REPRESENTING INTERACTIONS BETWEEN SOLAR RADIATION AND EARTH'S SURFACE IN LARGE-SCALE MODELS

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Frascati, Italy

Our road map

- Today (10.00- 11.00):

  Context: **Science issues and caveats, challenges to face.**

- Today (12.30- 13.30):

  Tools: **Doing the right thing!**

- Tomorrow (10.00- 11.00):

  Applications: **Partitioning of Solar fluxes in Land Surface Canopies based on operational ESA and NASA products**

Key issues: topic for next hour

- Are the radiative fluxes and state variables retrieved from remote sensing useful for Climate and/or NWP models?

  2 RT fluxes: albedo, FAPAR

  1 state variable: LAI.

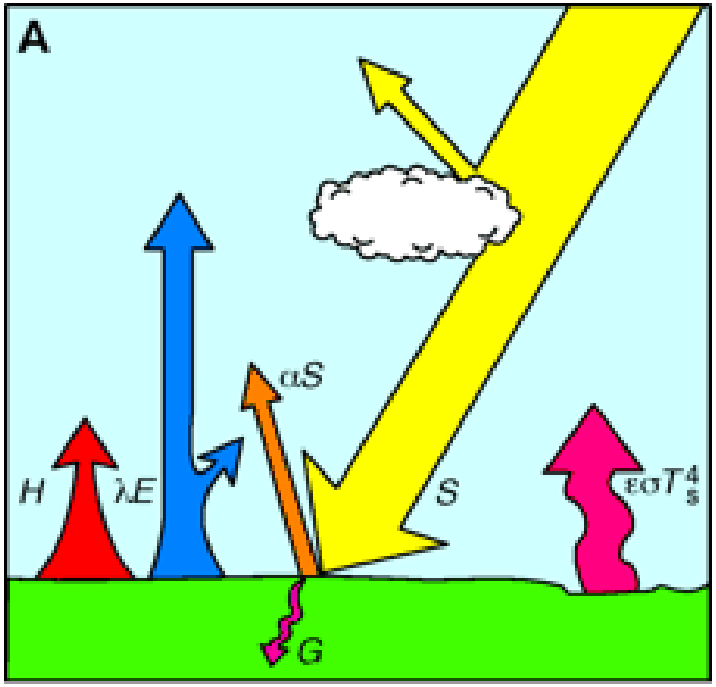
  Series of proxies e.g., Land cover, % tree cover

- How Climate/NWP models can (must) adapt themselves to this ‘new’ situation where accurate global land products are available?

  Adjusting (improving) their RT surface shemes

GEOPHYSICAL CONTEXT

How does radiation redistribute energy between the atmosphere and the biosphere?



Surface radiation budget

- The "surface" corresponds to the boundary condition of RT atmospheric problem

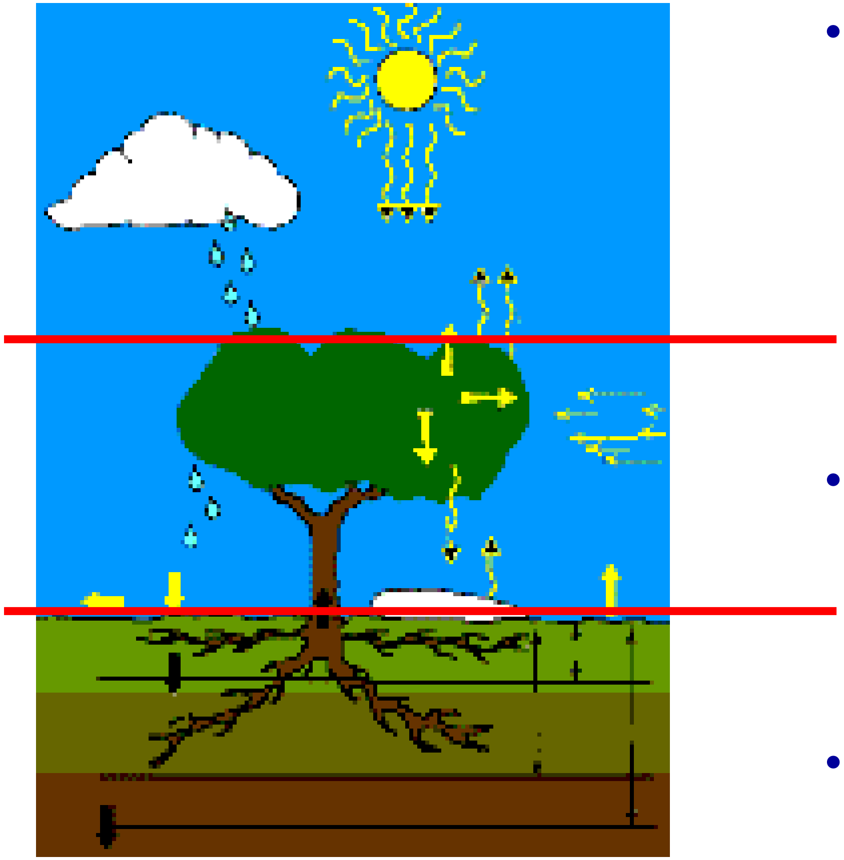
  Need to understand and represent the albedo of that "surface".

- The energy absorbed below that "surface" controls the sensible and latent heat fluxes to the PBL

- The processes underpinning the heat fluxes are generally represented explicitly or parameterized in SVAT models

Ref: Sellers et al. (1997) Science, 275, 502-509

Energy partitioning between the vegetation and the soil layer



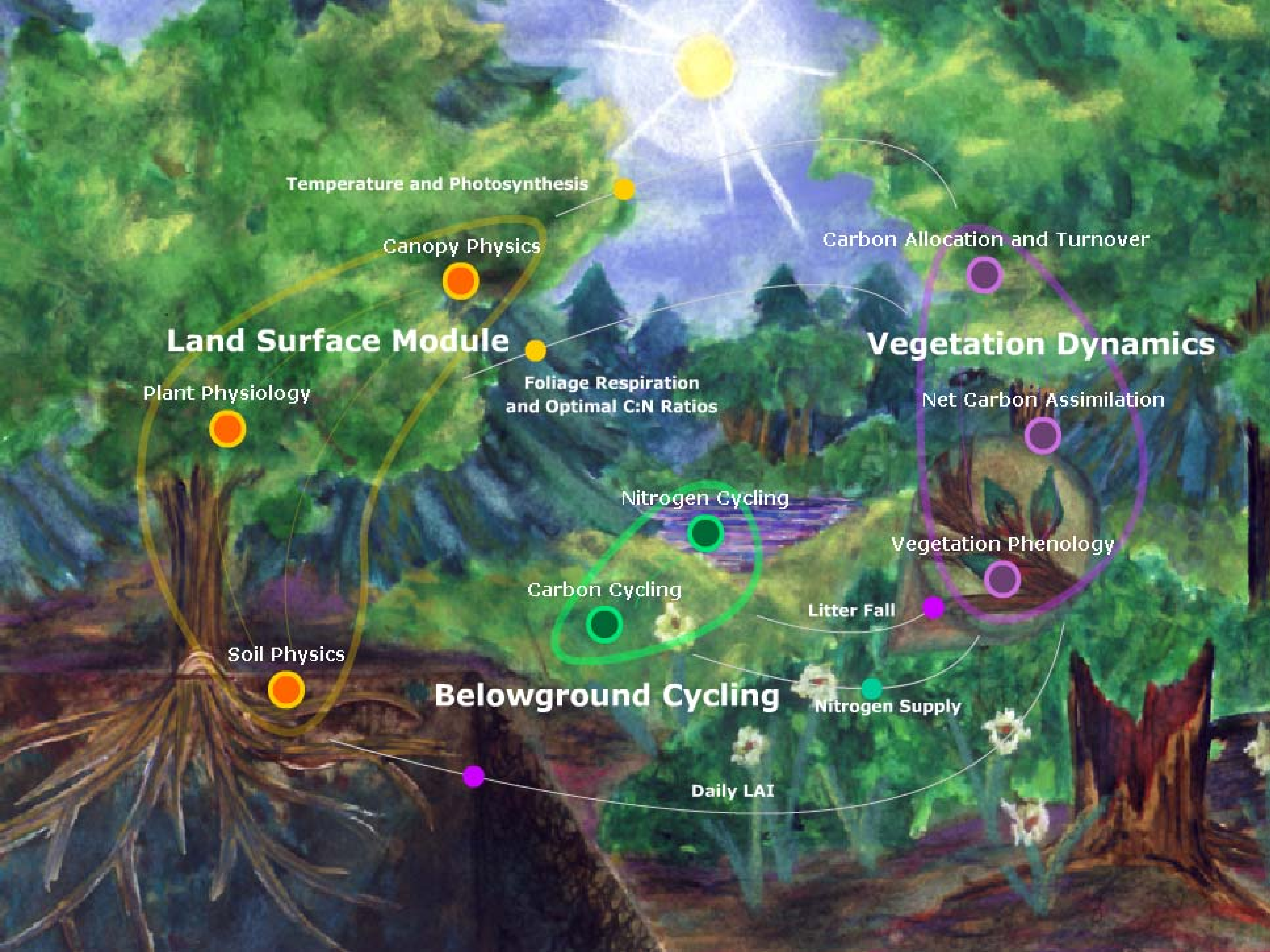
- The “surface” corresponds to the upper boundary condition of the vegetation plus soil RT and other problems

  Need to understand and represent the RT processes yielding the distribution of energy below that “surface”, e.g., transmitted fluxes.

- The remaining energy in the soil “layer” is used to solve the heat conduction equation and soil hydrology, e.g., snow melting, evaporation.

- The energy left into the vegetation “layer” is used to drive the water, e.g., evapotranspiration, and the carbon cycle, e.g., NPP, NEP,..

Ref: Bonan, G. B. (2002) Cambridge Univ. Press


Temperature and Photosynthesis
Canopy Physics
Carbon Allocation and Turnover
Land Surface Module
Vegetation Dynamics
Foliage Respiration
and Optimal C:N Ratios
Plant Physiology
Net Carbon Assimilation
Nitrogen Cycling
Vegetation Phenology
Carbon Cycling
Litter Fall
Soil Physics
Belowground Cycling
Nitrogen Supply
Daily LAI

The Role of Radiation and Other Renascent Subfields in Atmospheric Science

W. J. Wiscombe[1] and
V. Ramanathan[2]

Ref: (1985) Bull. A. Met. Soc.

Abstract

The horizons of atmospheric science are undergoing a considerable expansion as a result of intense interest in problems of climate. This has caused somewhat of a renaissance in hitherto-neglected subfields of atmospheric science. Focusing on atmospheric radiation as the renascent subfield of most direct concern to us, we describe the exciting research and educational challenges that lie ahead in this subfield, and offer possible ways in which these challenges might be met.

1. Introduction

Atmospheric science today stands on the brink of a metamorphosis as profound as the one that transformed it in the 1920s and 1930s. From a science focused almost exclusively on midlatitude dynamics, with the primary goal being short-term weather prediction, it is undergoing a quantum leap in perspective. That leap is largely being propelled by subfields outside of the former mainstream: atmospheric radiation, atmospheric chemistry, cloud and aerosol physics, and micrometeorology, among others. As a result, atmospheric science is beginning to re-embrace those subfields after almost a half-century of intense focus on the midlatitude dynamics subfield.

There was, of course, ample reason for that dynamical focus, stemming both from the history of meteorology and from the kind of researchers that were attracted to it. Modern meteorology really began, after all, with the realization that midlatitude weather systems moved in potentially predictable ways. The two world wars brought into weather forecasting a flood of bright mathematicians and physicists, both in Europe and the United States. Not only were the problems they faced primarily dynamical in character, but their natural predispositions were mathematical. Midlatitude dynamics offered many knotty and challenging mathematical problems, which they set upon with great relish.

Much really good and useful research is still being done in midlatitude dynamical modeling and forecasting (viz. the impressive amount of work addressing the First Global GARP

- ozone depletions,
- greenhouse effects,
- unpredicted extremes of temperature and precipitation (including Sahelian and Midwest droughts),
- aerosol impacts, volcanic and man-made (most recently: El Chichón and "nuclear winter"),
- sea-surface temperature (SST) anomalies and El Niño,
- cloud-climate interactions,
- acid rain,

and so on. Many of these problems were first identified and studied by scientists working outside of the traditional meteorology discipline. That is undoubtedly because climate is a much broader subject, drawing as it does upon diverse branches of physics, chemistry, biology, and engineering. Climate forcings are usually *radiative and thermodynamic* in nature, and the response is usually *global* rather than being confined to a particular latitude zone.

Robert Dickinson of NCAR has aptly summed up the new situation (Dickinson, 1983):

> There has been a renaissance in climate studies over the last decade. Scientists in the different disciplines concerned with the climate system have grown increasingly appreciative of the connections between the various components of the climate system, and of the hazards of overly narrow viewpoints.

Dickinson goes on to explain the genesis of these "overly narrow viewpoints":

> The large-scale motions of the atmosphere, and their role in transport and energy conversions, have been the primary climate variables of concern to dynamic meteorologists. In the past, everything else occurring in the atmosphere, e.g., radiation, clouds, small-scale turbulence, and rainfall, were lumped together as "physics" and *considerable intellectual effort was devoted to showing these terms were less important than the dynamics of motions* . . . [italics ours]

WHERE DO WE STAND ?

1. GCMs REPRESENTIONS
2. INPUT PRODUCTS FROM EO

Two broad classes of GCMs for representing "Surface" radiation fluxes

Class 1:

Set of surface parameters tied to a land cover map:

Option: "surface" albedo and Leaf Area Index (LAI) can be assigned separately.

Class 2:

1-D/2-stream RT scheme to represent the radiation transfer processes as a function of Leaf Area Index (LAI) and other parameters tied to a land cover map

Class 2 : This is the way!

- Possibility to generate internally consistent radiation, water and carbon fluxes – from diagnostic to prognostic variables

  e.g., if model has something called "trees" which in the model are required to absorb solar radiation as a driver, it should be contributing to determination of albedo as well.

- Still depends on Land cover information:

  Some vegetation and soil properties may have to be assigned.

- Possibility to account for processes related to 3-D vegetation structural effects :

  3-D effects are significant contributors to radiation (short term climate), heat, water and carbon cycles (long term climate).

3-D structural effects and short term climate: the snow case with ECMWF/NCEP

Ref: Viterbo and Betts, 1999, JGR

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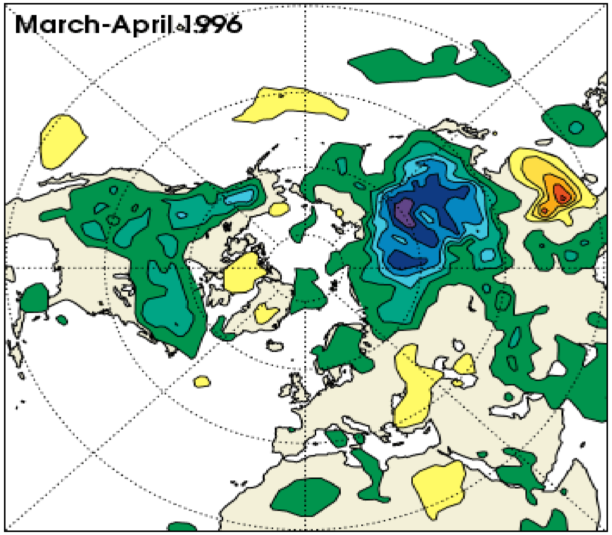
Everyone Complains About the Weather...

Betts and his BOREAS colleagues observed that, in the spring, daily weather forecasts significantly underestimated air temperatures over the boreal forest, sometimes by as much as 10—15°C (18—27°F) (Viterbo and Betts, 1999). Additionally, the BOREAS team found that predictions of cloud cover over the boreal region were often far off the mark. Everyone complains about the weather, but how could the forecasts be so wrong so often?



This map shows the average errors in the European Centre for Medium-Range Weather Forecasts at 850mb (roughly equivalent to an altitude of 1500m) for March and April of 1996. The predictions, made five days in advance, were compared to actual measurements. The 1996 model did not include the adjustments to forest albedo.

