Characterization of albedos of complex land surfaces from a climate model's viewpoint and how their measurement can be used to constrain structural details of the model

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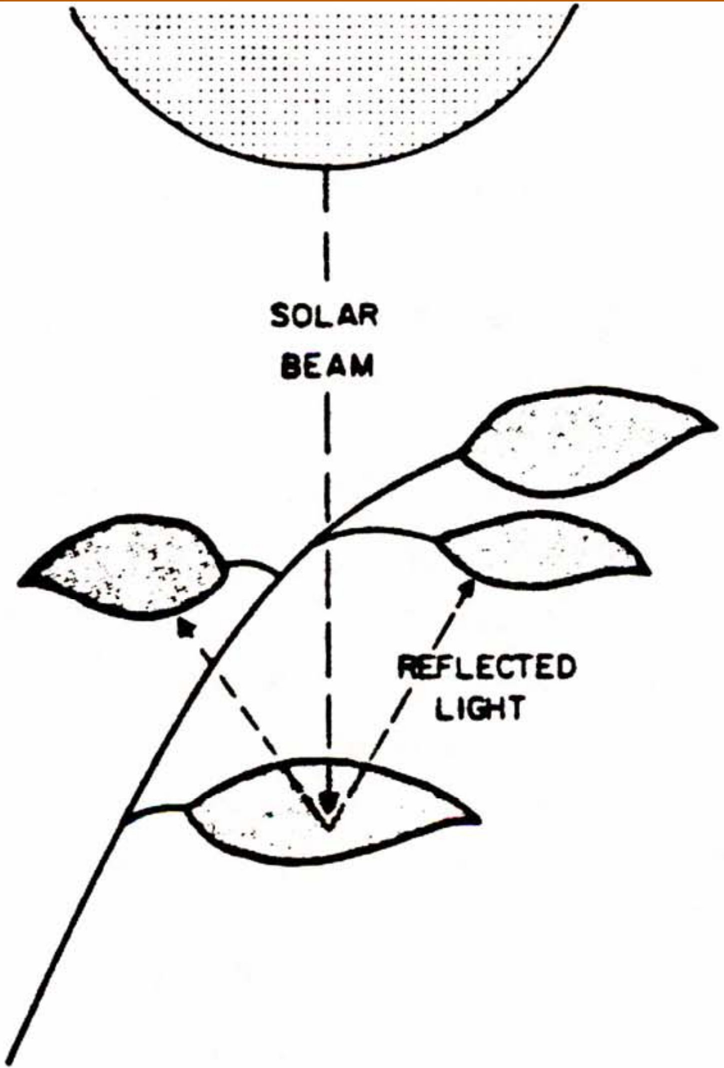
Background

- Absorption of solar radiation drives climate system exchanges of energy, moisture, and carbon.
- Early models by 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



