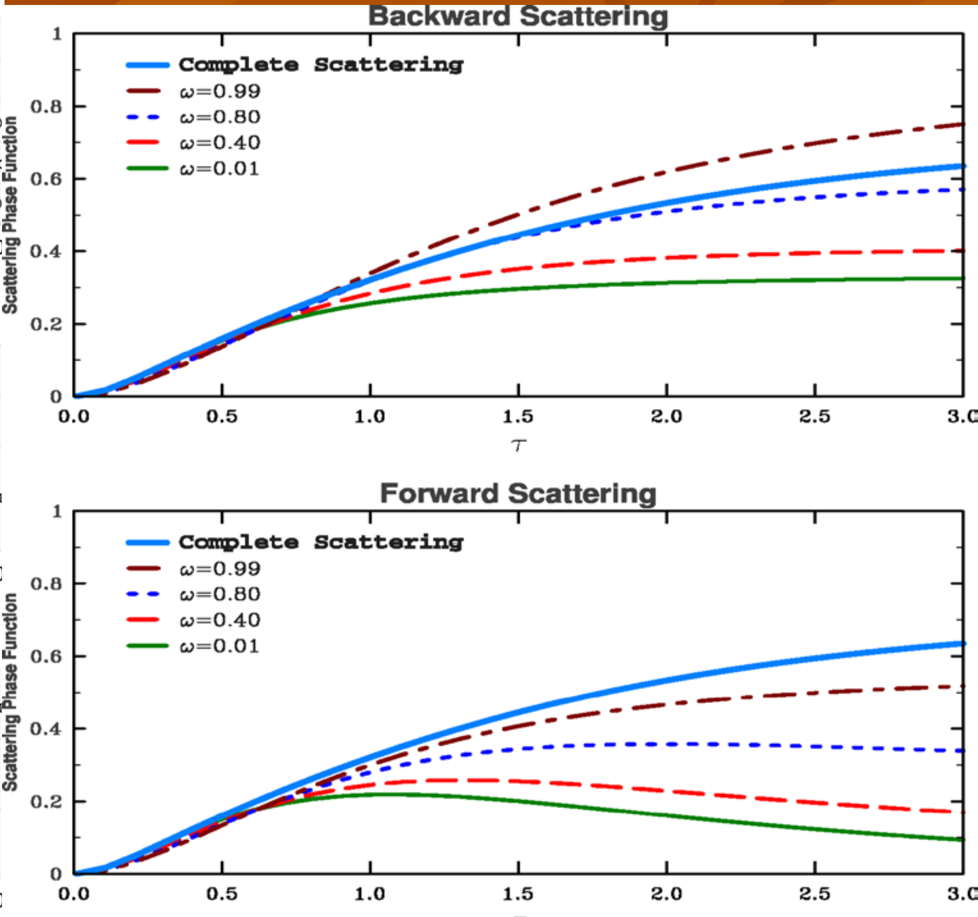
- $\mathrm{LAI} = \mathrm{LAI}_{max}\ f(x)$, where $x = (1.-r^2)$, $f(x) = x^\nu$ $0 \leq \nu \leq 1$, $\nu = \frac{1}{2}$ or 1 gives half-sphere or rotated parabola.

Analysis of Spherical Bush

- Note: if distribution for transmission has analytic integral, so does that for forward and backward single scattering
- Single scattering in arbitrary direction (for sphere at least) simply related to forward and backward scattering.

Spherical/spheroidal Bush Scattering (Dickinson et al., Dickinson – in review)





To be multiplied by ω/(4π)

To be multiplied by $\omega^2/(4\pi)$

Clustering

- If clustered at a higher level of organization, predominant effect is to multiply leaf optical properties by probability of a photon escape p_e from cluster (can be directional):
- In general, for p_e a constant, $p_a = 1. – p_e$,

$$\omega_{cluster} = \omega_{leaf}\, p_e / (\, 1. - \omega_{leaf} p_a) \, .$$

- Works for LAI of cluster out to 1. Spherical bush solutions and observational studies suggest maybe useful approximation for all expected LAI.

Overlapping Shadows

- Many statistical models can be used to fit spatial distribution of individual plant elements and hence the fractional area covered by shadows
- Simplest default (random) model for shadows is fraction of shadow $f_s = (1. – \exp(-f_c S))$ where f_c is fractional area covered by vertically projected vegetation, and S is the area of an individual plants shadow relative to it projected area, eg. $1/ \mu$ for sphere. Besides sun shadow, reflected radiation sees sky-shadow.

Shadow determines fraction of incident solar radiation intecepted by canopy

- For overlapping shadow, reduction of shadow area from nonoverlap requires addition of some distribution of LAI to canopy. Simplest is as a uniform layer above individual objects but other assumptions are feasible.

Combining with Underlying Surface

- Climate model does not use “albedo a” but how much radiation per unit incident sun absorbed by canopy A_c and by ground A_g.

$$A_g = (1. - f_s(1. - T_c))\ (1. - a_g)$$

$A_c = f_s\ (1 - a_c)$ + reflected by soil into canopy sky shadow (shadow overlap?)

The need for complex pfts

- Current pft modeling only works if a pft’s shadows are only cast on bare ground.
- When e.g. grass under trees, the understory canopy gets less radiation and the overstory more than provided by the single pft treatment. Single tree/bus will intercept about twice as much solar radiation as inferred from current treatment, and any understory vegetation correspondingly less.

Mitigating factors

- In closed canopies, 3-D effects relatively small
- System albedo smaller effect can be compensated by use of observational albedo
- Canopy and understory will adjust to errors in absorbed solar by sensible and long wave fluxes fluxes so may not be large differences in temperatures.

Biggest Effects Expected

- PAR in error by up to a factor of two likely to impact carbon assimilation and hence growth of dynamic vegetation
- Modeling of vertical structures (e.g., N and Vmax) in canopy only good for closed canopy.

Complex canopies

- Tree pft plus a grass pft (savanna)
- Shrub plus grass for Arctic and semiarid systems

Information Needed

- Fraction of area covered by over-story canopy
- Albedo of understory
- LAI of the canopy
- Detailed determination of canopy albedo allowing for 3-D effects
- Details of canopy geometry, esp. H/W.
- Constrain total albedo with data (MODIS).

Conclusions

- Next advance in treating vegetation is to recognize 3-D geometries where most important. Need both details of modeling and observational constraints.