(Figure from Viterbo, P. and A.K. Betts, 1999: The impact on ECMWF forecasts of changes to the albedo of the boreal forests in the presence of snow. J. Geophys. Res. (In press, BOREAS special issue). Courtesy A.K. Betts)

Forecast Errors (°C)

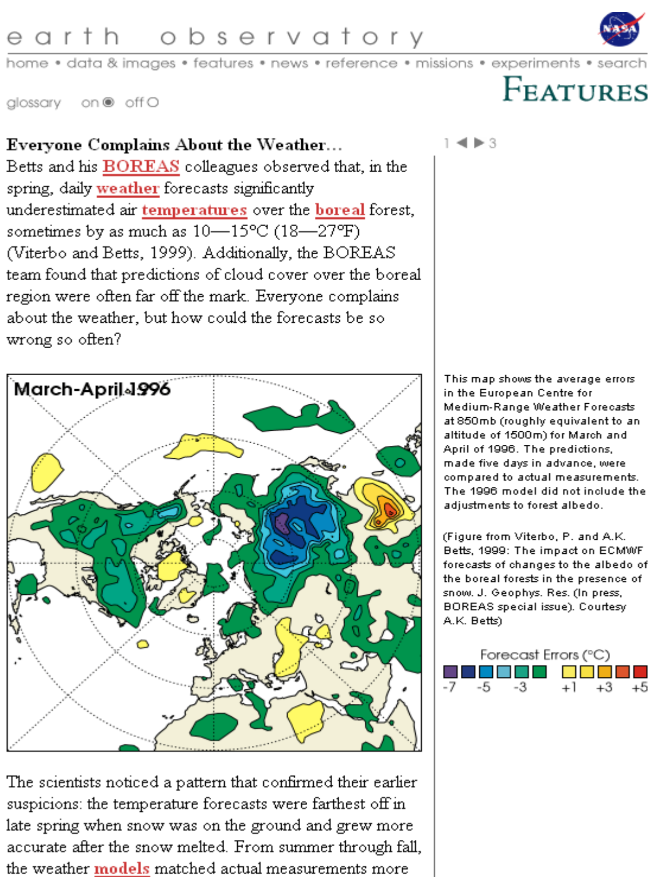
-7 -5 -3 +1 +3 +5

The scientists noticed a pattern that confirmed their earlier suspicions: the temperature forecasts were farthest off in late spring when snow was on the ground and grew more accurate after the snow melted. From summer through fall, the weather models matched actual measurements more

"...weather forecasts significantly underestimated air temperatures over boreal, sometimes by as much as 10-15 C..."

Ref: http://eobglossary.gsfc.nasa.gov/

3-D structural effects and short term climate: the snow case with ECMWF/NCEP



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"...—the BOREAS team found that the models were overestimating **albedo** (the amount of **light** reflected by the surface). ..."

Ref: Viterbo and Betts, 1999, JGR

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Two broad classes of EO products for representing solar RT processes in GCMs

Category A :

Set of radiation fluxes and state variables of the RT problems

Category B:

Set of surface indicators mostly related or derived from land cover maps

Examples of "Relevant" RS products (Category B) for RT processes in GCMs

- Land cover maps – based on "decision tree logic" and "fuzzy knowledge" like old climatology when clouds were classified from their shape, appearance..

  Global product available from MERIS & MODIS and other "historical initiatives" such as IGBP.

- Indicator of 3-D vegetation structural effects – based on angular contrast

  Global products available from MISR.

NB: They can serve as proxy to assess quantitative information

“Relevant” RS products for RT processes in GCMs

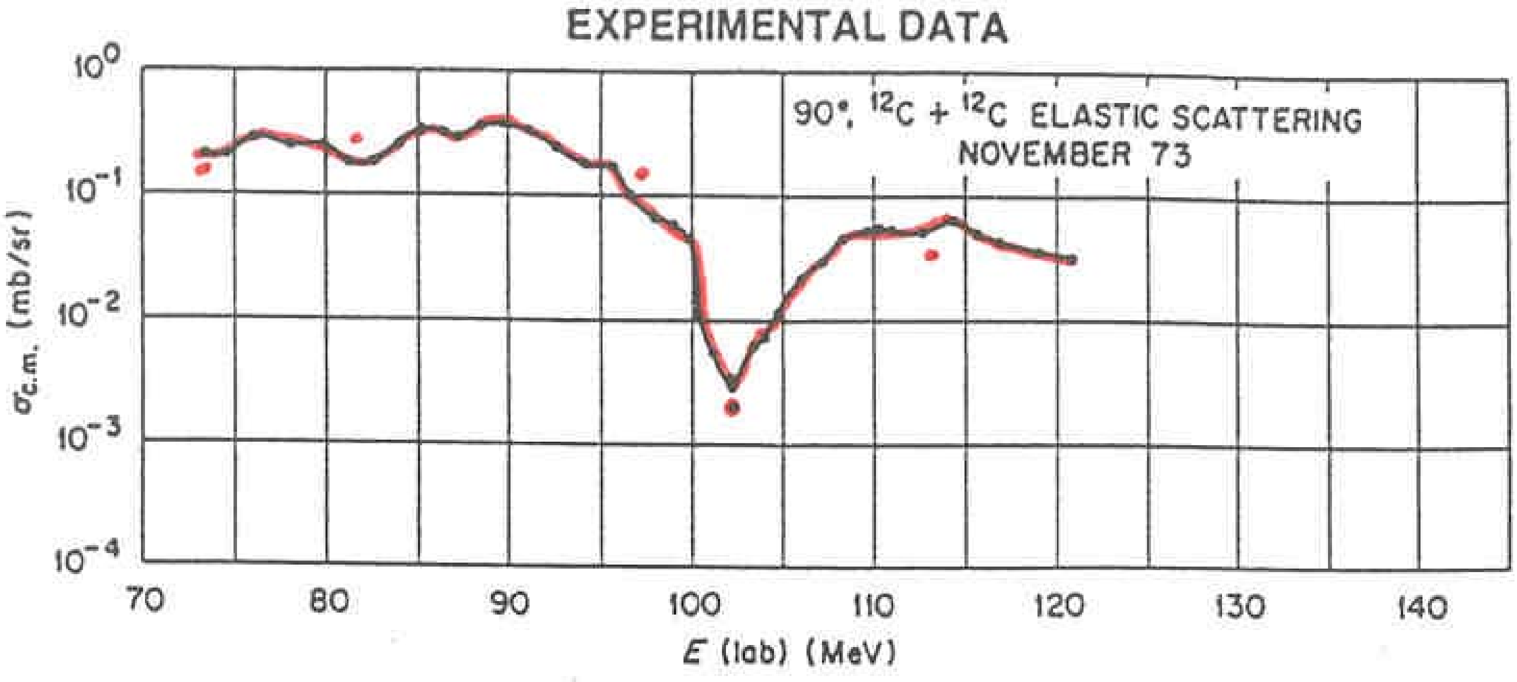
- Surface albedo – requires solving a BC problem
  Global products available from MODIS, MISR, MERIS and others such as geostationary satellites.

- Absorbed flux in the visible part (FAPAR) – based on a balance equation at the spatial resolution of the retrieval
  Global products available from MODIS, MISR, MERIS and others such as SeaWiFS.

- Leaf Area Index (LAI) – based on solutions of a 3-D inverse problem at the spatial resolution of the retrieval
  Global products available from MODIS and MISR

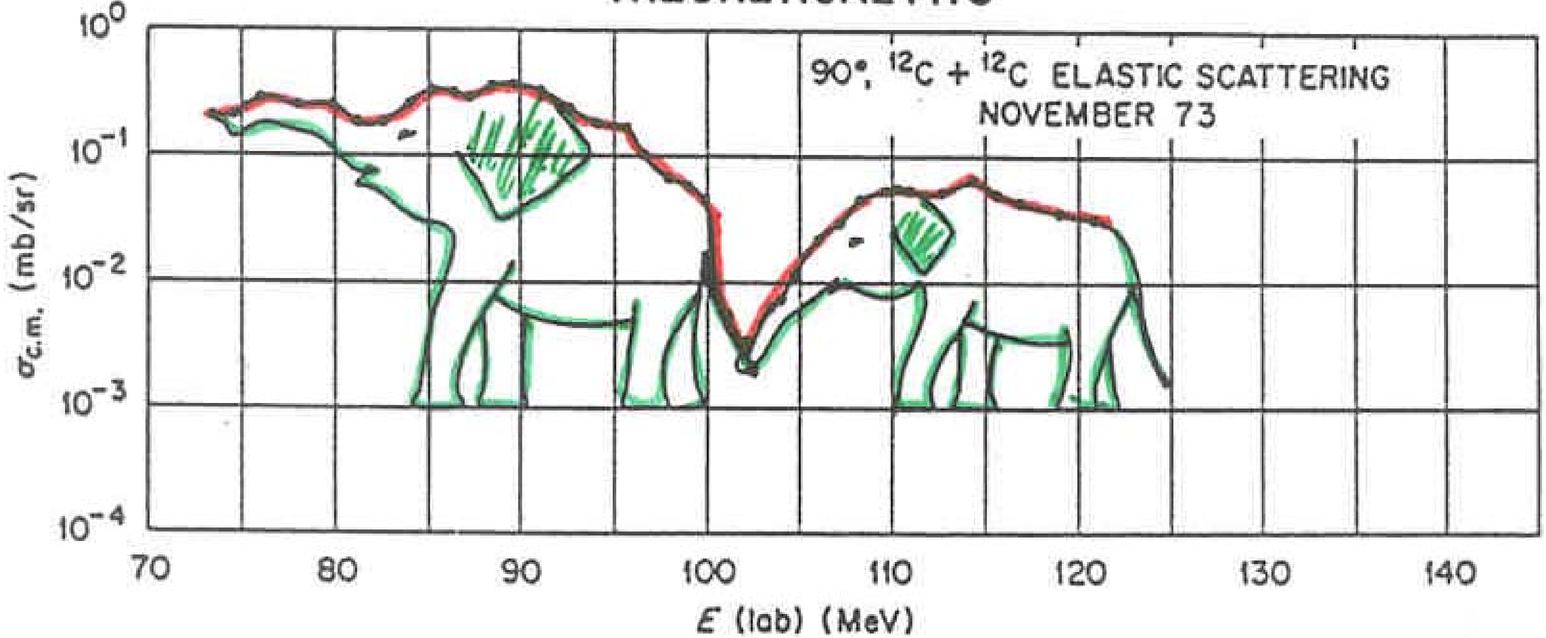
PHYSICAL QUANTITIES ABOUT VEGETATION LAYERS ARE OBTAINED BY SOLVING AN INVERSE PROBLEM

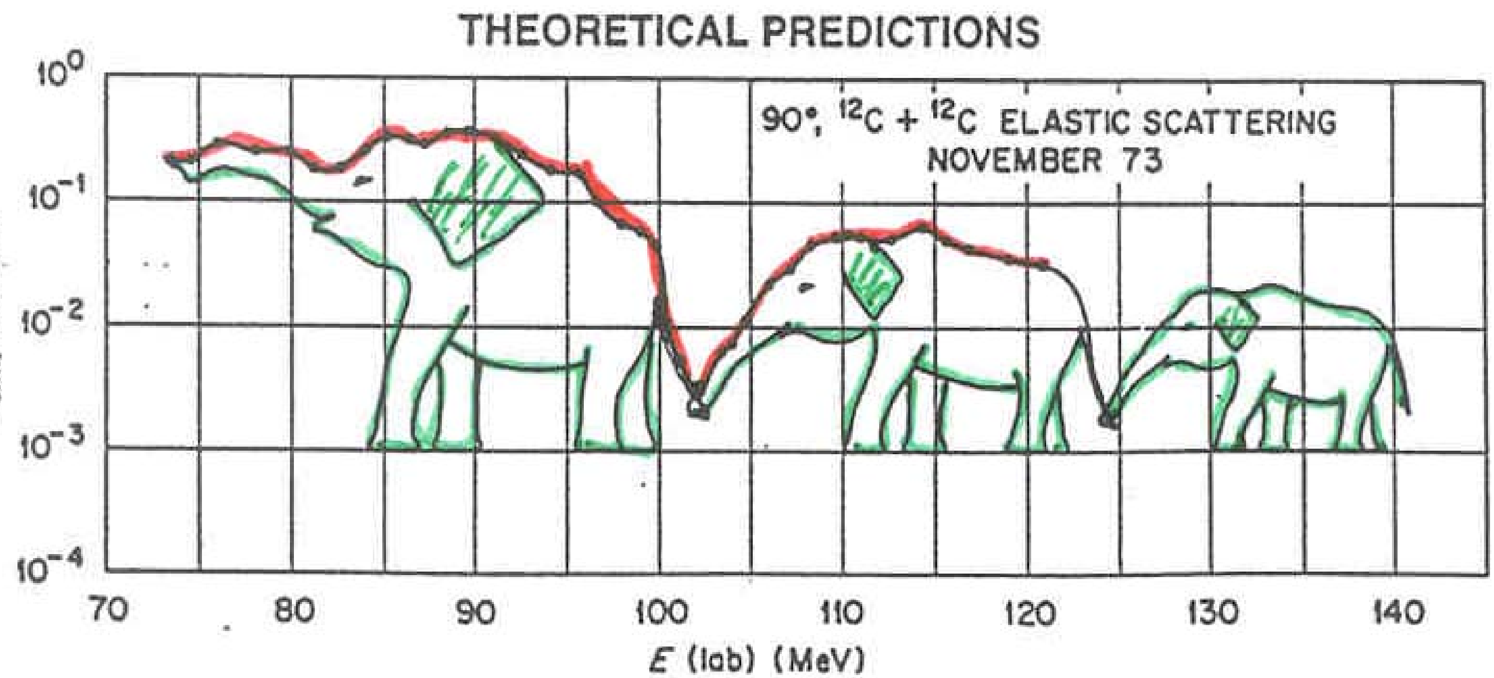
Association of physical measurements and models representing the biosphere



The process of fitting data, adapted from Subramanian R. in *Science with a Smile*.

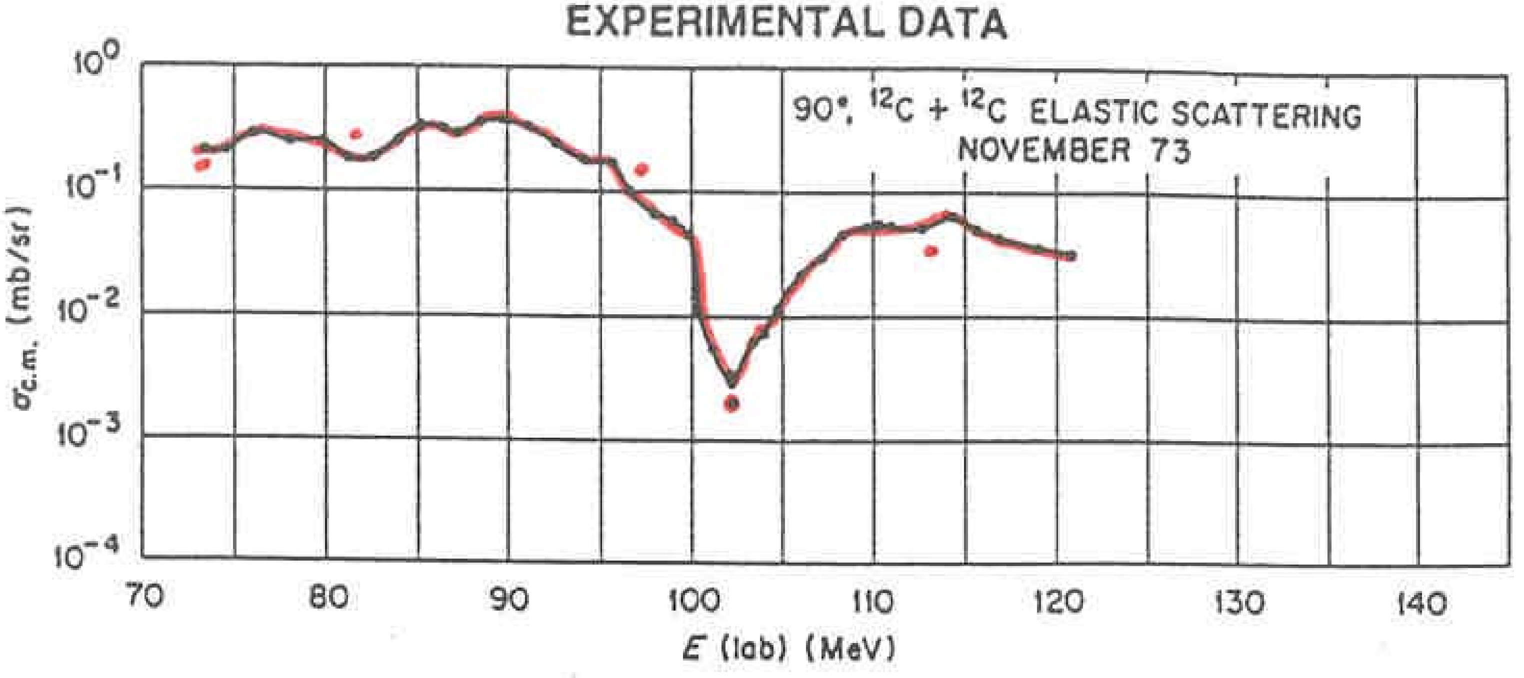
THEORETICAL FITS





THEORETICAL PREDICTIONS
90°, ¹²C + ¹²C ELASTIC SCATTERING
NOVEMBER 73
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\sigma_{c.m.}$ (mb/sr)
70
80
90
100
110
120
130
140
E (lab) (MeV)