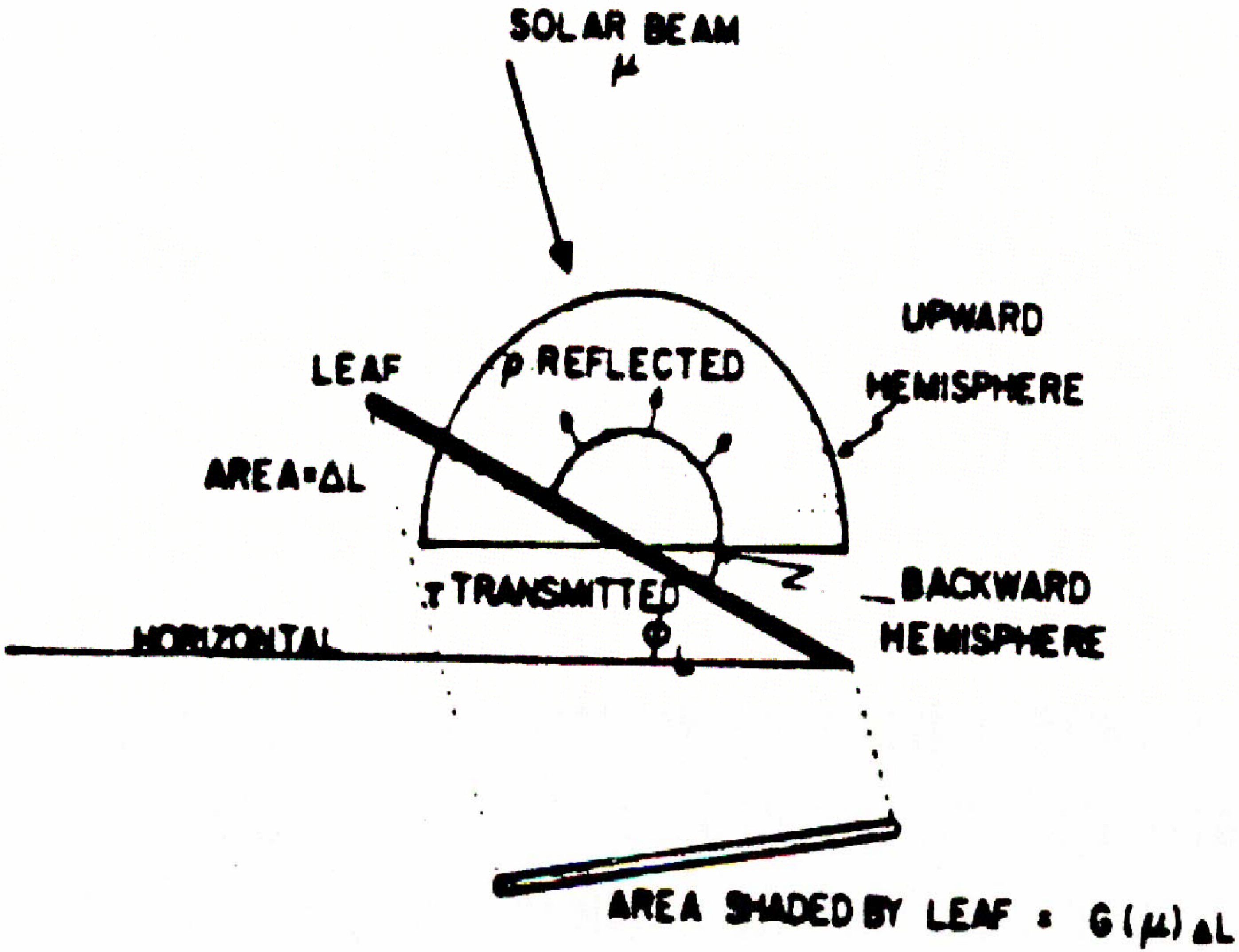
Sketch of the partial trapping of light reflected from a canopy leaf by overlying leaves.

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

Leaf Orientation (ref. Dickinson, 1983)



Sketch of the geometry of leaf scattering.

Leaf orientation geometry: sun at an angle θ_s whose cosine is μ_s and leaf oriented with normal vector θ_s, λ (i.e. zenith and azimuth) and $\mu_L = \cos \theta_s$

- Fraction of incident light intercepted per unit leaf area is :

  $\cos(\theta_s - \theta_L) = \mu_L \mu_L + \mathrm{sqrt}[(1 - \mu_L^2)(1 - \mu_L^2)]\cos \phi$
- Where the two terms cancel, cos( ) = 0, switch from sunlight to shaded leaf upward. Happens when leaf normal + sun direction > 180 deg. Integrate over ϕ to describe the contributions of sunlight and shaded. Expressions too complicated to use for integrations over leaf angle –need to approximate.
- Easy to determine upward scattering for vertically or horizontally incident sun, so weighted average over these two terms, $W = \mu_s^2$

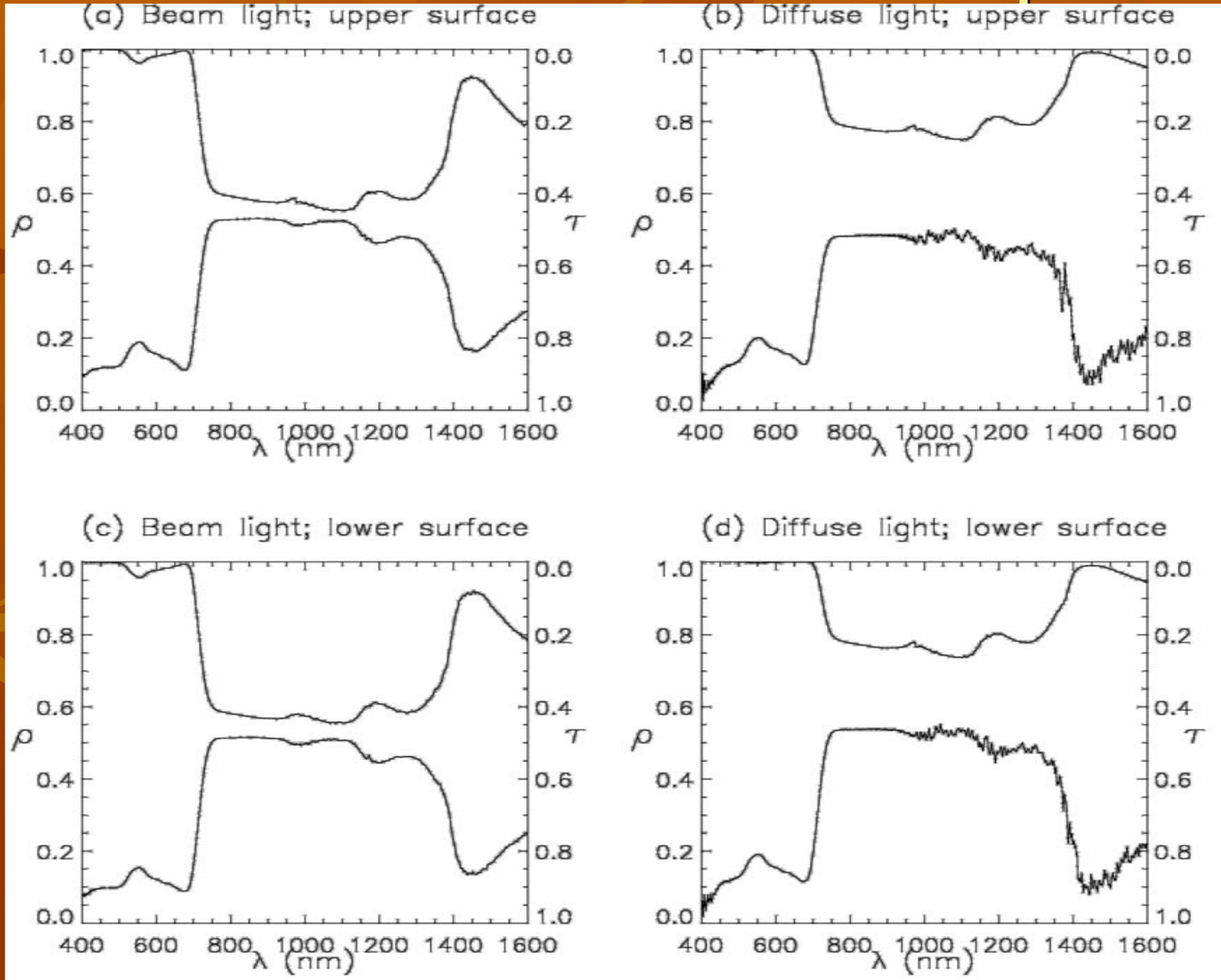
Leaf Orientation Distribution

- Numerous suggestions: easiest is to expand arbitrary orientation in even polynomials of μ_L to obtain a distribution $F(\mu_L) = w\,(1. + b\,\mu_L{}^2)$ where $w = 1/(1. + 1/3\,b)$. Set $b = 2\,a/(1-a)$, then observed orientations from $a = -1$, $b = -1$ to $a = 1$, $b = \infty$
- Overhead sun (spherical leaves r is leaf reflection and t is leaf transmission): upward scattering is $G\,[(r+t) + 2/3\,(r-t)\,\mu_L{}^2]$
- Sun on horizon sees equal area of sunlight and shaded leaves, and leads to upward scattering: $G\,[r + t]\,\mathrm{sqrt}(1. - \mu^2)$
- Integrate over leaf angle, for diffuse radiation, weight overhead sun 2/3 – get between results of Pinty and Sellers. $G\,[0.5(r+t) + 2/9\,(r-t)]$