Association of physical measurements and models representing the biosphere



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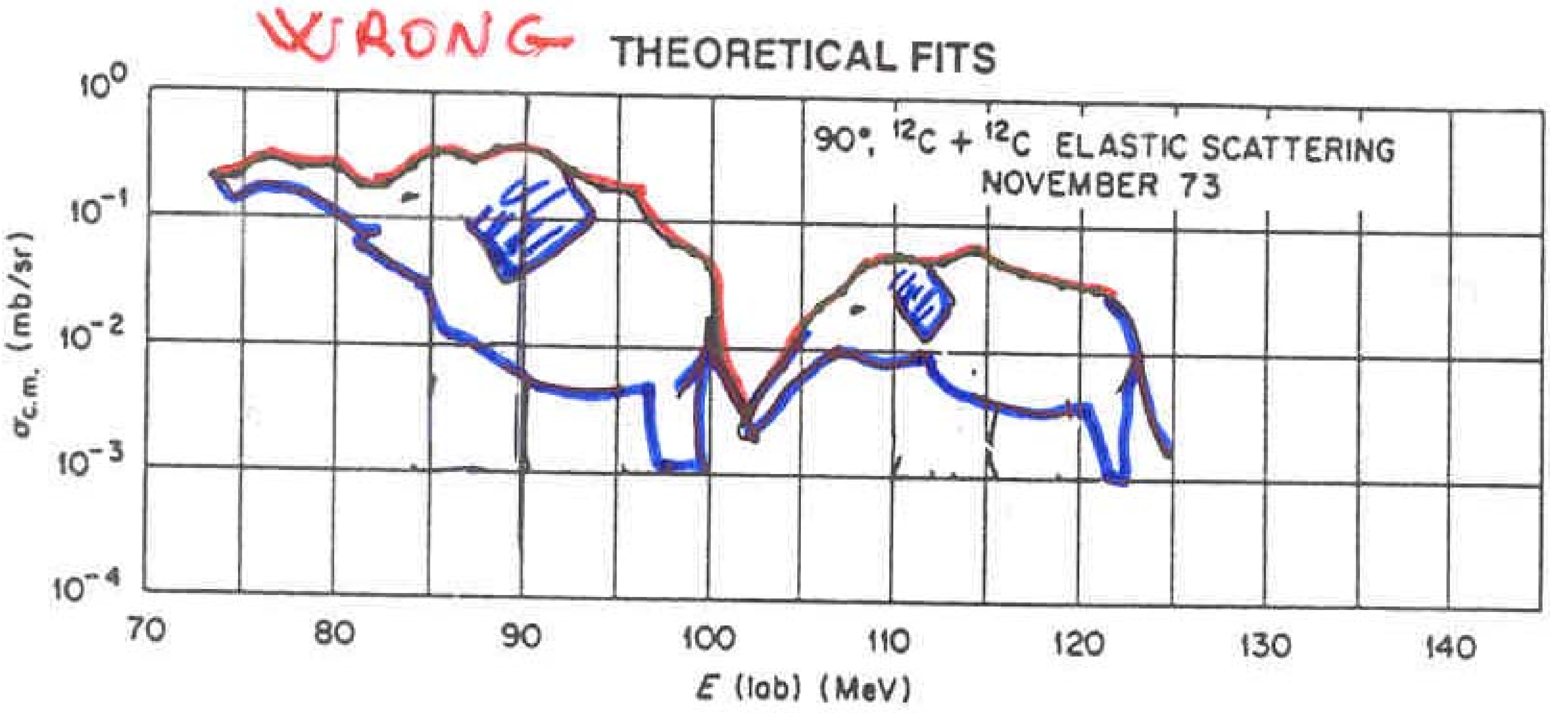
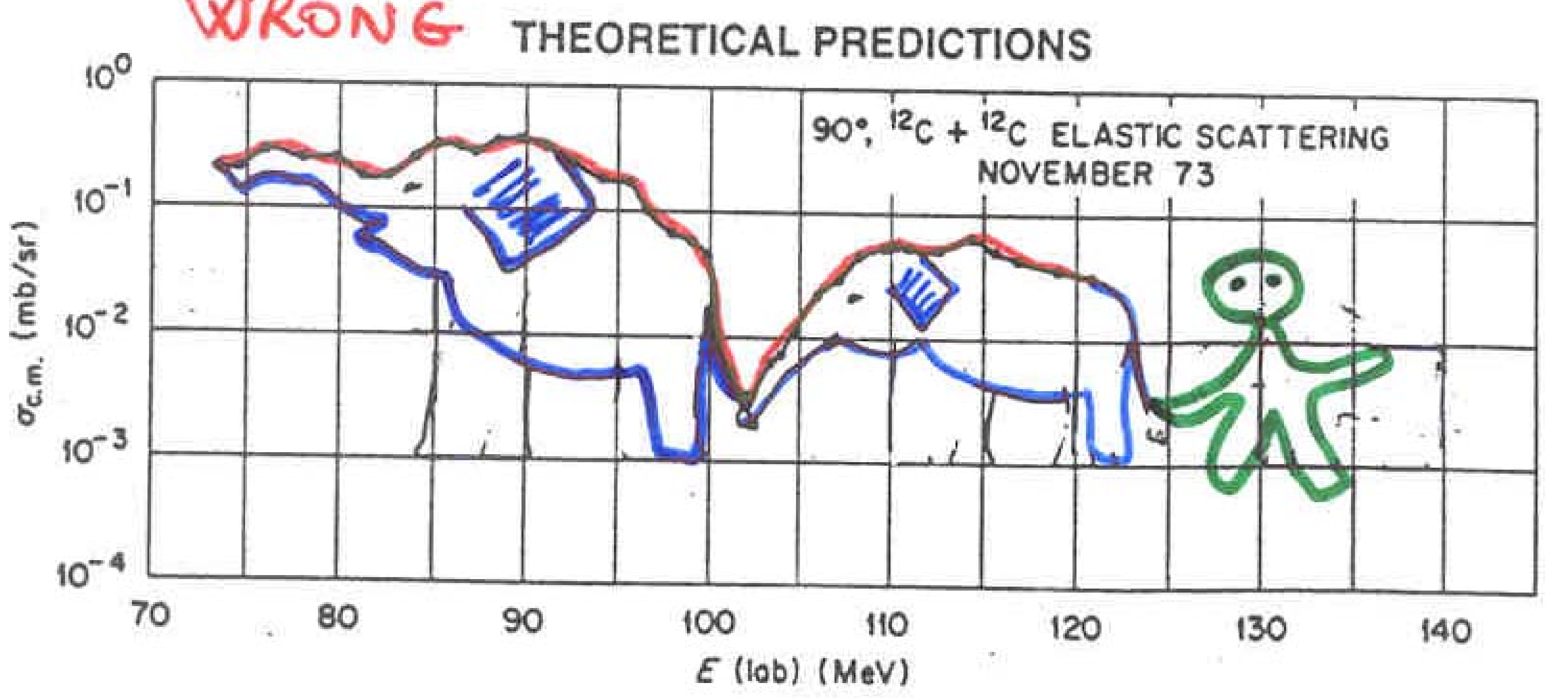

WRONG THEORETICAL FITS
90°, ¹²C + ¹²C ELASTIC SCATTERING
NOVEMBER 73
σc.m. (mb/sr)
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
70
80
90
100
110
120
130
140
E (lab) (MeV)


WRONG
THEORETICAL PREDICTIONS
90°, $^{12}C + ^{12}C$ ELASTIC SCATTERING
NOVEMBER 73
$\sigma_{c.m.}$ (mb/sr)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
70
80
90
100
110
120
130
140
E (lab) (MeV)

Challenges for the EO Land community

- 4 identified ECVs namely Albedo, FAPAR, LAI and ultimately Land Cover are linked via radiation and phenological processes:

  They MUST be retrieved consistently and then specified in the same manner in host models

- Multiple datasets of these ECVs are available from different institutions:

  They MUST be analyzed and exploited to establish a coherent set of information across platforms and institutions.

Adequacy of EO products for further assimilation by Climate/NWP models

- Are they consistent between themselves?
- Are they delivered with documented uncertainty?
- Are they accurate enough so that the models can benefit?
- Do they fit large-scale model's expectations?
- Do Climate/NWP models use the appropriate modeling tools to represent the available products?

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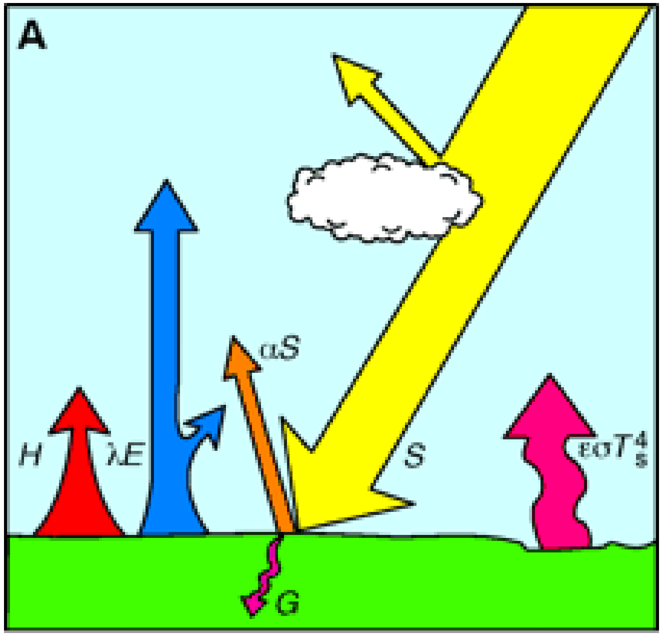
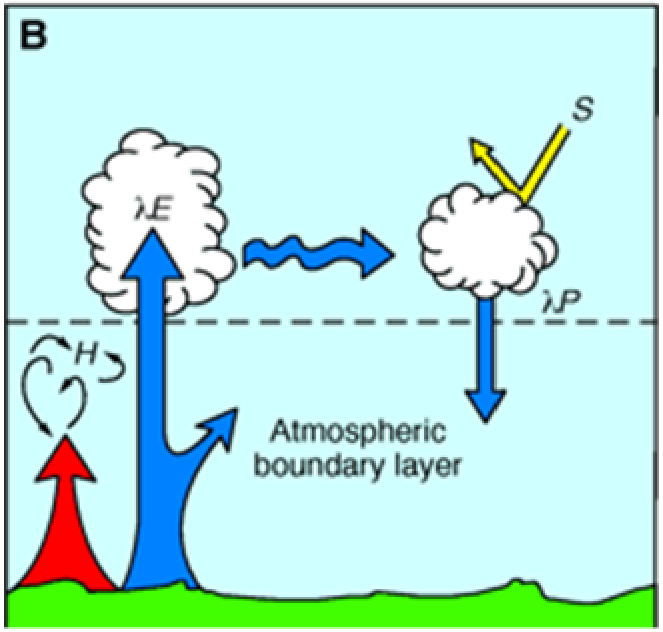
Land-Atmosphere coupling



Surface radiation budget



Atmospheric heat fluxes

$$E^{\uparrow}(z_0, \Omega_0) = \alpha(z_0) E^{\downarrow tot}(z_0, \Omega_0)$$

Albedo is mostly required for estimating how much radiation is absorbed in the land surface system

Ref: Sellers et al. (1997) Science, 275, 502-509

Needs of Atmospheric Models with respect to Surface albedo products

To represent the ratios of upward to downward radiant fluxes, i.e., Albedo, integrated over some spectral domains, e.g., [0.3-0.7] and [0.7-3.0] :

- For any given Sun position that is, any model grid cell at any time of the day and season

- For any arbitrary state and composition of the overlying atmosphere that is, any particular irradiance field resulting from the distribution of clouds and aerosols generated by the model

Case of a black-surface : the trivial coupling problem

$$I^{\uparrow}(z_{top}, \Omega_0, \Omega; \tau_a, \vec{p}_a)$$

$$I^{\downarrow}(z_{top}, \Omega') = I_0 \delta(\Omega' - \Omega_0)$$

z_{top}

Atmosphere

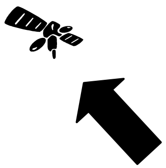
$$I^{\downarrow tot}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a) = I^{\downarrow dir}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a) + I_B^{\downarrow diff}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a)$$

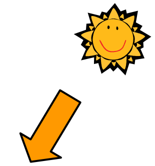
z_0

$$I^{\uparrow}(z_0, \Omega_0, \Omega; \tau_a, \vec{p}_a) = 0$$

All quantities are monochromatic

Land-atmosphere coupling problem





$$I^{\uparrow}(z_{top}, \Omega_0, \Omega; \tau_a, \vec{p}_a, \gamma_s, \vec{p}_s) \qquad I^{\downarrow}(z_{top}, \Omega') = I_0 \delta(\Omega' - \Omega_0)$$

Z_{top}

Atmosphere

$$I^{\downarrow tot}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a, \gamma_s, \vec{p}_s) = I^{\downarrow dir}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a)$$
$$+ I_B^{\downarrow diff}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a)$$
$$+ I_{ms}^{\downarrow diff}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a, \gamma_s, \vec{p}_s)$$

Z_0

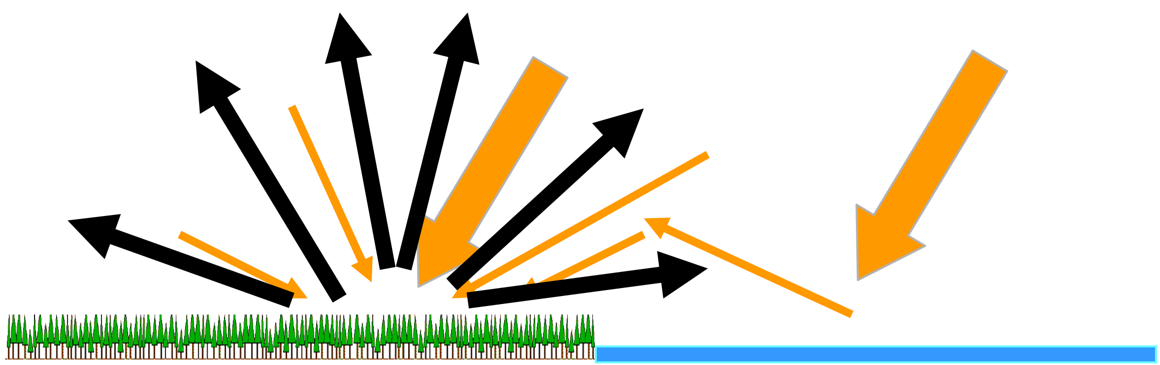
$$I^{\uparrow}(z_0, \Omega_0, \Omega; \tau_a, \vec{p}_a, \gamma_s, \vec{p}_s) = \frac{1}{\Pi}$$
$$\int_{2\Pi^-} \gamma_s(z_0, \Omega' \rightarrow \Omega; \vec{p}_s) . I^{\downarrow tot}(z_0, \Omega_0, \Omega'; \tau_a, \vec{p}_a, \gamma_s, \vec{p}_s) \, |\mu'| \, d\Omega'$$

All quantities are monochromatic

The Albedo or the Bi-Hemispherical Reflectance Factor (BHR)

$$BHR(z_0,\Omega_0;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s)=\frac{\int_{2\Pi^+} I^{\uparrow}(z_0,\Omega_0,\Omega;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s)\,|\mu|\,d\Omega}{\int_{2\Pi^-} I^{\downarrow tot}(z_0,\Omega_0,\Omega';\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s)\,|\mu'|\,d\Omega'}$$