Spectral leaf optical properties

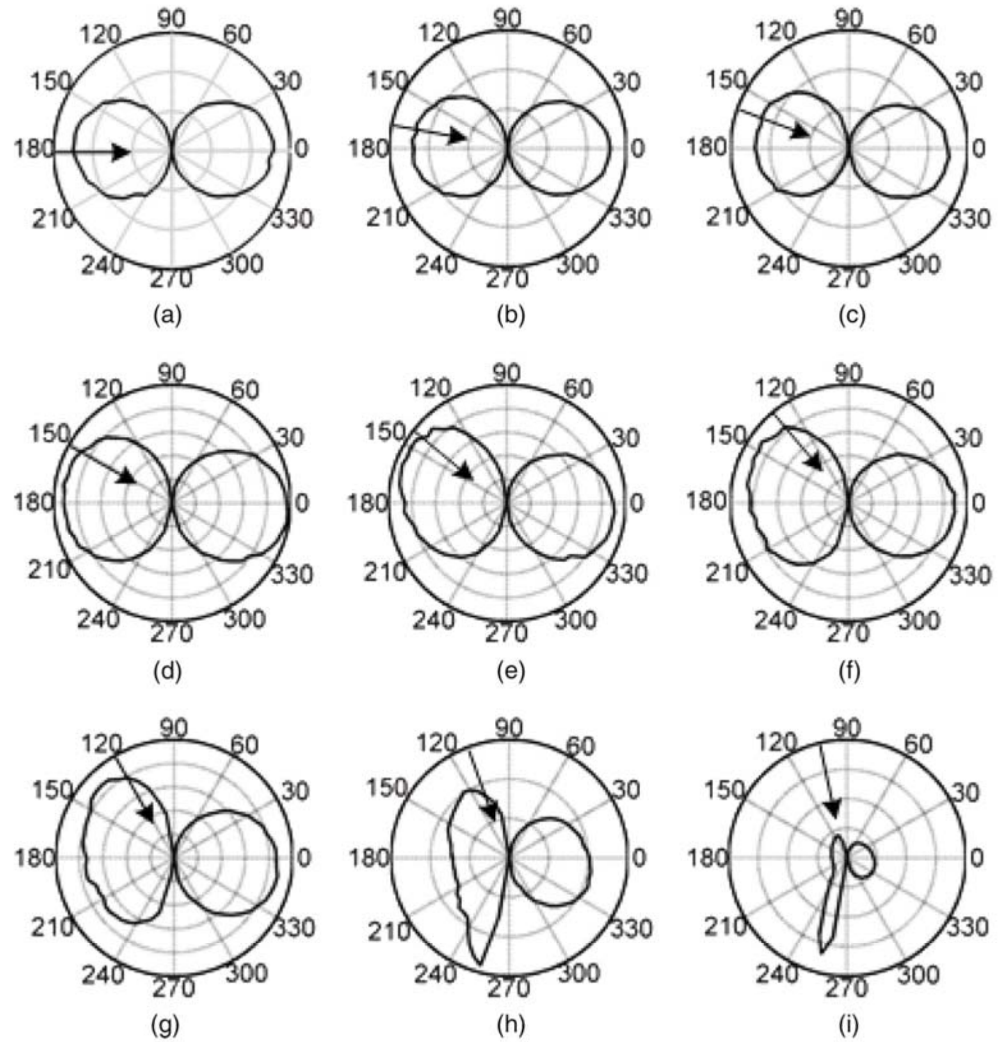
- Observations –
  - spectral dimension – r versus t, need to divide into 3 regions?
  - Scattering includes specular term with magnitude depending on structure of leaf surface.
- Models
  - Describe structure in detail use Monte-Carlo statistical simulation
  - RT through flat plates- PROSPECT model(Jacquemoud)
  - Parameterization simple enough for climate model-

Spectral properties- upper versus lower?-Hume et al technical report



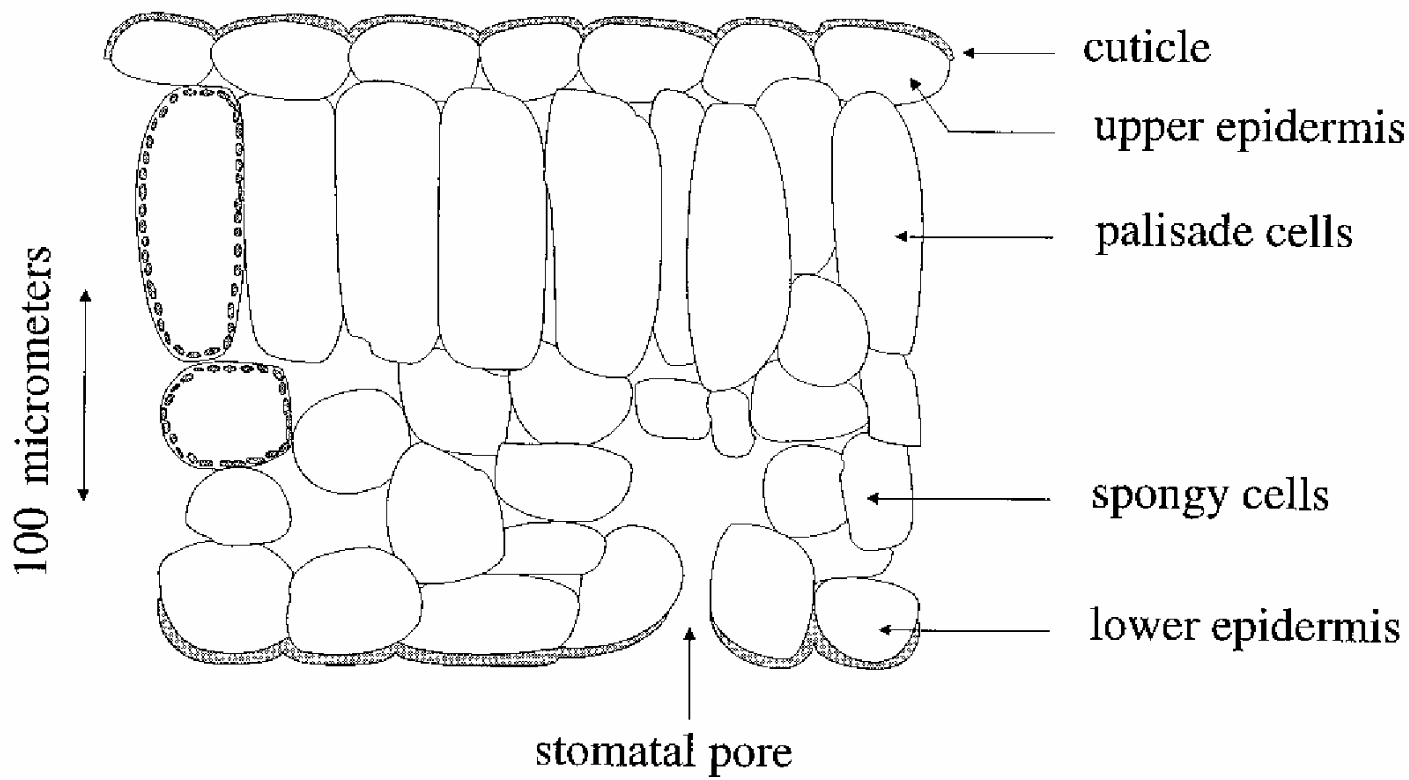
The spectral hemispherical reflectance (ρ) {lower curve} and spectral hemispherical transmittance (τ) {upper curve} of dicot leaf 1 (*E. Moorii*). (a) the upper leaf surface irradiated with beam light, (b) the upper leaf surface irradiated with diffuse light, (c) the lower leaf surface irradiated with beam light and (d) the lower leaf surface irradiated with diffuse light.