The albedo or BHR can be measured locally in situ but it depends on a number of atmospheric and surface attributes



All quantities are monochromatic

Usual simplifications and proxies (1)

I - Assume that the surface is Lambertian with respect to all sources of illumination

$$I^{\uparrow}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha) = \frac{\alpha(z_0)}{\Pi}\int_{2\Pi^-} I^{\downarrow tot}(z_0,\Omega_0,\Omega';\tau_a,\vec{p}_a,\alpha)\,|\mu'|\,d\Omega'$$

isotropic illumination source at the bottom of the atmosphere

$$\alpha(z_0) = \frac{\Pi I^{\uparrow}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)}{E^{\downarrow tot}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)}$$

$$\alpha(z_0) = \frac{E^{\uparrow}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)}{E^{\downarrow tot}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)}$$

All quantities are monochromatic

Usual simplifications and proxies (2)

I I - Assume that surface is Lambertian with respect to the diffuse assumed isotropic illumination

$$I^{\uparrow}(z_0,\Omega_0,\Omega;\tau_a,\vec{p}_a,\alpha,BRF) = \frac{1}{\Pi}\int_{2\Pi^-}\gamma_s(z_0,\Omega' \rightarrow \Omega;\vec{p}_s) I^{\downarrow dir}(z_0,\Omega_0;\tau_a,\vec{p}_a)\,|\mu'|\,d\Omega'$$

$$+\frac{1}{\Pi}\int_{2\Pi^-}\gamma_s(z_0,\Omega' \rightarrow \Omega;\vec{p}_s) I_{tot}^{\downarrow diff}(z_0,\Omega_0,\Omega';\tau_a,\vec{p}_a,\alpha)\,|\mu'|\,d\Omega'$$

$$I^{\uparrow}(z_0,\Omega_0,\Omega;\tau_a,\vec{p}_a,\alpha,BRF) = \frac{1}{\Pi}\int_{2\Pi^-}\gamma_s(z_0,\Omega_0 \rightarrow \Omega;\vec{p}_s) I_0\delta(\Omega'-\Omega_0)\exp(-\frac{\tau_a}{|\mu_0'|})\,|\mu'|\,d\Omega'$$

$$+\frac{\alpha(z_0)}{\Pi}E_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)$$

assumed isotropic at the bottom of the atmosphere

$$I^{\uparrow}(z_0,\Omega_0,\Omega;\tau_a,\vec{p}_a,\alpha,BRF) = BRF(z_0,\Omega_0,\Omega;\vec{p}_s)\frac{I_0\mu_0}{\Pi}\exp(-\frac{\tau_a}{|\mu_0'|})$$

$$+\frac{\alpha(z_0)}{\Pi}E_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)$$

All quantities are monochromatic

Usual simplifications and proxies (3)

$$BRF\ (z_0, \Omega_0, \Omega; \vec{p}_s) = \frac{\Pi I^{\uparrow dir}(z_0, \Omega_0, \Omega; \tau_a, \vec{p}_a, BRF)}{I_0 \mu_0 \exp(-\frac{\tau_a}{|\mu_0^{'}|})}$$

The BRF cannot be measured in situ but in the laboratory

$$\alpha(z_0) = \frac{\Pi I_{tot}^{\uparrow diff}(z_0, \Omega_0; \tau_a, \vec{p}_a, \alpha)}{E_{tot}^{\downarrow diff}(z_0, \Omega_0; \tau_a, \vec{p}_a, \alpha)}$$

The albedo under isotropic diffuse illumination also called the White Sky Albedo can probably be approximated in situ under overcast conditions

All quantities are monochromatic

Back to the Albedo or BHR via the DHR(1)

I I - Assume that surface is Lambertian with respect to the assumed diffuse isotropic illumination

$$BHR(z_0,\Omega_0;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s) = DHR(z_0,\Omega_0;\gamma_s,\vec{p}_s)\, f^{\downarrow dir}(z_0,\Omega_0;\tau_a,\vec{p}_a)$$

$$+\,\alpha(z_0)\, f_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)$$

$$f^{\downarrow dir}(z_0,\Omega_0;\tau_a,\vec{p}_a) = \frac{I_0\mu_0 \exp(-\frac{\tau_a}{|\mu_0'|})}{E^{\downarrow tot}(z_0,\Omega_0;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s)}$$

$$f_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha) = \frac{E_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)}{E^{\downarrow tot}(z_0,\Omega_0;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s)}$$

$$DHR(z_0,\Omega_0;\gamma_s,\vec{p}_s) = \frac{1}{\Pi}\int_{2\Pi^+} BRF(z_0,\Omega_0,\Omega;\gamma_s,\vec{p}_s)\,|\mu|\,d\Omega$$

The Directional Hemispherical Reflectance factor (DHR) or Black Sky albedo depends on surface properties only but it cannot be measured in situ

All quantities are monochromatic

Pinty etal., (2005): Journal of the Atmospheric Sciences

The Blue sky albedo

$$BHR(z_0,\Omega_0;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s) = DHR(z_0,\Omega_0;\gamma_s,\vec{p}_s)\, f^{\downarrow dir}(z_0,\Omega_0;\tau_a,\vec{p}_a) + \alpha(z_0)\, f_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)$$

I I I- Keeping some level of directionality in the incoming diffuse illumination

The ‘decoupled’ contributions

$$BHR(z_0,\Omega_0;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s) = DHR(z_0,\Omega_0;\gamma_s,\vec{p}_s)\, f^{\downarrow dir}(z_0,\Omega_0;\tau_a,\vec{p}_a) + \alpha(z_0)\, f_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)$$

$$+ \zeta(z_0,\Omega_0;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s)$$

The ‘coupled’ contribution

All quantities are monochromatic

Pinty etal., (2005): Journal of the Atmospheric Sciences

Adopting the Blue sky Albedo parameterization?

Generating spectrally integrated broadband visible and near-infrared Black (or DHR) and White (BHR_{iso}) sky albedos requires solving a series of challenging problems:

- A coupled land-atmosphere radiation transfer inverse problem:

  make the best possible use of instrument capabilities to increase the constraints on the possible solutions

- Angular integrations over various hemispheres:

  require using parametric BRF models

- Conversion from a panoply of narrow band measurements to broadband estimates:

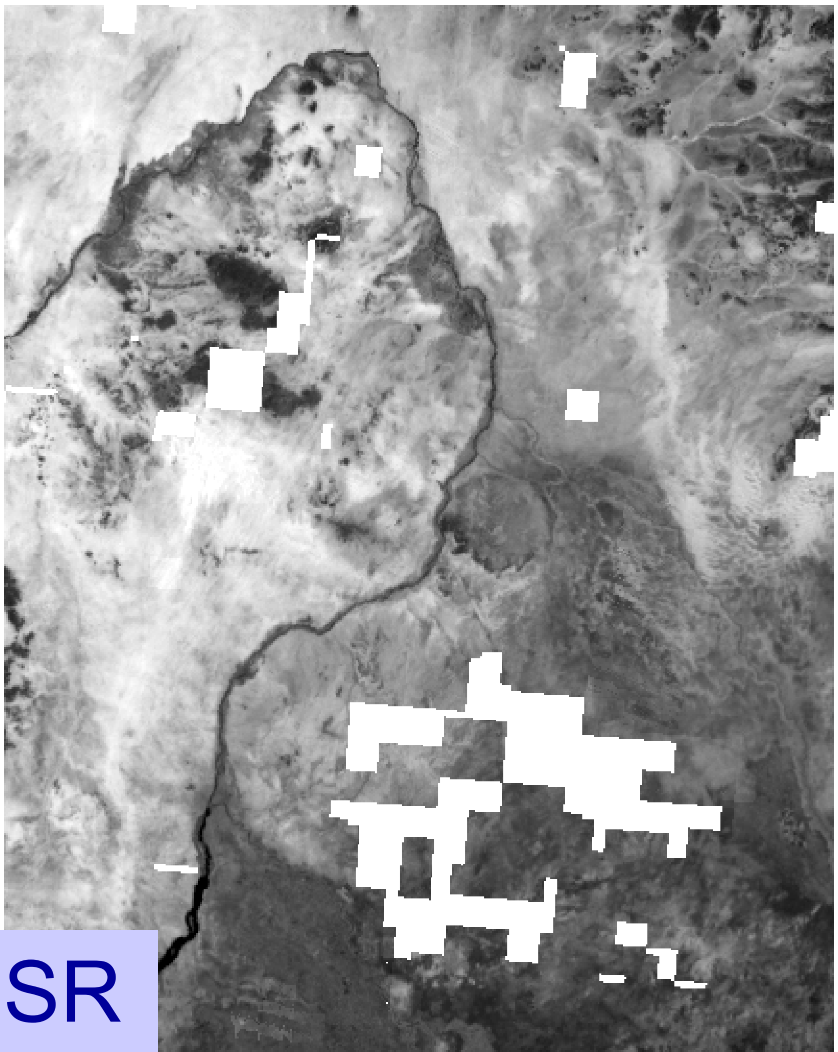
  require using existing in situ reflectance measurements and/or model simulated scenarios

EO product comparison

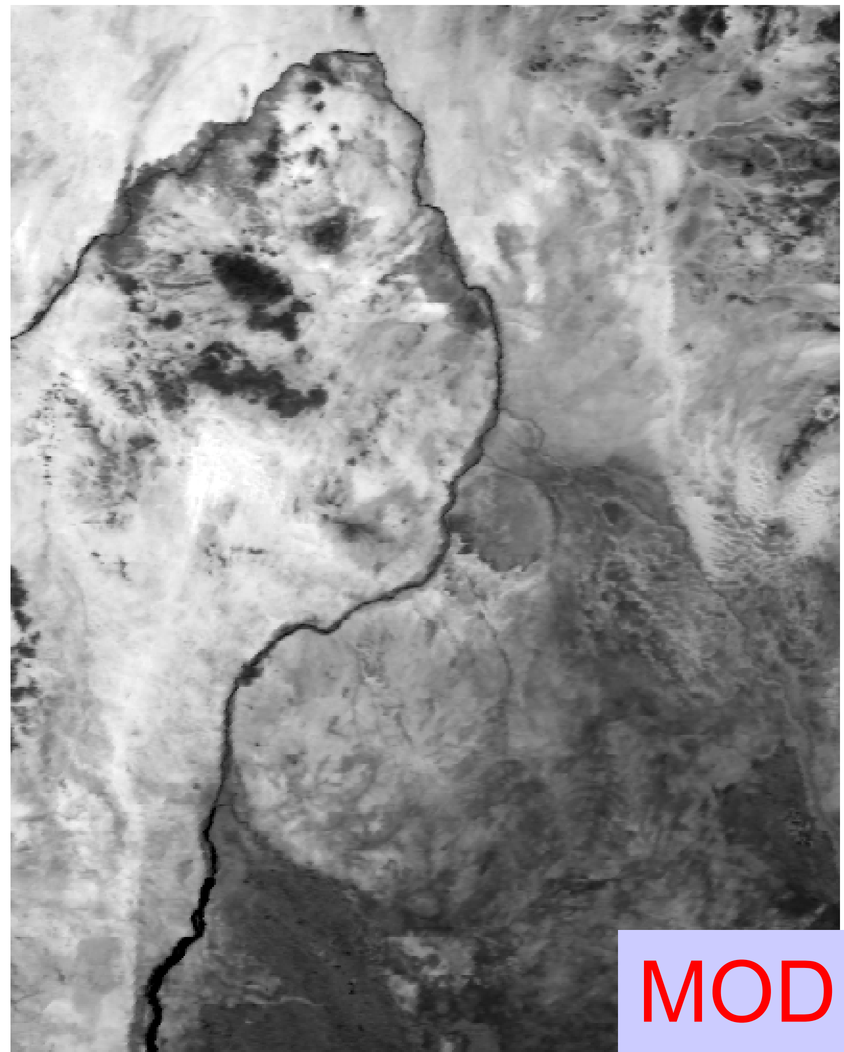
- Broadband surface albedo products are routinely generated MODIS and MISR instruments
- MODIS delivers Black Sky and White Sky albedos products (independent from atmospheric properties)
- MISR delivers ‘true’ Surface albedo products (depends on atmospheric properties)
- Black and White sky albedo to be produced from MISR BRFs to yield comparable products

EO product comparison

- MODIS and MISR broadband White Sky surface albedos.