Scattering phase function – diffuse + specular (Greiner et al. , 2007)



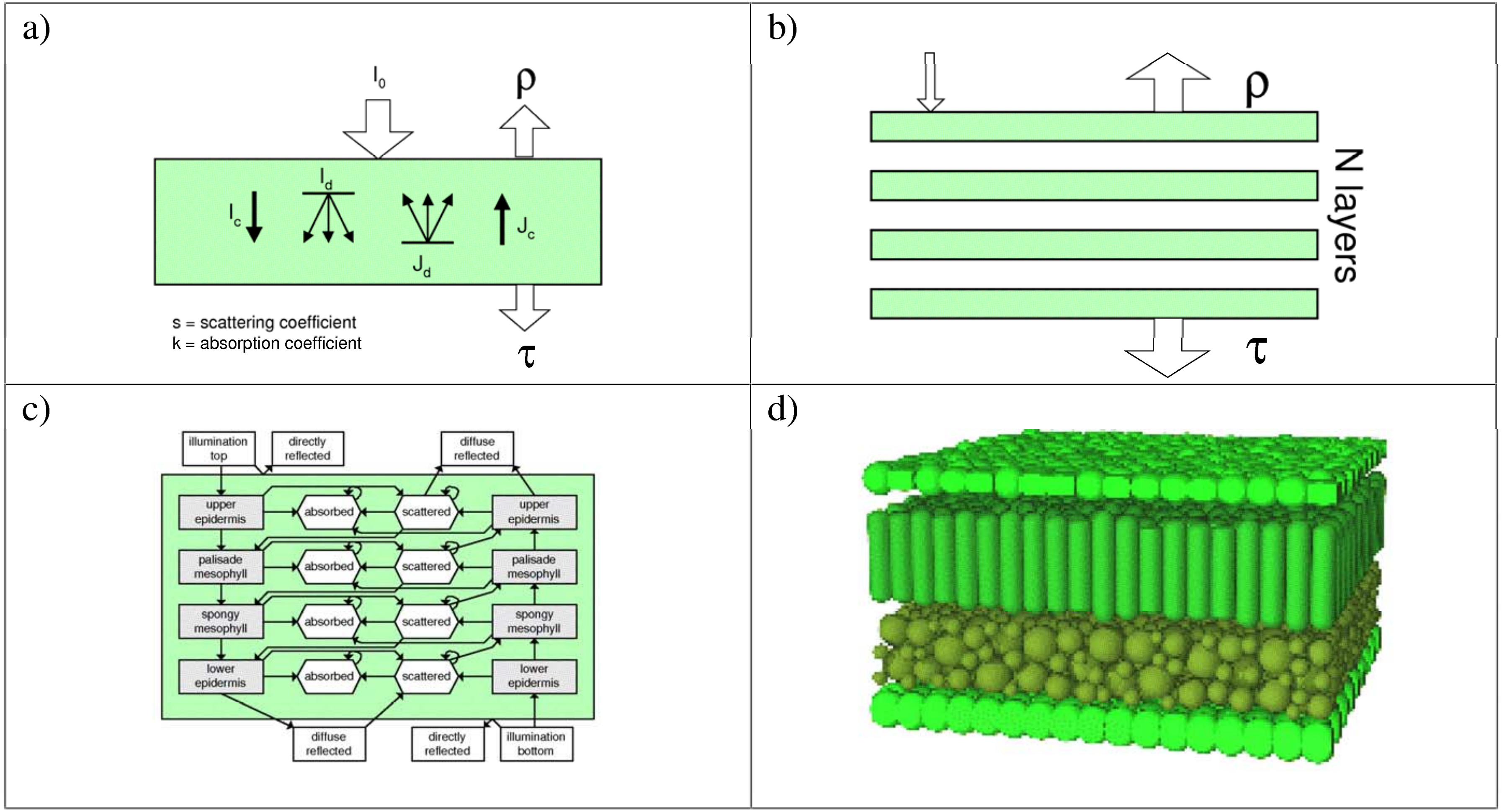
Measured BSDF data for sugar maple leaves at θ_i illumination angles of (a) 0°, (b) 10°, (c) 20°, (d) 30°, (e) 40°, (f) 50°, (g) 60°, (h) 70°, and (i) 78°.