MISR

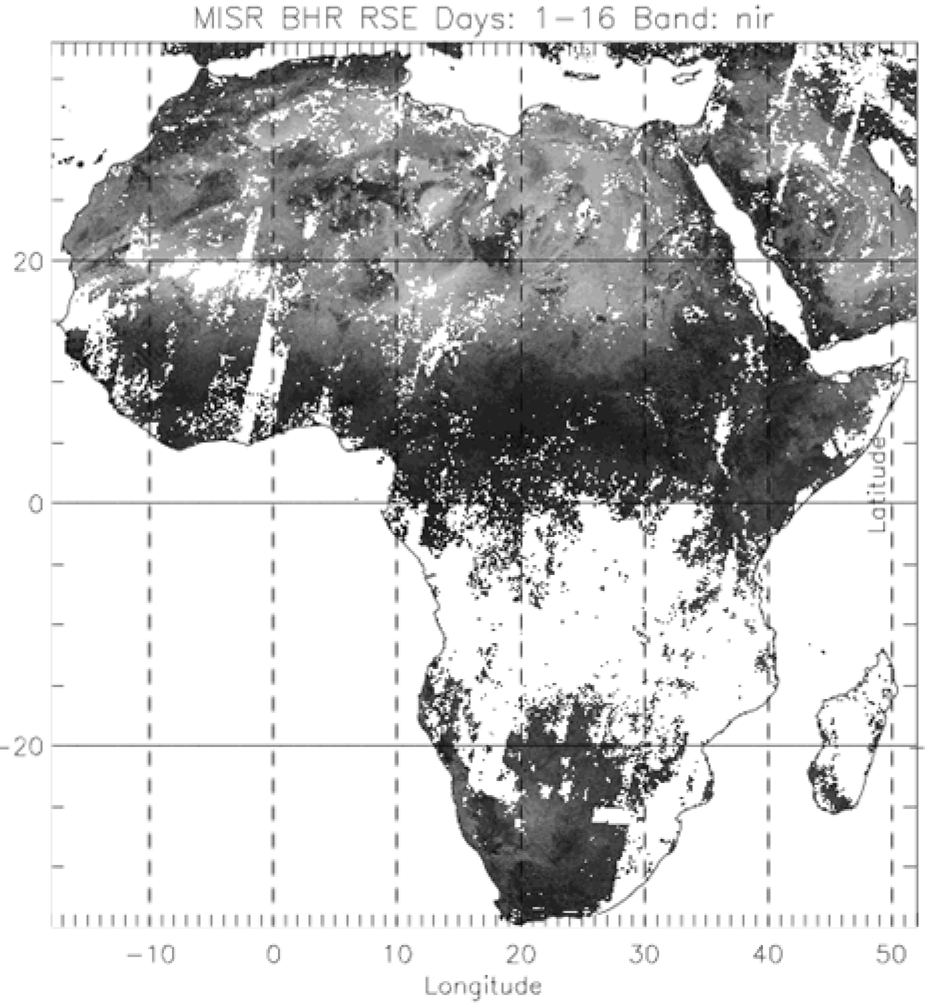


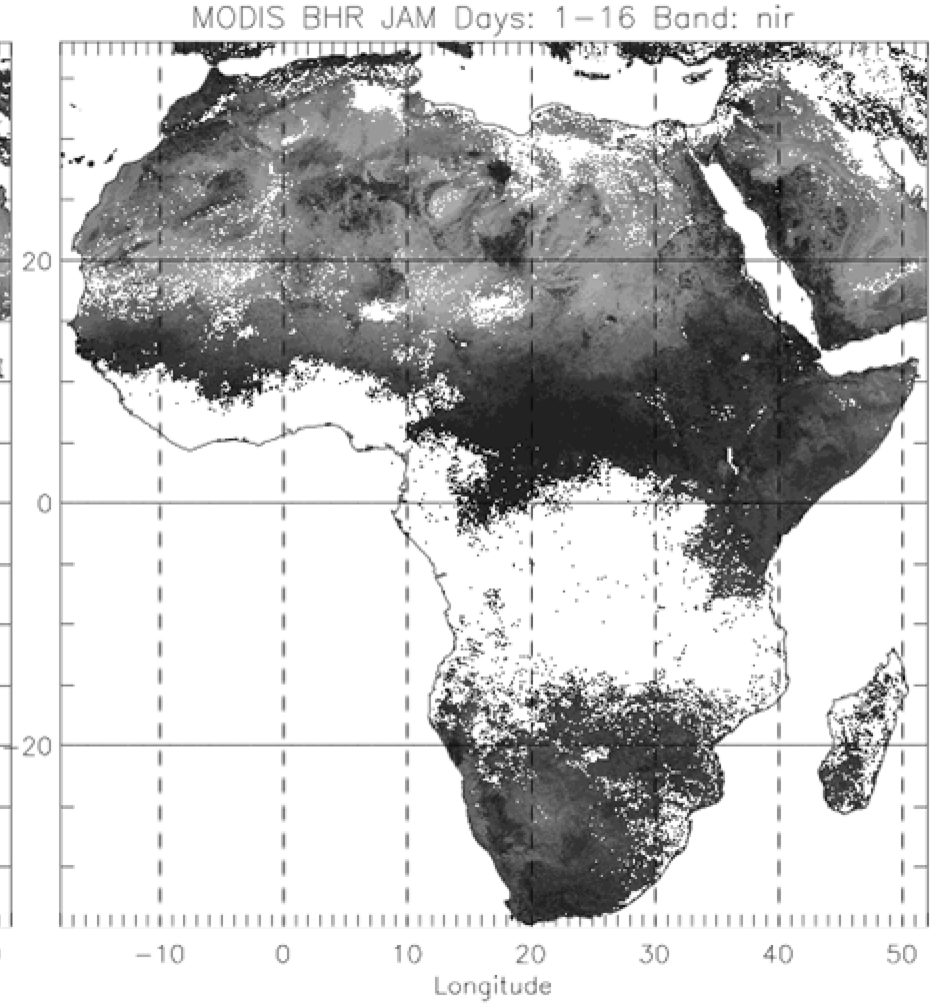
MODIS

EO product comparison

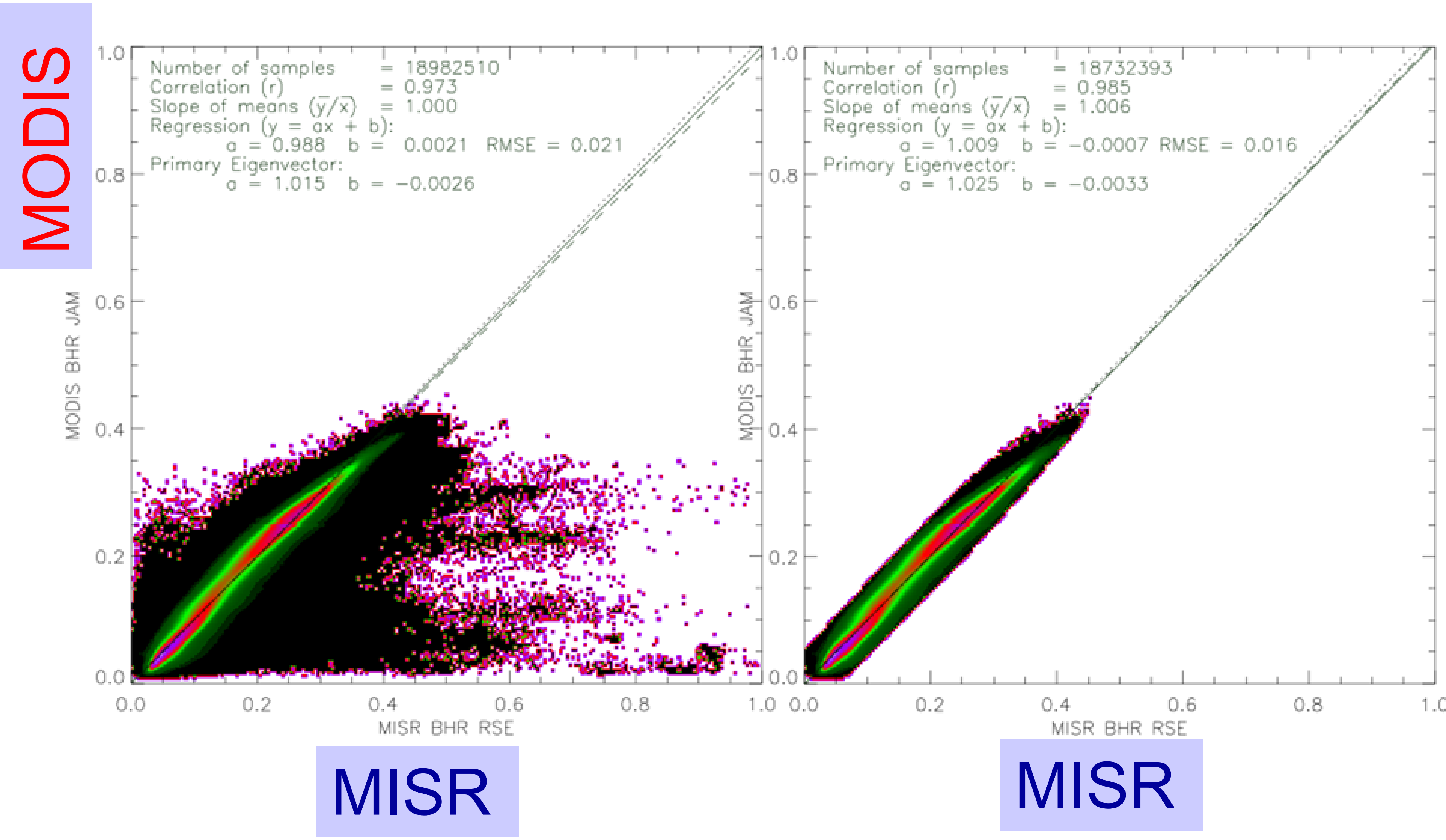
MISR

MODIS

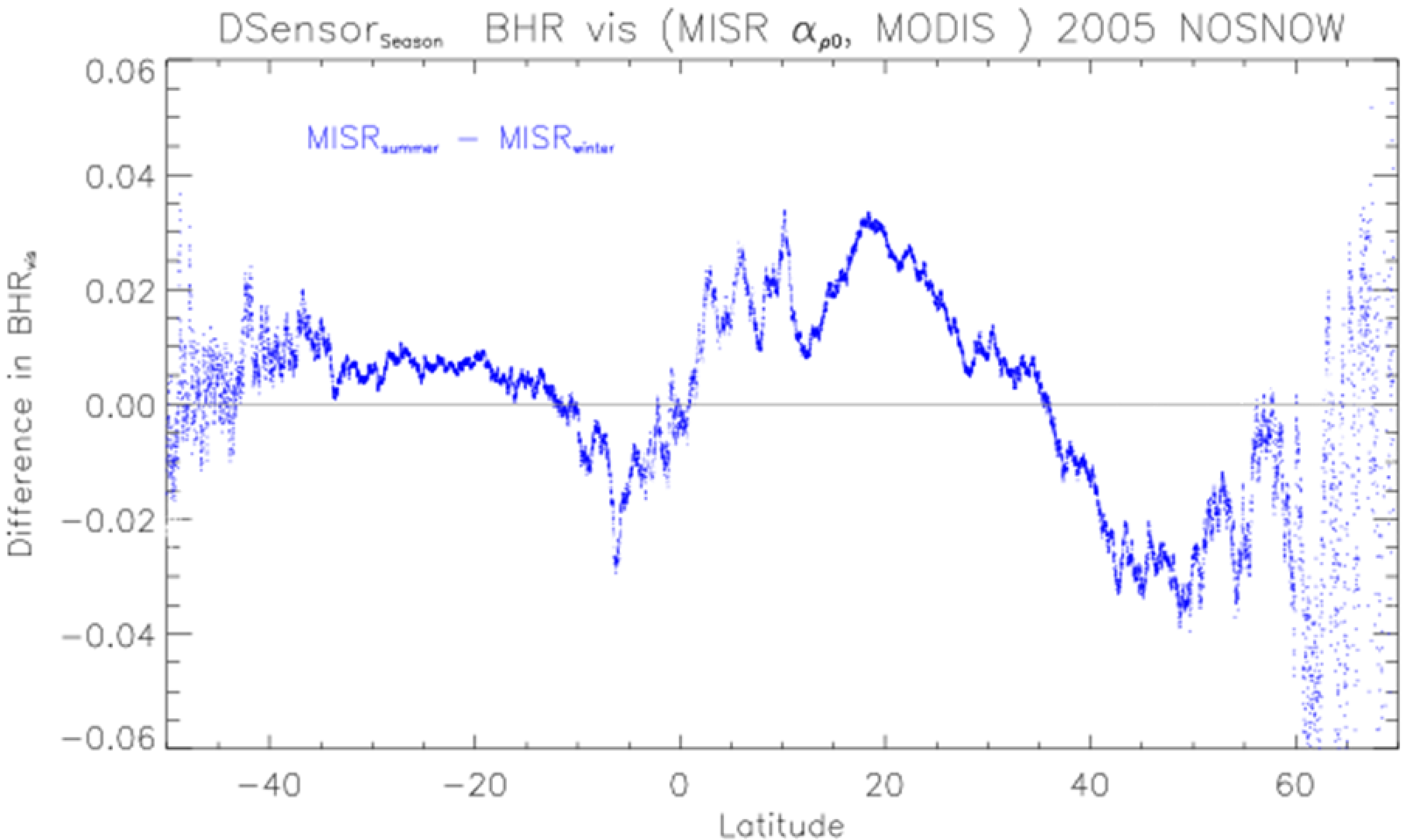




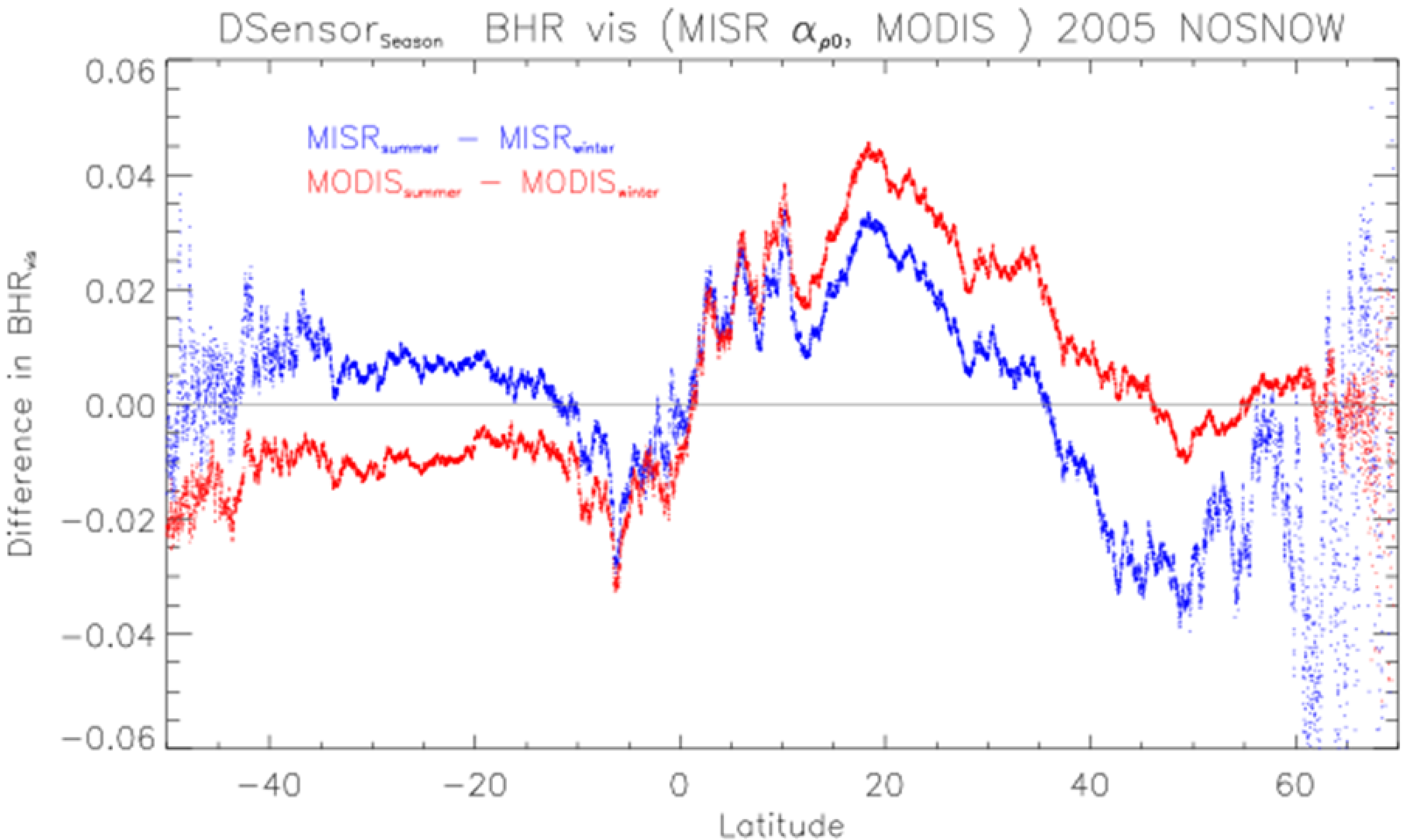
EO product comparison



Seasonal changes



Seasonal changes



EO product comparison

- Looks OK regarding the MODIS and MISR broadband surface albedos

  ……but some issues to be investigated (calibration and sampling)

- FAPAR products from different platforms show quite a significant scatter and strong biases.

  …..Need to compare same physical quantities (Sun angle, incoming radiation, ‘leaf’ color…)

Adequacy of EO products for further assimilation by Climate/NWP models

- Are they consistent between themselves?
- Are they delivered with documented uncertainty?
- Are they accurate enough so that the models can benefit?
- Do they fit large-scale model's expectations?
- Do Climate/NWP models use the appropriate modeling tools to represent the available products?

One first significant issue/caveat!

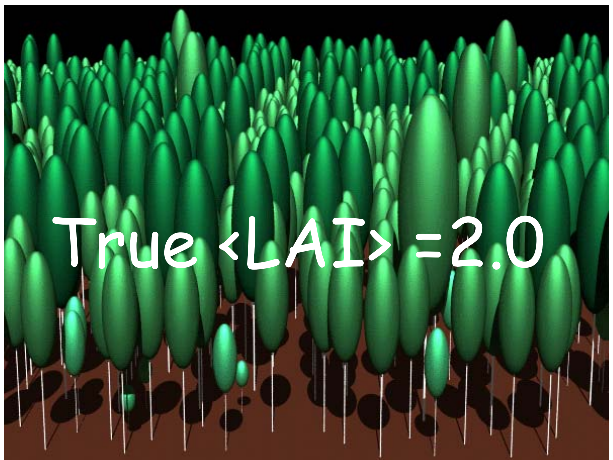
- LAI is (and must be) retrieved using 3-D RT model solutions when vegetation structure is anticipated to induce significant RT effects (specified *apriori* via a land cover map!) .

- The RT fluxes generated by GCMs are, in the best case scenario, estimated using 1-D RT models, i.e., 2-stream solutions.

Using RS products as such in GCMs can only yield inconsistencies in flux estimates

Problem:

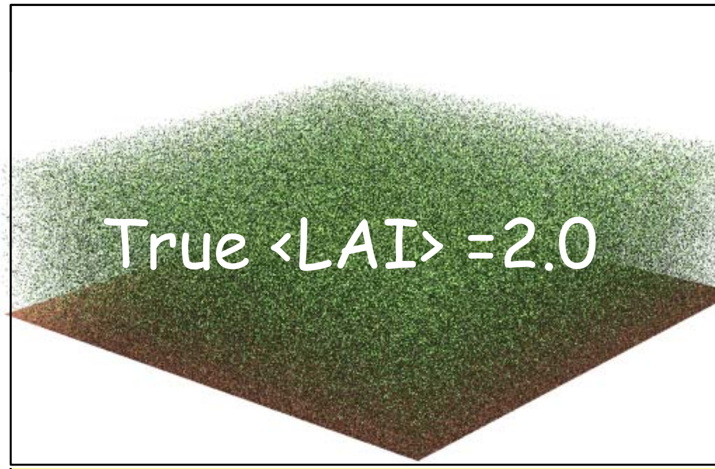
Using "true'', i.e., domain-averaged, optical depth and other true radiation transfer (RT) state variables (<X>) in a 1D RT scheme can only yield seriously erroneous radiant flux estimates



3-D heterogeneous system

Direct transmission at 30 degrees Sun zenith angle,

$$T_{3-D}^{direct}(<LAI>) = 0.596$$



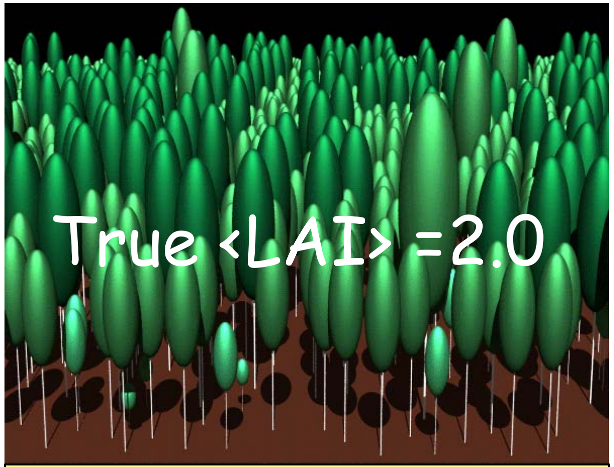
1-D system representation

Direct transmission at 30 degrees Sun zenith angle,

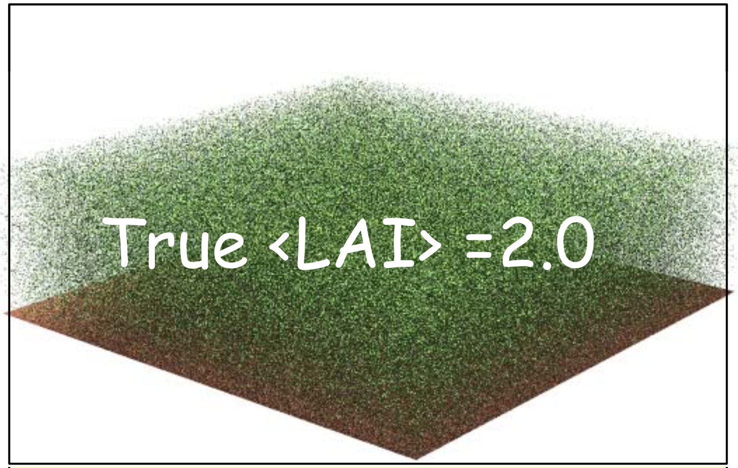
$$T_{1-D}^{direct}(<LAI>) = \exp\left(-\frac{<LAI>}{2\mu_0}\right) = 0.312$$

Problem:

Using "true'', i.e., domain-averaged, optical depth and other true radiation transfer (RT) state variables (<X>) in a 1-D RT scheme can only yield seriously erroneous radiant flux estimates



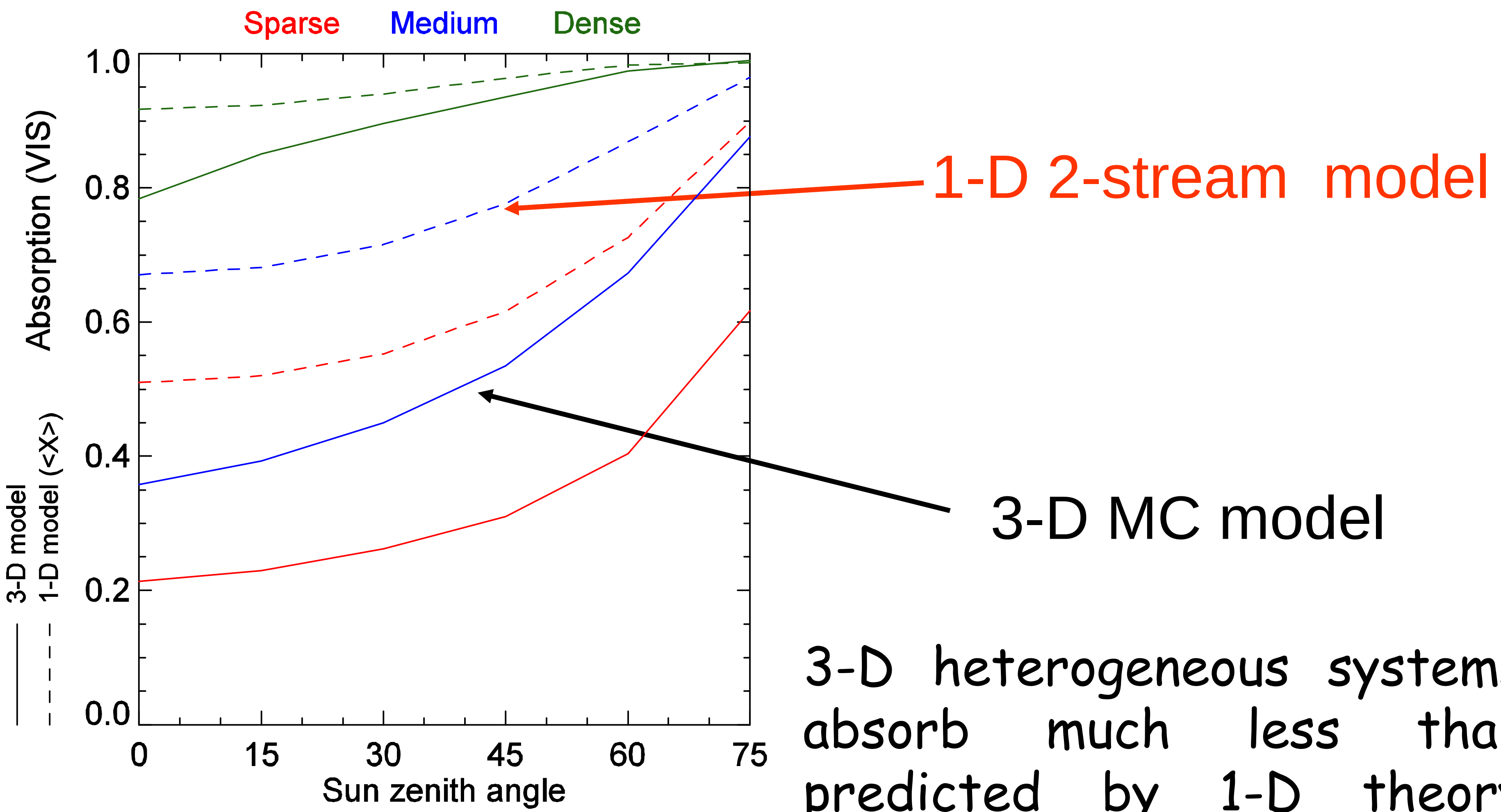
3-D heterogeneous system



1-D system representation

3-D systems are more transparent than their 1-D equivalent with respect to the directly transmitted fluxes

Absorption in the visible (PAR) domain



3-D heterogeneous systems absorb much less than predicted by 1-D theory using true state variables in the visible domain

Comparing/constraining or assimilating the radiation fluxes retrieved from EO against those generated by GCMs is not valid when using the true state variables in the GCMs representation

How to fix the problem?

1. Parameterizing 3-D vegetation systems using “effective” instead of “true”, domain averaged state variables for RT processes in GCMs.

   Solving a type of 2-stream problem as done for the atmospheric layers

2. Prepare for the ingestion/assimilation of RS flux products into Land Surface schemes

   Retrieve 2-stream model parameters from EO flux products

Requirements from a 1D RT model

- 3 state variables:

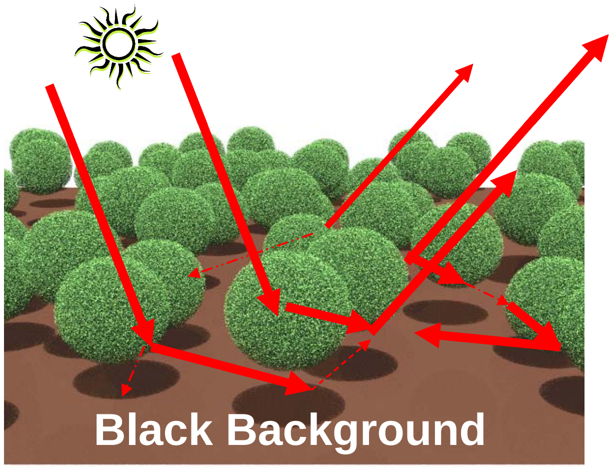
1. *Optical depth: LAI*
2. *single scattering albedo :*
   Leaf reflectance+ Leaf transmittance
3. *asymmetry of the phase function*
   Leaf reflectance/transmittance

- 2 boundary conditions:

1. *Top: Downward flux from the atmosphere*
2. *Bottom : Upward flux from the soil*

Decompose the complex problem into simpler problems to solve

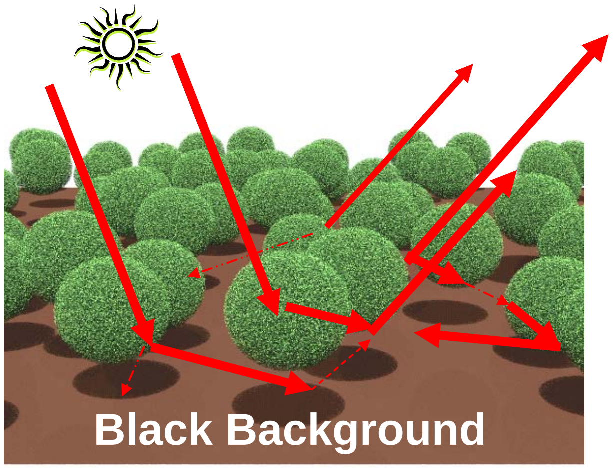
$$DHR(z_0, \mu_0; \rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0, \mu_0; \rho_{sfc})$$

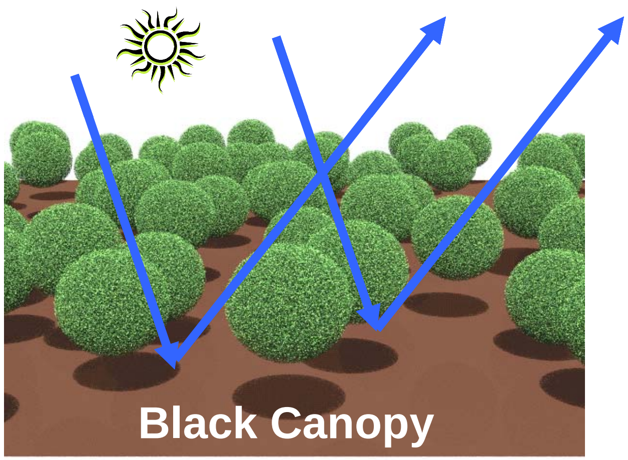


Ref: Pinty et al. (2004) Journal Geophysical Research, doi:10,1029/2004JD005214

Decompose the complex problem into simpler problems to solve

$$DHR(z_0,\mu_0;\rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0,\mu_0;\rho_{sfc}) + \rho_{sfc}\left[DHR^{Uncollided}_{background}(z_0,\mu_0)\right]$$





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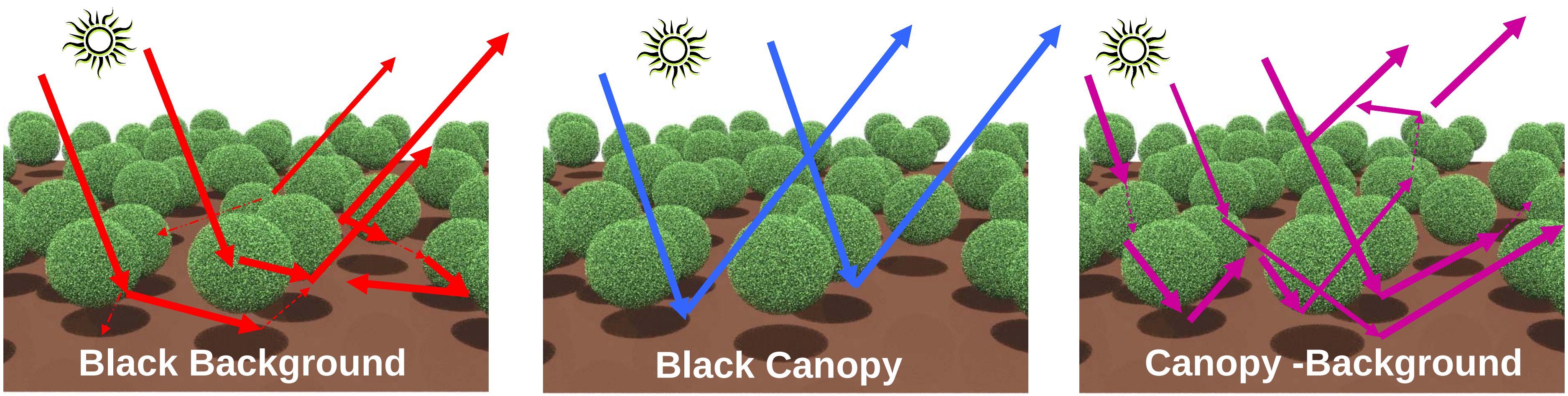
Decompose the complex problem into simpler problems to solve

$$DHR(z_0, \mu_0; \rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0, \mu_0; \rho_{sfc}) + \rho_{sfc}\left[DHR^{Uncollided}_{background}(z_0, \mu_0)\right] + \rho_{sfc}\left[DHR^{Collided}_{background}(z_0, \mu_0; \rho_{sfc})\right]$$



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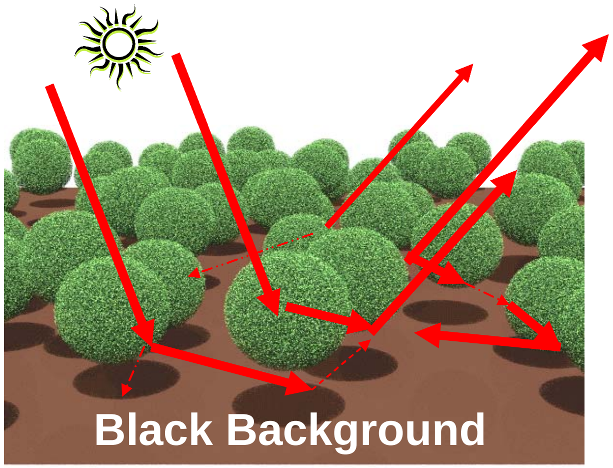
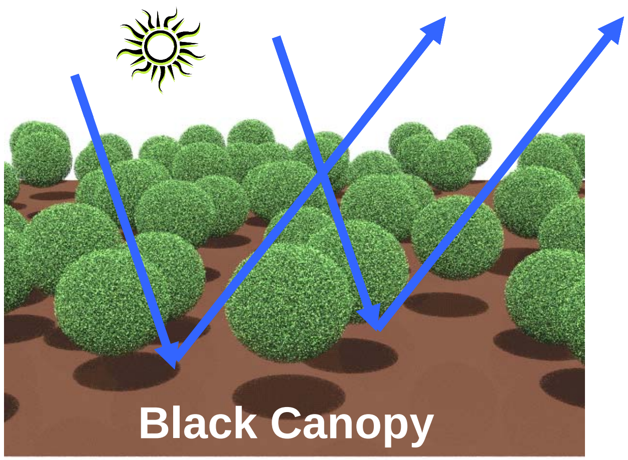
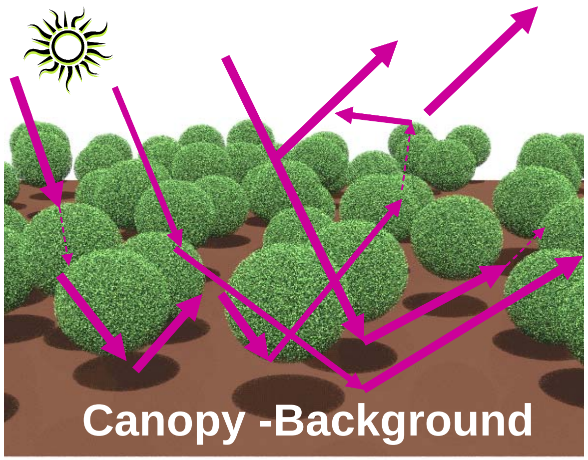
Decompose the complex problem into simpler problems to solve

$$DHR(z_0,\mu_0;\rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0,\mu_0;\rho_{sfc}) + \rho_{sfc}\left[DHR^{Uncollided}_{background}(z_0,\mu_0)\right] + \rho_{sfc}\left[DHR^{Collided}_{background}(z_0,\mu_0;\rho_{sfc})\right]$$