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: $(1.- f_c) + f_c \exp (- ½ LAI/ f_c)$ versus $\exp(- ½ LAI)$
  - Both 1 – ½ LAI for small LAI, but (1.-fc) versus 0 for large LAI – non-vegetated fraction a canopy "gap"

Remote Sensing Community Ideas

- Geometry recognized as important contributor to reflected radiation
- Strahler/Li – geometric shape/shadowing effects, add numerical treatment of canopy RT (GORT).
- Quite a few simpler /more approximate approaches: e.g. GEOSAIL apparently developed for FIFE –idea is to use plane parallel RT model over sunlight canopy, and add in reflectance's from sunlight background, and shaded canopy and background.

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 = $\int_0^1 dx\, D(x) \exp(-\frac{1}{2} x\, LAX_{max})$. 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

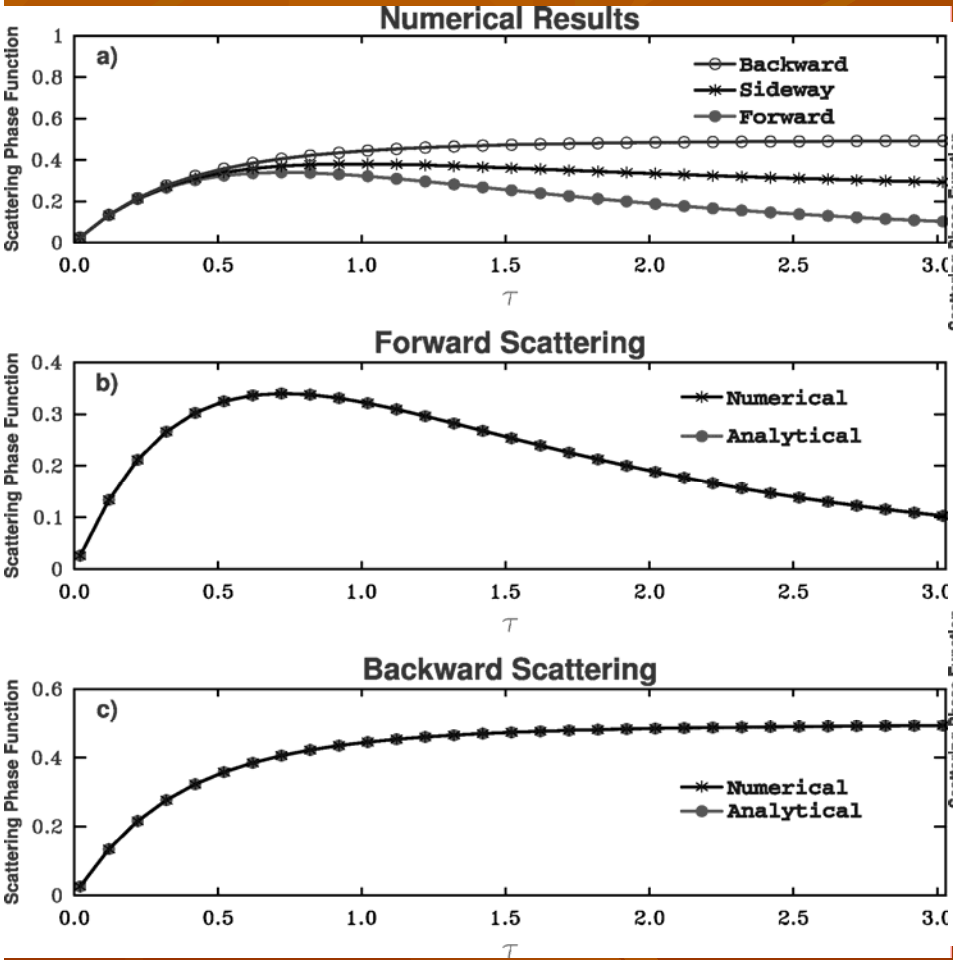
$$T = 2 \int r dr \exp\left(- \tfrac{1}{2} LAI(r) \right).$$