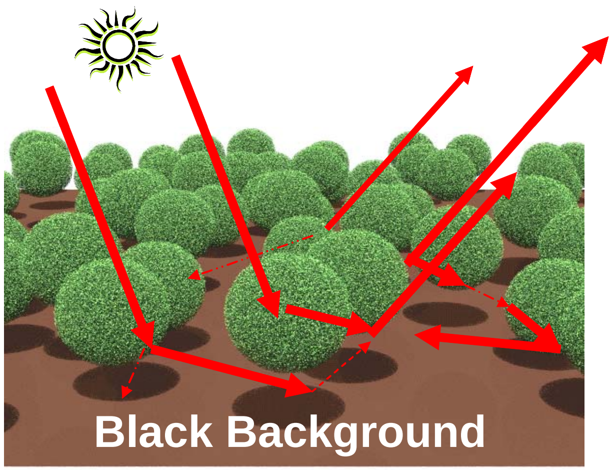
- Regulates the ***absorption*** processes associated with vegetation photosynthesis

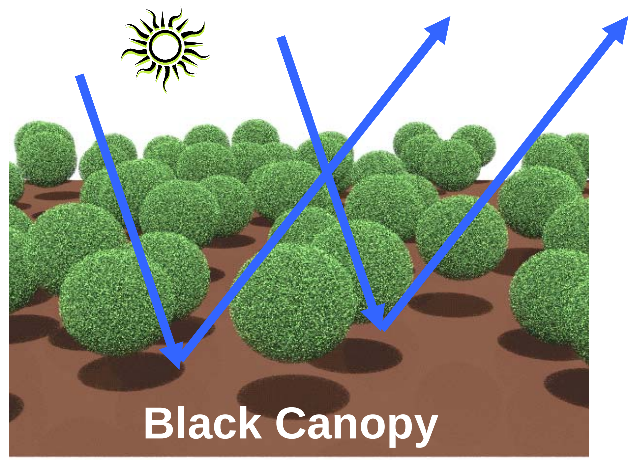
- Strongly depends on the **density** of green vegetation

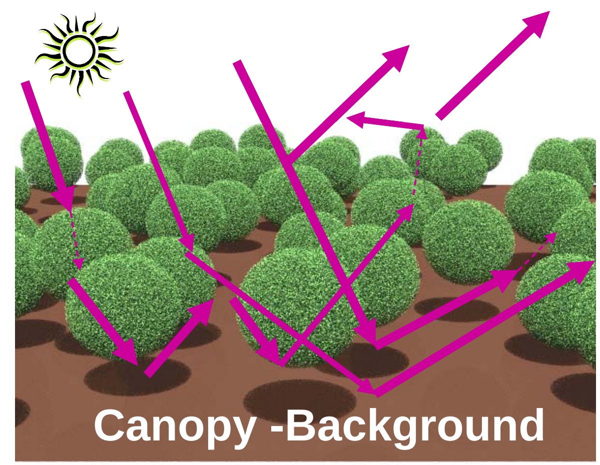
Ref: Pinty et al. (2004) Journal Geophysical Research, doi:10,1029/2004JD005214

Decompose the complex problem into simpler problems to solve

$$DHR(z_0,\mu_0;\rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0,\mu_0;\rho_{sfc}) + \rho_{sfc}\left[DHR^{Uncollided}_{background}(z_0,\mu_0)\right] + \rho_{sfc}\left[DHR^{Collided}_{background}(z_0,\mu_0;\rho_{sfc})\right]$$







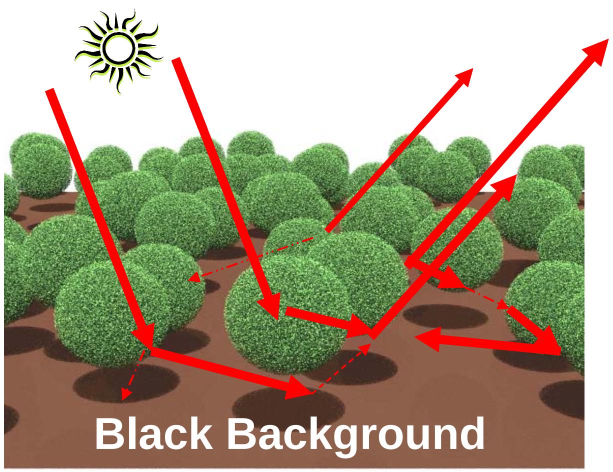
- Regulates the ***absorption*** processes associated with vegetation photosynthesis
- Strongly depends on the **density** of green vegetation

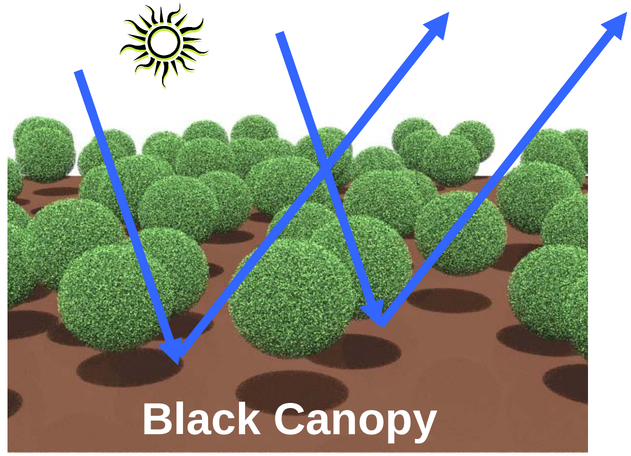
- No absorption process by vegetation associated with this wavelength-independent contribution
- Strongly controlled by **3-D distribution of vegetation architecture**

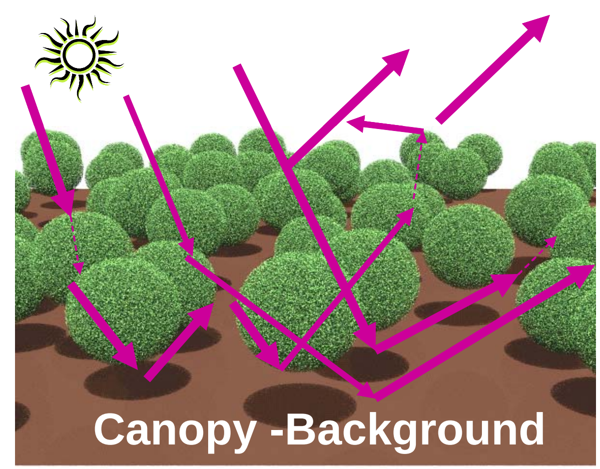
Ref: Pinty et al. (2004) Journal Geophysical Research, doi:10,1029/2004JD005214

Decompose the complex problem into simpler problems to solve

$$DHR\,(z_0,\mu_0;\rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0,\mu_0;\rho_{sfc}) + \rho_{sfc}\left[DHR^{Uncollided}_{background}(z_0,\mu_0)\right] + \rho_{sfc}\left[DHR^{Collided}_{background}(z_0,\mu_0;\rho_{sfc})\right]$$







- Regulates the ***absorption*** processes associated with vegetation photosynthesis
- Strongly depends on the **density** of green vegetation

- No absorption process by vegetation associated with this wavelength-independent contribution
- Strongly controlled by 3-D distribution of vegetation architecture

- Controlled by multiple scattering events between the background and the canopy
- Mostly negligible contribution in the visible domain of the solar spectrum

Ref: Pinty et al. (2004) Journal Geophysical Research, doi:10,1029/2004JD005214

The Black Canopy contribution to the DHR (Black Sky albedo)

Black Canopy problem solved by finding the analytical solution to

$$DHR_{BlackCanopy}(\mu_0) = \rho_{sfc} \exp\left(-\frac{\widetilde{LAI}}{2\mu_0}\right) \overline{T}_{blackCanopy} \quad \text{where} \quad \overline{T}_{BlackCanopy} = 2\int_0^1 \exp\left(-\frac{\widetilde{LAI}(\mu)}{2\mu}\right)\mu d\mu$$

with $\xi(\mu) \approx a + b(1-\mu)$

we get

$$\overline{T}_{BlackCanopy} = \exp(-\widetilde{LAI}^{\star}/2) \left[1 - \widetilde{LAI}^{\star}/2 + (\widetilde{LAI}^{\star}/2)^2 \exp(\widetilde{LAI}^{\star}/2)\, \Gamma(0, \widetilde{LAI}^{\star}/2)\right]$$

where

$$\Gamma(0, \widetilde{LAI}^{\star}/2) = \int_{\widetilde{LAI}^{\star}/2}^{\infty} t^{-1} \exp(-t)\, dt$$

and, finally

$$\overline{T}_{BlackCanopy} \approx \exp(-\widetilde{LAI}^{\star}) \approx \exp(-\langle LAI \rangle \zeta^{\star}) \qquad \widetilde{LAI}^{\star} \to 0$$

Definition of the "effective" LAI from the Black canopy contribution

$\widetilde{LAI}$ is forced to satisfy the exponential law:

$$T_{1-D}^{direct}(\widetilde{LAI}) = \exp\left(-\frac{\widetilde{LAI}}{2\mu_0}\right) = \exp\left(-\frac{<LAI>\xi(\mu_0)}{2\mu_0}\right) = T_{3-D}^{direct}(LAI)$$

$$\xi(\mu_0 = 1) = -\ln(1 - F_C)\frac{2}{<LAI>}$$

Domain-averaged structure factor

The Black Background contribution to the DHR (Black Sky albedo)

Black Background problem solved with a revisited version of a standard 2-stream model, e.g., Meador and Weaver (1980) using sets of scattering coefficients relevant to the case of vegetation canopies

Two-Stream Approximations to Radiative Transfer in Planetary Atmospheres: A Unified Description of Existing Methods and a New Improvement

W. E. MEADOR AND W. R. WEAVER
NASA, Langley Research Center, Hampton, VA 23665

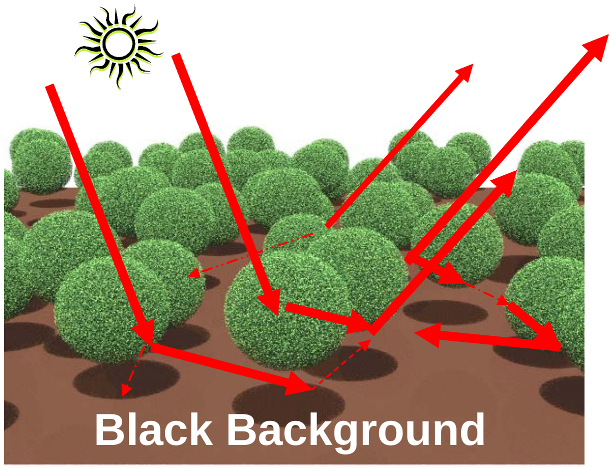
(Manuscript received 15 October 1979)

ABSTRACT

Existing two-stream approximations to radiative transfer theory for particulate media are shown to be represented by identical forms of coupled differential equations if the intensity is replaced by integrals of the intensity over hemispheres. One set of solutions thus suffices for all methods and provides convenient analytical comparisons. The equations also suggest modifications of the standard techniques so as to duplicate exact solutions for thin atmospheres and thus permit accurate determinations of the effects of typical aerosol layers. Numerical results for the plane albedos of plane-parallel atmospheres (single-scattering albedo = 0.8, 1.0; optical thickness = 0.25, 1, 4, 16; Henyey-Greenstein phase function with asymmetry factor 0.75) are given for conventional and modified Eddington approximations, conventional and modified two-point quadrature schemes, the hemispheric-constant method and the delta-function method, all for comparison with accurate discrete-ordinate solutions. A new two-stream approximation is introduced that reduces to the modified Eddington approximation in the limit of isotropic phase functions and to the exact solution in the limit of extreme anisotropic scattering. Comparisons of plane albedos and transmittances show the new method to be generally superior over a wide range of atmospheric conditions (including cloud and aerosol layers), especially in the case of nonconservative scattering.

Decompose the complex problem into simpler problems to solve

$$DHR(z_0, \mu_0; \rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0, \mu_0; \rho_{sfc})$$



Ref: Pinty et al. (2004) Journal Geophysical Research, doi:10,1029/2004JD005214

The 2 stream model of Meador & Weaver

Equations for atmospheres and clouds

$$+\ \pi F \omega_0 (1 - \beta_0) e^{-\tau/\mu_0}. \quad (11)$$

Two-stream methods are defined for present purposes as methods satisfying the simplified expressions

$$\frac{dI^+}{d\tau} = \gamma_1 I^+ - \gamma_2 I^- - \pi F \omega_0 \gamma_3 e^{-\tau/\mu_0}, \quad (12)$$

$$\frac{dI^-}{d\tau} = \gamma_2 I^+ - \gamma_1 I^- + \pi F \omega_0 \gamma_4 e^{-\tau/\mu_0}, \quad (13)$$

which are obtained from Eqs. (10) and (11) by assuming the μ dependence of I and approximating the integrals. The γ_i's are determined by the approximations used and are independent of τ in all cases. As will be shown, their values are constrained by physical requirements; for example, the constraint $\gamma_3 + \gamma_4 = 1$ follows immediately from energy conservation.

Equations for vegetation

$$\frac{dI^+}{d(\widetilde{LAI'}/2)} = \gamma_1 I^+ - \gamma_2 I^- - \pi F \gamma_3 \omega_l \exp(-\widetilde{LAI'}/2\,\mu_0)$$

$$\frac{dI^-}{d(\widetilde{LAI'}/2)} = \gamma_2 I^+ - \gamma_1 I^- + \pi F \gamma_4 \omega_l \exp(-\widetilde{LAI'}/2\,\mu_0)$$

The Gamma coefficients of the 2-stream model of Meador & Weaver – Atmosphere & Clouds

The Gamma coefficients of the 2-stream model of Meador & Weaver (vegetation)

$\tilde{r}_l$: Leaf reflectance

$\tilde{t}_l$: Leaf transmittance

$$\omega_l = \tilde{r}_l + \tilde{t}_l$$

$$\delta_l = \tilde{r}_l - \tilde{t}_l$$

Scattering order	γ_1	γ_2	γ_3	γ_4
First [b]	2	0	$2\left[\frac{\omega_l}{4} + \mu_0 \frac{\delta_l}{6}\right]/\omega_l$	$2\left[\frac{\omega_l}{4} - \mu_0 \frac{\delta_l}{6}\right]/\omega_l$
First and second [b]	$2\left[1 - \frac{\omega_l}{2} + \frac{\delta_l}{6}\right]$	0	idem	idem
All	idem	$2\left[\frac{\omega_l}{2} + \frac{\delta_l}{6}\right]$	idem	idem

with respect to the external collimated source of radiation

The Black Background contribution to the DHR (Black Sky albedo)

$$
\begin{aligned}
R_{veg}^{Coll}(z_{toc},\mu_0) = & \frac{\omega_l}{(1-k^2\mu_0^2)\left[(k+\gamma_1)\exp\left(k\frac{\widetilde{LAI}}{2}\right)+(k-\gamma_1)\exp\left(-k\frac{\widetilde{LAI}}{2}\right)\right]} \\
& \left[(1-k\mu_0)(\alpha_2+k\gamma_3)\exp\left(k\frac{\widetilde{LAI}}{2}\right)\right. \\
& -(1+k\mu_0)(\alpha_2-k\gamma_3)\exp\left(-k\frac{\widetilde{LAI}}{2}\right) \\
& \left.-2k(\gamma_3-\alpha_2\mu_0)\exp\left(-\frac{\widetilde{LAI}}{2\mu_0}\right)\right]
\end{aligned}
$$

$$
\begin{aligned}
T_{veg}^{Coll}(z_{bgd},\mu_0) = & \exp\left(-\frac{\widetilde{LAI}}{2\mu_0}\right) \\
& \left\{1-\frac{\omega_l}{(1-k^2\mu_0^2)\left[(k+\gamma_1)\exp\left(k\frac{\widetilde{LAI}}{2}\right)+(k-\gamma_1)\exp\left(-k\frac{\widetilde{LAI}}{2}\right)\right]}\right. \\
& \left[(1+k\mu_0)(\alpha_1+k\gamma_4)\exp\left(k\frac{\widetilde{LAI}}{2}\right)\right. \\
& -(1-k\mu_0)(\alpha_1-k\gamma_4)\exp\left(-k\frac{\widetilde{LAI}}{2}\right) \\
& \left.\left.-2k(\gamma_4+\alpha_1\mu_0)\exp\left(\frac{\widetilde{LAI}}{2\mu_0}\right)\right]\right\}
\end{aligned}
$$