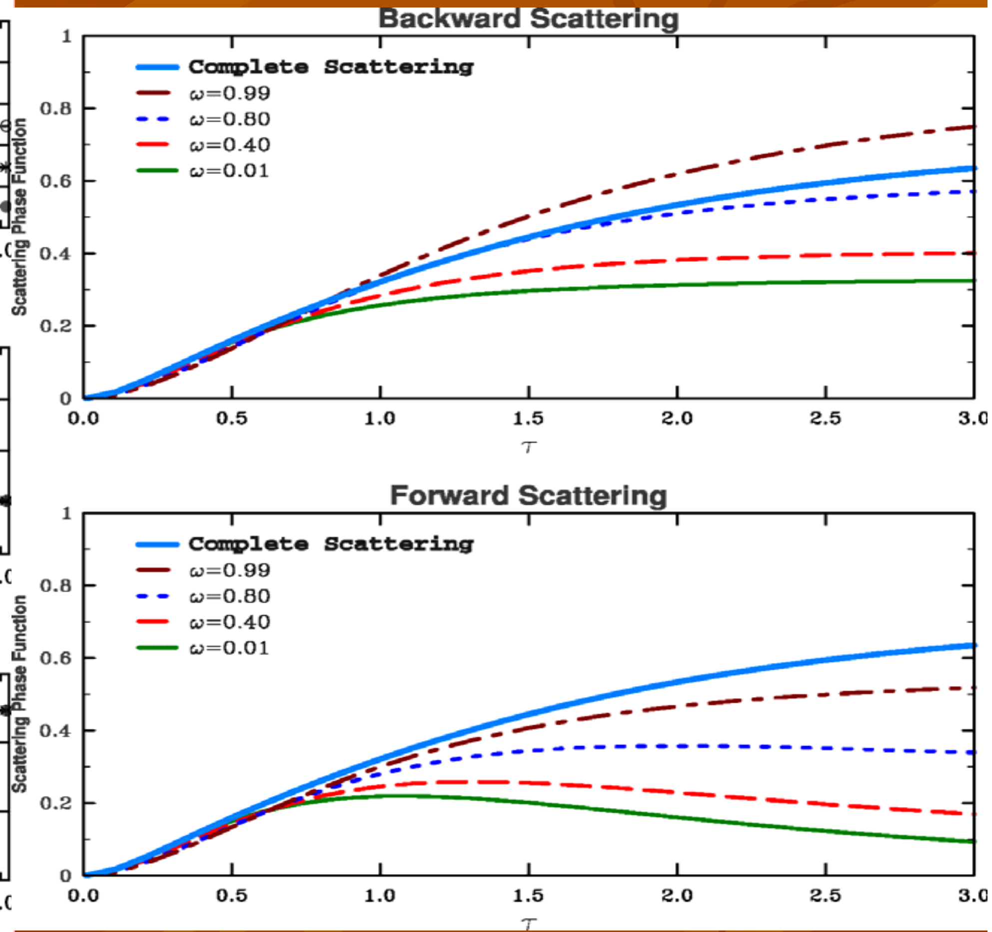
- $LAI = LAI_{max} f(x)$, where $x = (1.-r^2)$, $f(x) = x^{\nu}$ $0 \leq \nu \leq 1$, $\nu = \tfrac{1}{2}$ or 1 gives half-sphere or rotated parabola.

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 $\omega/(4\pi)$

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/ μ 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?)

Conclusions

- Climate model radiation needs to be improved by making it more realistic in several aspects:
  - Recognize spatial distribution of LAI – constrained by current satellite data
  - Consequent 3-D effects on how much solar is absorbed – need good descriptions of shadowing and 3D RT.
  - Leaf orientation contributions
  - Variability of leaf optical properties in near-IR?