The fraction of absorbed flux is simply obtained from the closure of the balance equation

Ref: Meador and Weaver (1980) JAS & Pinty et al.(2006) JGR

Two-stream model parameters

- 3 (effective) parameters of the canopy:

Leaf Area Index *amount of leaf material*

Canopy reflectance + transmittance

canopy color

Canopy reflectance/transmittance

- 1 (true) parameter of the background:

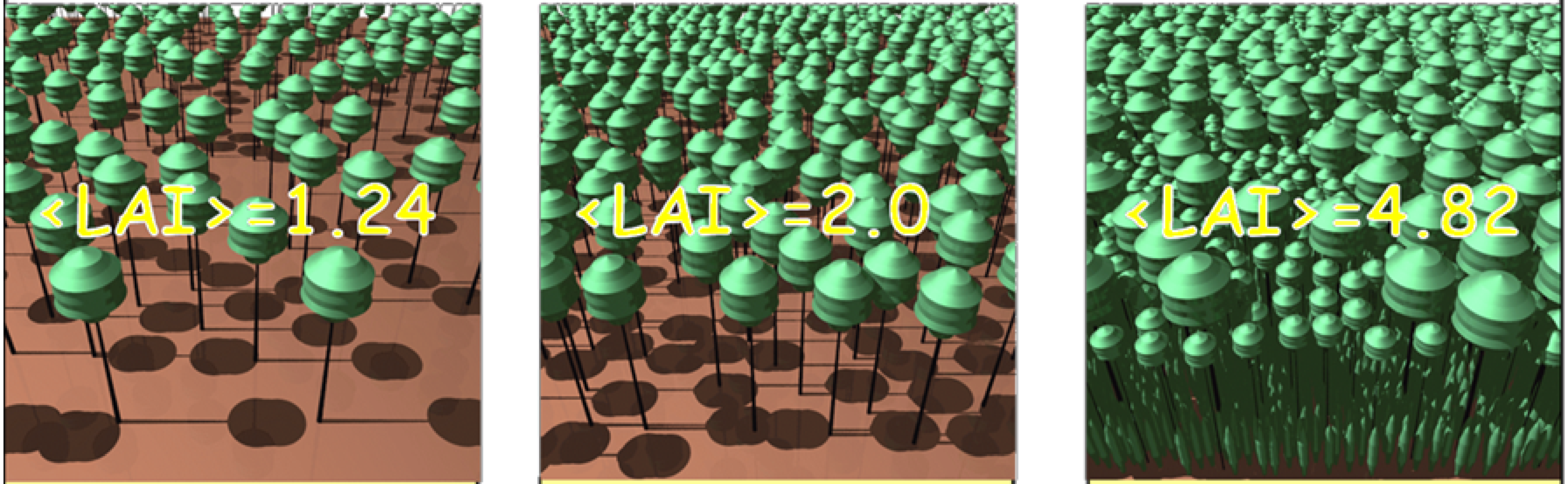
background Albedo *soil color*

Pinty etal., (2006): Journal of Geophysical Research, doi:10.1029/2005JD005952

Results:

Implementing DHR and BHR solutions and assessment of the performances of the 2-stream RT scheme against Monte Carlo RT simulations

Evaluation with 3-D heterogeneous vegetation scenarios

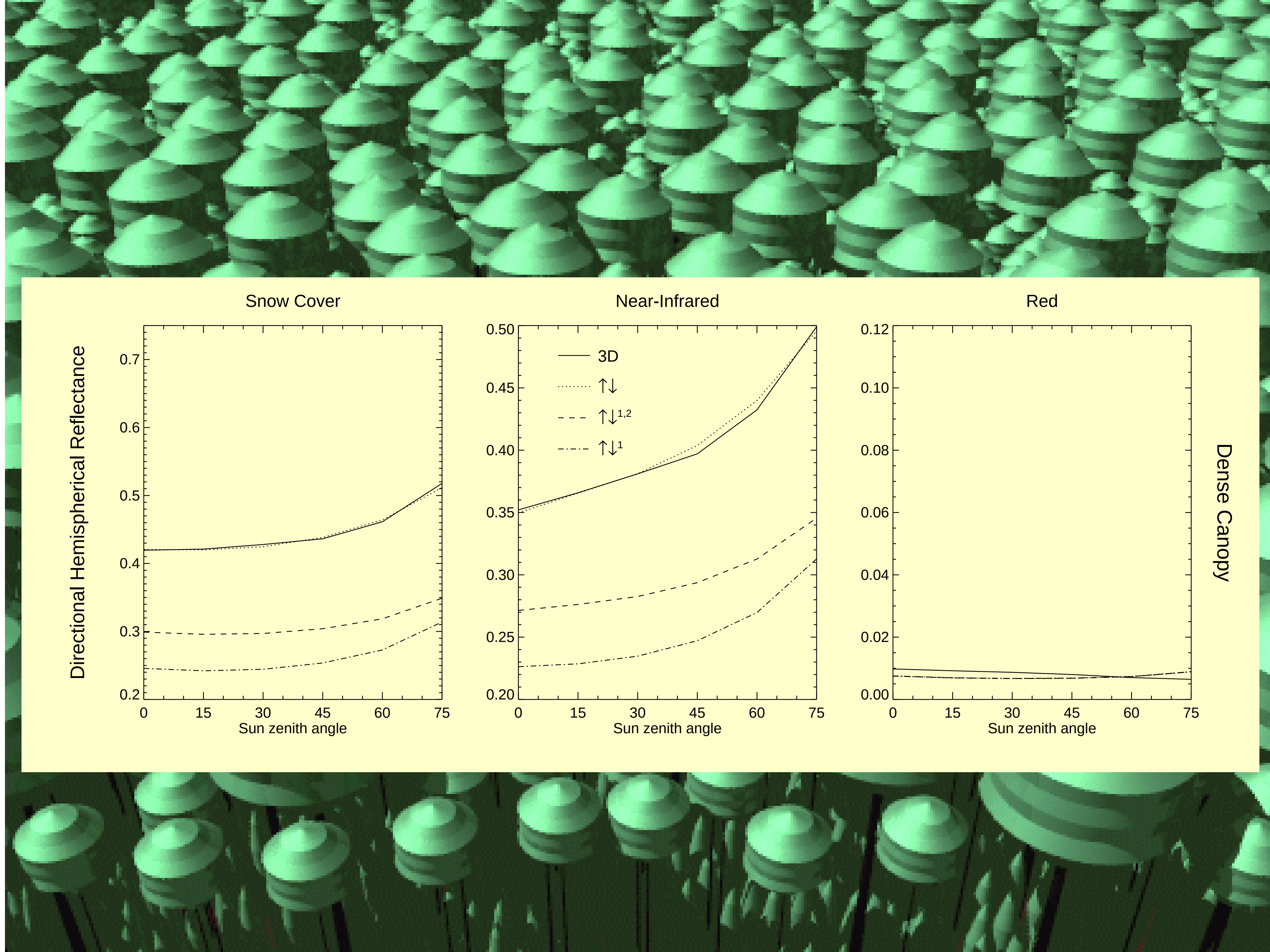


SPARSE | MEDIUM | DENSE

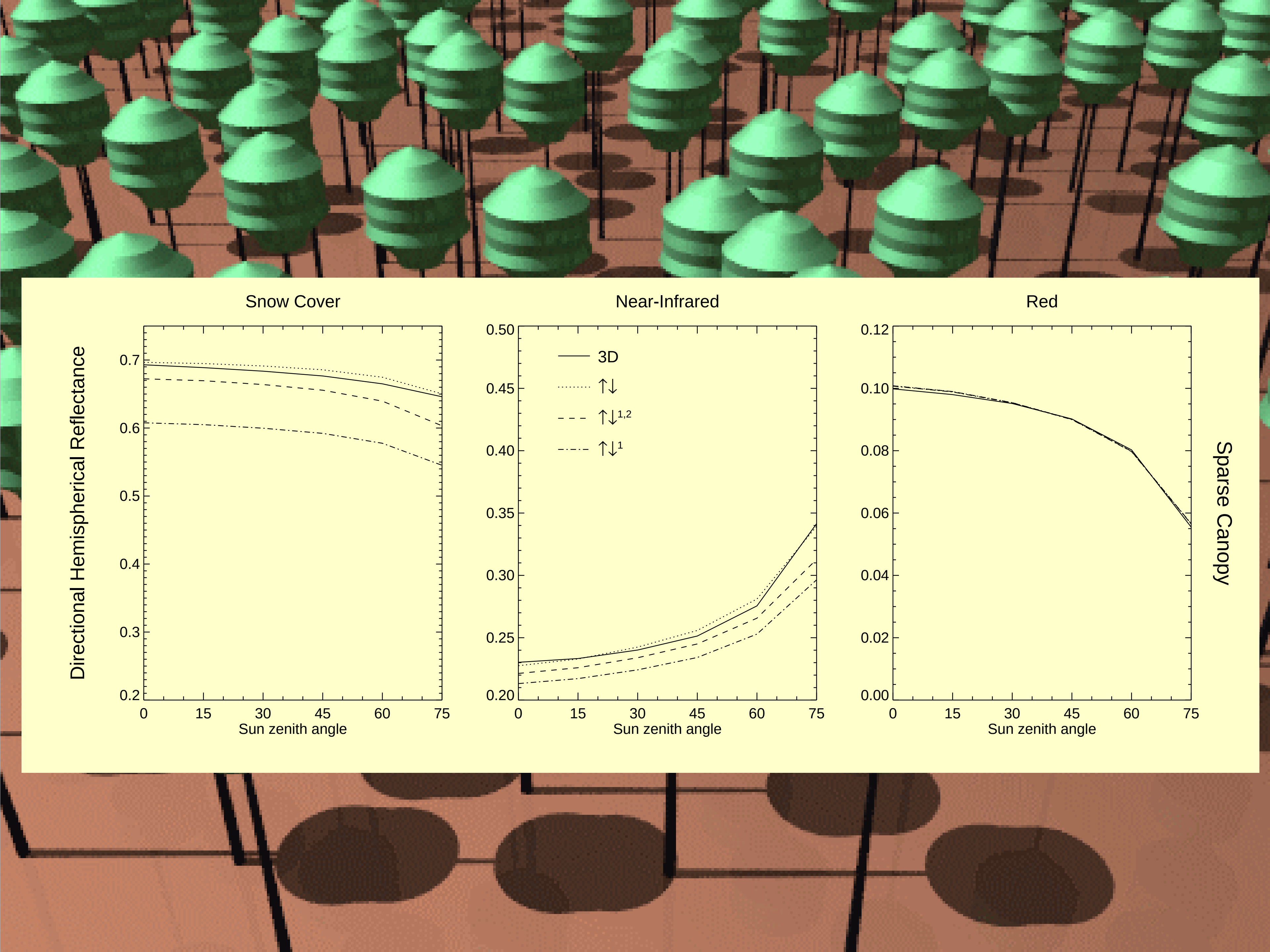
Results:

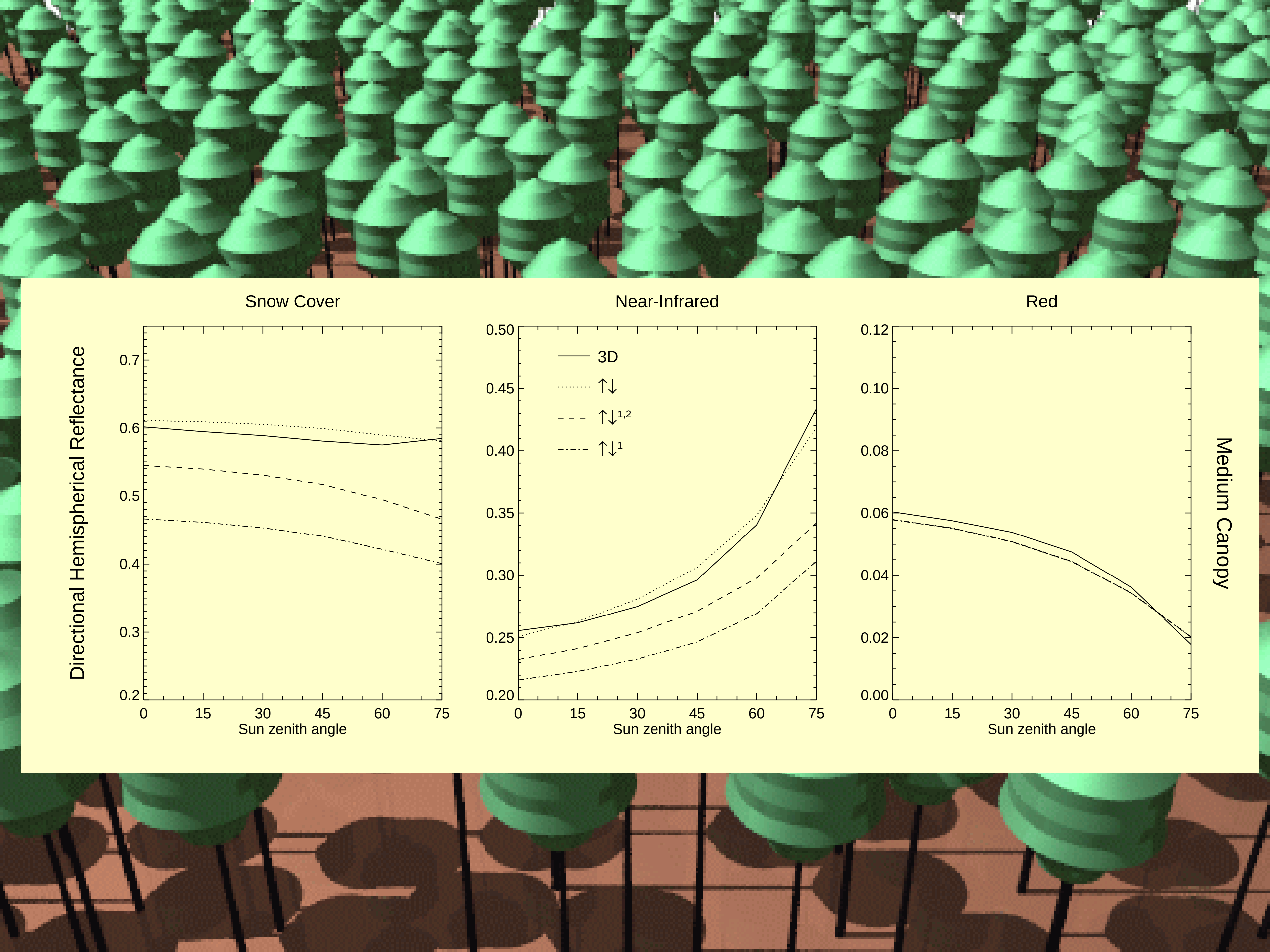
Implementing DHR and BHR solutions and assessment of the performances of the 2-stream RT scheme against Monte Carlo RT simulations

Legend adopted for displaying the results		
——— (solid line)	3D	Monte Carlo simulations using **true** state variables
········ (dotted line)	↑↓	2-stream simulation using **effective** state variables
– – – (dashed line)	↑↓[1,2]	Same as above but for the first two orders of scattering
–·–·– (dash-dot line)	↑↓[1]	Same as above but for the first order of scattering only



Snow Cover
Near-Infrared
Red
Directional Hemispherical Reflectance
Dense Canopy
3D
↑↓
↑↓1,2
↑↓1
0.7
0.6
0.5
0.4
0.3
0.2
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0 15 30 45 60 75
Sun zenith angle
Sun zenith angle
Sun zenith angle


Snow Cover
Near-Infrared
Red
Directional Hemispherical Reflectance
Sparse Canopy
3D
↑↓
↑↓1,2
↑↓1
0.7
0.6
0.5
0.4
0.3
0.2
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0 15 30 45 60 75
Sun zenith angle



Snow Cover
Near-Infrared
Red
Directional Hemispherical Reflectance
Medium Canopy
Sun zenith angle
Sun zenith angle
Sun zenith angle
0.7
0.6
0.5
0.4
0.3
0.2
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0 15 30 45 60 75
0 15 30 45 60 75
0 15 30 45 60 75
3D
↑↓
↑↓1,2
↑↓1

Adequacy of EO products for further assimilation by Climate/NWP models

- Are they consistent between themselves?
- Are they delivered with documented uncertainty?
- Are they accurate enough so that the models can benefit?
- Do they fit large-scale model's expectations?
- Do Climate/NWP models use the appropriate modeling tools to represent the available products?